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Quantifying the Benefits of Roadside Vegetation

Prepared by

University of Texas Arlington

Kyeong Rok Ryu, Ph.D.

Joowon Im, Ph.D.

June Young Park, Ph.D.

Alireza Shamshiri, Ph.D.

Steven Tanner McCullough

Shikha Somani

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16. Abstract

Transportation agencies and state DOTs have established roadside vegetation programs to enhance sustainability, quality of life, and the aesthetics of the transportation systems. However, a comprehensive toolkit to quantify the benefits and risks of various roadside vegetation types and applications has been largely lacking across the nation, including Texas. This study introduces the Roadside Vegetation Evaluation Toolkit (RVET) for quantifying the benefits of roadside vegetation to address this gap, aiding transportation planners, environmental practitioners, and landscape designers within TxDOT in evaluating roadside vegetation. Incorporating extensive geospatial data, the RVET covers five major aspects: environmental benefits, operational and maintenance measures, lifecycle costs, public perception of roads and vegetation, and public perception of aesthetics. The RVET will assist the statewide implementation of improved roadside vegetation management within the TxDOT system, enhancing the health and safety of Texans. This study delivers a comprehensive evaluation of roadside vegetation, providing valuable insights for stakeholders through detailed measurements across five major modules.

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Prepared for:

Texas Department of Transportation (TxDOT)

Project Manager:

Darrin Jensen

Prepared by:

Kyeong Rok Ryu, Ph.D.

Joowon Im, Ph.D.

June Young Park, Ph.D.

Alireza Shamshiri

Steven Tanner McCullough

Shikha Somani

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University of Texas Arlington | Department of Civil Engineering

425 Nedderman Dr., 416 Yates St.

Box 19308, Arlington, TX 76019

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The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of The Texas Department of Transportation (TxDOT).

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EXECUTIVE SUMMARY

To enhance sustainability, quality of life, and the aesthetics of the built environment, many agencies and Departments of Transportation (DOTs) have implemented roadside vegetation programs. Texas Legislation instructs TxDOT allocating funding for Green Ribbon Program when a highway improvement contract is let in a non-attainment, or near non-attainment county. An amount equal to not less than 0.05% and not to exceed 1% of the project cost shall be allocated for landscape improvements. Currently, there is no comprehensive toolkit quantifying potential benefits of roadside vegetation in Texas. Furthermore, existing guidelines and manuals typically focus on specific aspects of roadside vegetation, such as operations and maintenance, including mowing, cutting, safety, fertilization, herbicide use, and permitted species. This study aims to examine the impacts of roadside vegetation on various state-specific parameters, such as environmental benefits, operational and maintenance considerations, lifecycle costs, and public perception of roads, vegetation, and aesthetics. This toolkit aims to assist everyone working within the TxDOT roadside vegetation division in evaluating proposed roadside vegetation in five comprehensive aspects:

- Environmental Benefits
- Operation and Maintenance (O&M)
- Lifecycle Costs
- Public Perception of Roads and Vegetation
- Public Perception of Aesthetics

Additionally, vegetation is highly variable across the state, and affected by climate and localized environments. Consequently, to achieve a detailed comprehensive evaluation throughout the state of Texas roadways, this study incorporated various geospatial data into the toolkit. The datasets considered and processed through the toolkit include:

(1) TxDOT Roadway Inventory: this includes the primary elements for locating project information and extracting important parameters and elements required for roadside vegetation

(2) TxDOT Control Sections: to make the site selection easier

(3) Precipitation Data: this is provided for each roadway segment, implemented through the intersection of the annual average precipitation raster map (USDA NAIP 1991-2020)

(4) Geological Soil Group Data: sourced from ORNL DAAC (2018), this data classifies

roadside vegetation site soil types, including soil types A, B, C, and D.

Given the thoroughness of the evaluations in each of these modules, the toolkit specifically assesses roadside vegetation by examining detailed aspects within each module which are as follow:

- Environmental benefits

The Roadside Vegetation Evaluation Toolkit (RVET) investigates the most critical aspects of the environmental impacts and their economic benefits within a project. The toolkit investigates each projects impact on soil erosion, carbon capture, urban heat island effect and water runoff as well as each key points economic benefits. While this module uses academic literature to model these benefits, the goal of this module is to be able to provide these results at a high level for the initial planning process and as such should not be used in environmental impact statements.

- Operation and Maintenance

Given the importance of various aspects of operation and maintenance, the RVET provides comprehensive measures and recommendations for mowing, controlling invasive grasses using herbicides, seeding for erosion control, and managing the wildflower program. The goal of this module is to offer considerations for each section, equipping the user with essential information regarding the operations and total cost of each activity.

- Lifecycle Costs

To gain detailed insights into the long-term benefits of roadside vegetation, the RVET has implemented lifecycle cost measurements with a 20-year projection. This analysis includes the start year of the vegetation project, along with parameters for discount and inflation rates.

- Public Perception of Vegetation and Aesthetics

The RVET provides crucial insights into how roads, vegetation, landform, cultural and landscape features impact public perception. Through extensive literature reviews and 34[*] collected surveys, RVET assesses the appeal of roadside vegetation combinations from a driver's viewpoint, using a 5-point Likert scale to rate each sector as highly desirable, neutral, undesirable, or highly undesirable.

The RVET also evaluates road features by examining factors such as road type, number of lanes, speed limits, and clearing width. It assesses vegetation features through factors such as tree

[*] Public survey conducted was a small sample focus group from a local community and may not be representative of other regions.

height and vegetation type, with automated calculations for grass height and density based on survey inputs. The landform features reviews how topography shape public opinion on roadside vegetation. The cultural and landscape features consider native plant species, wildlife habitat suitability, roadside topography, and water features to determine their impact on the overall aesthetic and ecological quality of roadside environments.

The results and findings of the RVET are poised for statewide implementation of roadside vegetation management within the TxDOT roadway system. This research delivers an evaluation of roadside vegetation across five major modules.

CHAPTER 1 – INTRODUCTION

The TxDOT invests $36 million annually in the Green Ribbon Program, which includes roadside vegetation to create green road landscapes. According to Executive Order 1-92, "*The department will maintain highway vegetation in an environmentally sensitive and uniform manner consistent with the special conditions presented by local climate, topography, vegetation, and level of urbanization.*" The RVET is equipped with an integrated database that includes TxDOT roadway inventory, hydrological soil groups, precipitation, and control sections to quantify major tasks across five modules: environmental benefits, operation and maintenance, lifecycle costs, and public perception toward road, vegetation, and aesthetics. This toolkit supports and enables users involved in roadside vegetation management in Texas to evaluate:

(1) Environmental Benefits:
- Measuring carbon capture
- Heat island mitigation
- Soil loss
- Runoff reduction

(2) Operation and Maintenance: Providing insights and suggestions for
- Mowing.
- Herbicide application by providing suitable herbicides and associated safety and usage considerations.
- Seeding for erosion control includes proposing various types of wildflower and grasses suitable for controlling erosion control.
- Wildflower program which suggests suitable wildflowers per district according to the proposed Integrated Vegetation Management Program.
- Litter removal which measures the condition of each project based on the number of litters exist in each project, tailored to specific project conditions.

(3) Lifecycle Costs: Offering a 20-year projection of costs and benefits of measured parameters mainly considering installation, operation and maintenance, and environmental benefits over a 20-year projection.

(4) Public Perception of Road and Vegetation - Road Experiences: This explores how roadside vegetation and landscape design impact driver safety, visibility, and overall road

experiences. The presence of well-planned vegetation can serve functional roles, such as reducing glare from headlights, providing visual and auditory barriers in populated areas, and influencing driver behavior by altering perceived lane widths, potentially reducing speeds and accident severity. Vegetation can also improve the road experience by offering visual interest and breaking the monotony of roadside environments, which helps keep drivers' alert.

(5) Public Perception of Road and Vegetation – Aesthetics: This evaluates the preferences of road users and drivers regarding the aesthetics and visual appeal of roads and vegetation. It explores how various combinations of attributes, such as vegetation types, densities, and heights, influence perceptions of scenic beauty. Studies indicate that a diverse range of well-maintained vegetation can significantly enhance the visual appeal of roadways. Additionally, research shows that both cultivated and wild green elements contribute positively to the aesthetic experience, impacting overall satisfaction with the roadside environment. By examining these preferences, the toolkit aims to guide better landscape design practices that align with public expectations and improve the visual quality of transportation corridors.

This research aims to quantify the benefits of roadside vegetation in Texas by providing an evaluation toolkit to assess TxDOT roadside vegetation projects across five modules. This technical report explains the tasks performed to develop the RVET. The report is organized as follows:

- Chapter 1: Introduction
- Chapter 2: Current Practices and Knowledge
- Chapter 3: Research Objectives and Framework
- Chapter 4: Integrated Roadside Vegetation Database
- Chapter 5: Assessment Methods for Modules
- Chapter 6: Conclusions

CHAPTER 2 – CURRENT PRACTICES AND KNOWLEDGE

Considering the broad scope of roadside vegetation management and its critical importance based on project locations, this research presents a comprehensive literature review of existing manuals and practices from recent years. To provide a structured overview, this section is organized into three key categories: federal roadside vegetation practices, TxDOT roadside vegetation practices, DOTs roadside vegetation practices, and relevant research closely linked to roadside vegetation. The detailed findings for each category are explained below:

2.1 Federal's Guideline, Policy, and Recommendations

This section will briefly go over the different existing practices and policies that are in place for roadside vegetation. These policies typically cover the types of standards used for environmental impacts and standards used. The Federal Highway Administration (FHWA) has commissioned several studies that have resulted in best management practices and preferred policy for managers, these studies range from the logistics to the types of vegetation and pollinator species used to support the vegetation.

2.1.1 Existing TxDOT Vegetation Research and Practice

Currently there are a variety of reports delivered to TxDOT from various academic and government agencies regarding the best practices of roadside vegetation management. The research team has taken notice of several of these reports regarding maintenance, desired and used species as well as general procedure. Many of these reports span the range of nearly half a decade of research. The team's research stems originally from Research report 67-7 where standards and practices were implemented for seeding summer and winter grasses for erosion control by highways. These standards have been subsequently updated throughout each decade with additional guidelines regarding pre-emergent control, seeding mixes and other additions to improve roadside vegetation. Reports used by the research team are specifically the vegetative barrier reports submitted through the Transportation Institute at Texas A&M University for use at TxDOT. In addition, the FHWA has since commissioned best practice guidelines regarding various aspects of roadside vegetation management.

2.1.2 Federal Highway Administration Reports and Manuals

In 2007 the FHWA published a comprehensive report (FHWA-WFL/TD-07-005) that establishes the best approaches to integrating native vegetation to roadsides. The report breaks down the process into the initiation, actual planning phase and the implementation of the vegetation. Each of these sections has more detailed reports within regarding more specific subjects.

The initiation section is geared towards high level planning and providing universal terminology, examples and such for planners and other stakeholders involved. A large portion of this section specifically mentions each aspect of preliminary planning, identifying key stakeholders, timeline creation and recordkeeping. The latter half of the initiation in this report just establishes what terminology, plan conventions and technical concepts for non-engineers and planners.

FHWA breaks the planning phase into four major components:

1. Project objective definition, units and reference sites and future conditions.
2. Technical site assessment, including water availability, sloping, vehicle traffic etc.
3. Vegetation assessment, specifically the species list, requirements and needs.
4. Integration and strategy: The actual implementation and construction process.

The first phase covers the higher-level analysis of the project to layout the foundations for the other three sections of this report. The RVET toolkit combines portions from the other three sections but primarily focuses on this section for higher level analysis. The first step in the planning process as listed in this report is to define the level of change that is desired in this area. This can range from total restoration to visual enhancement or erosion control. Once this goal has been defined the other project parameters are defined in this phase, size and scope of the area. Ultimately the three subsequent sections of this toolkit are determining the specifics of achieving these goals. The last phase of this report details the logistics of implementing these changes and any requirements needed for construction. The RVET primarily equipped with quantity takeoff dashboard to estimate costs at an earlier level than in a traditional planning process.

This roadside manual that the FHWA has developed does not provide detail environmental factors of vegetative barriers, but describes the logistics of implementing them. The FHWA and USDOT have published reports that describe the effects of the plants on pollinators and the effects, pollinators have on supporting roadside vegetation. The report explains the biology of pollination and the benefits pollinators have on roadside habitats. The first part of the report details the importance of pollinators in both maintaining roadside vegetation and the surrounding areas including vegetation nowhere near roadsides. The report details the types of foods that various pollinators need as well as the types of shelters they require to live, giving insight to planners into what types of vegetation and what methods should be used to support them. The report details a decline in pollinators due to various factors like disease, lack of food and resources and the growing urbanization around cities. The report suggests that roadsides can be a potential stopgap for the decline in pollinators with roadside habitats being able to become diverse areas for pollinators and other forms of beneficial wildlife. The report references a study that stated the benefit of roadside vegetation is the greatest in runoff reduction in terms of dollar amounts. The report continues to detail the different challenges to implementing more roadside vegetation like invasive and noxious weeds. The report does give some best practices to promote pollinators, and they are as follows:

- Do not mow more than twice during the growing season.
- Optimal mowing time can vary based on the pollinators but delaying mowing until after the first frost will benefit pollinators.
- Delayed mowing can help spread wildflower seeds for next season's growth while benefiting overwintering and ground-nesting pollinators, as well as aiding in erosion control.

Other recommendations relate to herbicide use, controlled burning and grazing. The use of biological control agents has not been performed in this study and should be avoided. The report also details a handful of plants for various regions that can support pollinators with planting seasons, types and what they adapt for. The report also details several case studies with uses of these flowers, the report suggests that the best practices for flowers involve more hardy plants that require less mowing, as a 1996 case study in Indianna reported a nearly 85% reduction in mowing costs by using prairie wildflowers for erosion control. FHWA gives some guidelines for planting use, specifically that:

- For erosion control, more native/perennial bunch grasses should be included with wildflower mix.
- Landscape projects meant to be front facing should include a higher proportion of

wildflowers in their seeding mix.

- Seed mixes should be highly diverse, including at least 15 species of wildflowers.
- Include butterfly and moth host plants in seed mixes, such as milkweed.
- Attempt to include plant species that provide shelter for pollinators; for instance, native and tall grass species offer nesting sites for native bumblebees.
- Prioritize locally sourced native plant material.

The FWHA gives these guidelines as general practice for designers to use when creating roadside vegetation projects to be able to maximize the benefits to pollinators.

The FHWA also provides a handbook that was revised in 2008 that gives planners and practitioners guidelines for safety considerations for roadside vegetation (Eck 2008). Highway safety must not be comprised during any time in a project's timeline. The manual gives general guidelines that are primarily based on visual line of sight for drivers and prevention of visual blocking but does also cover other topics like drainage and pedestrian pathways.

Most of the recommendations in these guidelines are typically consistent with Department of Public Safety requirements for signage. All signs and stoplights must not be blocked by vegetation, even partially and must be visible from an appropriate distance. The manual also talks about blind cornering, if possible roadside projects must attempt to leave open spaces to allow drivers to maintain a good line of sight of the road ahead. This can include intersections, tight corners and railway intersections. This specifies that trees close to roadways must be paid special attention to but does give minimum distances that are recommended for prevention of accidents as shown in the table below.

Table 1. Clear Distances to See Signage (Eck 2008)

Speed Limit [mph]	Critical Signs [ft]	Noncritical Signs [ft]
30	250	150
40	350	200
50	450	250
60	600	300

A large portion of the manual is dedicated more to local operators and maintenance personnel for mowing operation and planning. The manual does detail comprehensive methods of keeping vegetation out of a driver's line of sight to allow for proper stopping distances.

For projects in more urbanized settings the manual describes the use of vegetation as a 'cushion' of sorts for pedestrian pathways. Vegetation projects should consider using vegetation in a way that does not obstruct driver views but is able to provide some form of barrier between pedestrian pathways and the roadway. The manual references the Americans with Accessibility Guidelines Handbook for trimming and pruning heights for trees that share space with roadways and pedestrian paths.

2.2 Texas Department of Transportation (TxDOT) Practices

The Texas Department of Transportation (TxDOT) development process sets an example of how landscape architects work with experts of other disciplines. Professionals trained in construction materials and management, earth and environmental scientists, geologists, aesthetics, and technology work with these landscape architects. Combining engineering and safety measures with environmental and aesthetic issues is the primary goal of these landscape architects who are assisting in highway design and planning. Landscape architects working in transportation sector have 6 main responsibilities such as: (1) commuter's safety; (2) conservation of natural resources like air, water, land, scenic locations, cultural, and historic resources; (3) minimizing the negative environmental cultural impacts; (4) mitigating erosion and drainage issues in new construction; (5) combining the transportation network into the surrounding landscape; and (6) improvement of the aesthetics of the transport systems.

Storey et al. provided a series of options and tools for TxDOT personnel based on Texas Pollutant Discharge Elimination System (TPDES) policy requirements for timely vegetation establishment, minimize project delays, and reduce long term vegetation management costs. This research was mainly done by (1) comparing TxDOT practices with other DOT's, (2) identifying methods of rapid vegetation establishment, (3) proposing a tool to assist design personnel who are not familiar with vegetation establishment, and (4) developing a guidebook for vegetation establishment. Stacks revised the roadside vegetation manual for TxDOT. The focus of the proposed guideline is as follows: (1) improve safety for travelers, (2) improve environmental protection, (3) preserve and promote native wildlife, (4) mitigate erosion by adequate drainage, and (5) enhance coordination for maintenance activities. The research provided has guidelines specifically for mowing, pruning, native grasses, and wildlife habitat (TxDOT 2018).

The TxDOT's Landscape and Aesthetics Design Manual incorporates many safety criteria in the guidelines for roadside landscape and aesthetic treatments. Planting guidelines used by TxDOT are as follows: 1) Roadside vegetation should be designed or maintained to accomplish specific goals of sight distance, clear view of obstructions, erosion control, and aesthetics. 2) Plants must not be planted where they may obstruct any signs, sightlines, or driver visibility. 3) On frontage roads, allow at least 3 feet clear space between the back of curb and any area to be maintained for maintenance personnel. 4) Plant use in intersection areas must be limited to low-growing varieties. 5) Plants must not be placed near merging lanes. 6) Landscape improvements must avoid the creation of unsafe conditions for motorists or maintenance personnel.

The Texas Department of Transportation emphasizes the importance of effective roadside vegetation management to ensure safety, environmental sustainability, and aesthetic appeal. TxDOT's approach encompasses a variety of practices including mowing, herbicide application, wildflower conservation, erosion control, and managing invasive species. TxDOT ensures that all vegetation management activities comply with state and federal regulations. Coordination between different maintenance divisions and environmental agencies is essential to achieve the desired outcomes (TxDOT 2018).

2.2.1 Levels of Vegetation Management

TxDOT categorizes vegetation management into different levels based on the type of highway (urban or rural) and specific conditions (e.g., areas near wildlife habitats or conservation zones) (TxDOT, 2018).

- Developed Urban Highways: These areas typically require higher levels of maintenance, including frequent mowing and trimming, ornamental plantings, and herbicide applications to control unwanted vegetation.
- Rural Highways: Maintenance in these areas focuses on safety, visibility, and preventing the spread of invasive species. Practices include spot mowing for safety and limited full width mowing cycles to balance ecological concerns and safety needs.

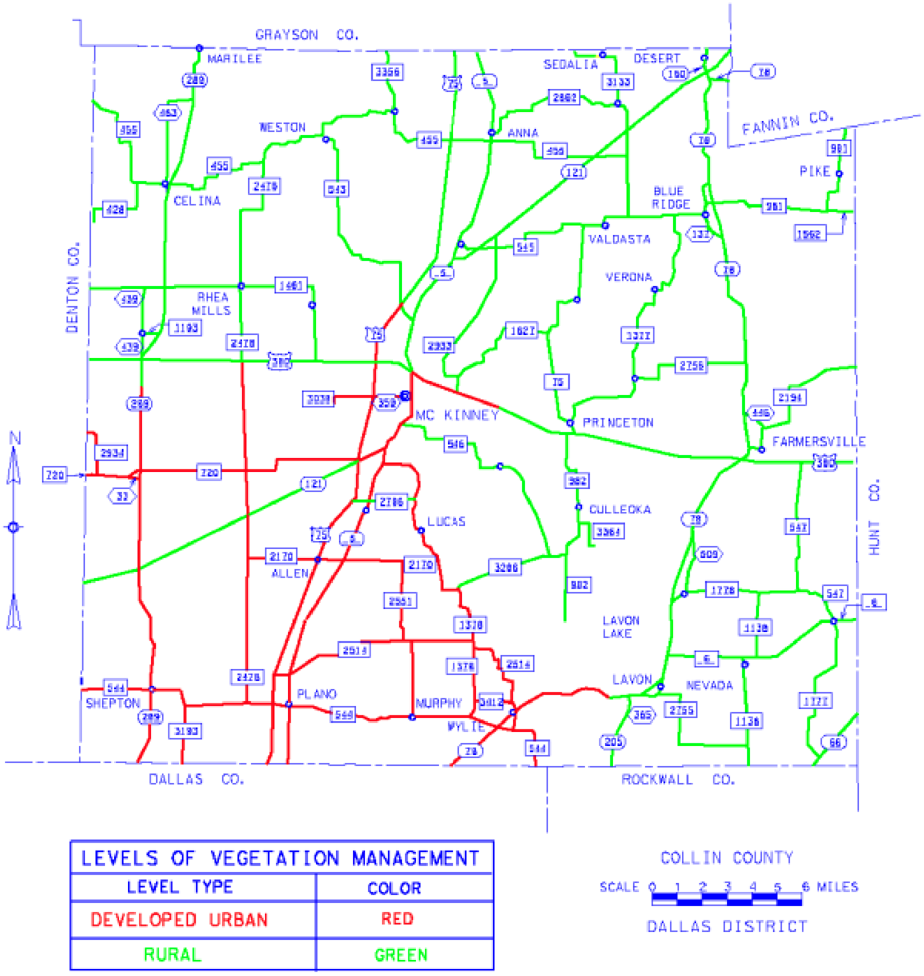

Figure 1. Two levels of right of way vegetation management, Developed Urban and Rural (TxDOT 2018)

2.2.2 Mowing Practices

Mowing is a key component of TxDOT's vegetation management strategy. Mowing frequency significantly influences grass composition. Short, sod-forming grasses adapt well to frequently mowed areas (3-4 times a year), whereas tall native grasses thrive in less frequently mowed areas. In non-mowed areas, tall native grasses increase, while introduced grasses decrease. Thus, mowing favors certain plant populations, often non-natives, adapted to roadside conditions. Mowing is identified as a significant disturbance that influences the successional process of roadside vegetation by altering resource allocation, including light, soil nutrients, and carbon allocation to shoots. The timing, frequency, and height of mowing cuts can greatly impact overall vegetation health. For example, frequent mowing tends to favor short, sod-forming grasses, while less frequent mowing allows for taller native species to thrive (Ming-Han Li et al. 2007). There are several types of mowing used:

- Modified Full-Width Mowing: This involves mowing up to a maximum width of 30 feet, primarily along rural highways. Exceptions to this width are made based on specific needs and conditions.
- Strip Mowing: Used mainly for medians and outer separations in rural areas, strip mowing maintains a neat appearance and prevents overgrowth that could impede visibility.
- Spot Mowing for Safety: This targets specific areas where vegetation might obstruct signs, sightlines, or create hazards for motorists.
- Special Mowing Situations: Includes areas like intersections, rest areas, and picnic areas which require tailored mowing practices to ensure safety and accessibility.

Mowing alters the light regime for plants. Leaving clippings behind can reduce light exposure, while removing them allows for more direct sunlight to reach regrowing plants. Mowing and removing clippings can cause a loss of over 50% of soil nutrients, impacting long-term soil health and plant growth. Frequent mowing can enhance plant species richness by reducing the size of dominant plants, allowing more species to coexist.

2.2.3 Herbicide Application

TxDOT uses both herbicide and mechanical methods to manage roadside vegetation. Herbicides are often preferred due to lower costs (less than 10% of mechanical trimming costs) and their ability to prevent regrowth for longer periods (Storey et al., 2011). The herbicide glyphosate is currently approved for use by the MNT division for its effectiveness and low risk of over-application. Glyphosate is the most effective when applied in the fall, especially in September and October, for reducing johnsongrass density. Environmental conditions, such as rainfall, also play a role, with glyphosate's efficacy reduced by rain within 12 hours of application (Allen & McCully, 1976a). Herbicides are employed to control unwanted vegetation, particularly noxious weeds and invasive species that mowing alone cannot manage. As per the Best Practices Handbook for Roadside Vegetation Management (2008), application techniques included using hand sprayers equipped with adjustable nozzles, and proper calibration of equipment is emphasized to ensure the correct concentration and coverage (Johnson 2008). Care must also be taken to avoid damage to desirable vegetation. The application of herbicides must be carefully coordinated with mowing operations to prevent damage to desirable plants and to ensure effective weed control (TxDOT, 2018). Herbicide treatments are applied during specific growth stages of the target plants to maximize their efficacy. TxDOT follows strict guidelines to minimize environmental impact and ensure the safety of road users.

2.2.4 Wildflowers and Native Plants

TxDOT prioritizes the use of native and introduced grasses, wildflowers, and legumes to enhance roadside environments (TxDOT 2018). It emphasizes using native and naturalized plants because they are better adapted to Texas's extreme temperatures, varying rainfall, and differing soil conditions, requiring less maintenance, water, and fertilization. Key advantages of these plants include stabilizing the soil through deep root systems that reduce erosion and improve soil health. They also support local wildlife by offering vital food and shelter, while wildflowers and grasses enhance the visual appeal, seamlessly integrating highways with the natural landscape. TxDOT has made strides toward including more native species in its planting mixes, driven by the need to reduce maintenance costs and address concerns about invasive species. The use of native plants improves the ecological integrity of roadside environments while also meeting aesthetic and functional goals (Li et al., 2007). The establishment of wildflowers and native plants is particularly emphasized in highway rights-of-way (ROW), where fast-growing annuals such as wheat or rye grass are used to stabilize slopes and serve as nurse crops for desired perennials. This approach helps improve the appearance of ROW during the initial establishment year required by perennials that form the majority of TxDOT seed mixes. It is noted that incorporating compost into the soil or applying it as mulch can retain soil moisture effectively. However, while a 4-inch layer of compost can be beneficial, layers greater than 2 inches may hinder seed emergence, particularly for perennial grasses, which struggle to establish when compost mulch exceeds 1 inch in depth. The use of compost with varying feedstock constituents is also explored, as it can influence nutrient availability and the overall success of vegetation establishment. Overall, the integration of wildflowers and native plants into TxDOT's practices is aimed at enhancing biodiversity, improving roadside aesthetics, and providing long-term ecological benefits. Through careful plant selection and strategic compost use, TxDOT further ensures the success of its roadside vegetation projects.

2.2.5 Pruning Practices

Tree Pruning is necessary to maintain clear zones and sight distances, particularly around utility lines and road signs. Correct Pruning also promotes the health of trees and shrubs by removing dead or diseased branches. Safety is the primary concern in pruning, which involves maintaining clear zones on either side of and above the roadway, and removing low branches that could pose hazards to equipment operated on the right of way. Aesthetic pruning is done to enhance the visual appeal of roadside vegetation without compromising plant health. All pruning practices must adhere to recognized standards, such as those set by the American National Standards Institute (ANSI A300 Part 1-2001), ensuring consistency and quality. Pruning may also involve removing suckers, branches that grow too close together, or branches that cross and rub against each other. It is important to avoid unacceptable practices, such as severe pruning that can damage trees or create an unsightly appearance. Utility companies are held accountable for correcting improper pruning to ensure that roadside vegetation remains healthy and aesthetically pleasing (TxDOT, 2018). TxDOT ensures that pruning is conducted safely, effectively, and in a manner that supports both the health and aesthetics of roadside vegetation.

2.2.6 Erosion Control

Erosion control is crucial for maintaining the integrity of road infrastructure. Therefore, TxDOT utilizes various techniques such as sodding, seeding, and installing erosion control blankets. All field plots, regardless of slope, soil type, or mowing practices, effectively control erosion. Vegetation yielded sediment amounts significantly below TxDOT’s allowable limits, indicating strong erosion control capabilities (Li et al. 2007). The establishment of perennial vegetation is a primary method for erosion control. TxDOT requires a uniform vegetative cover with a density of at least 70 percent of the native background vegetative cover before a Notice of Termination (NOT) can be filed. Temporary erosion control measures, such core logs, are designed to provide erosion control for at least three years without active maintenance by the operator. TxDOT specifies that all soil disturbing activities must be completed, and temporary erosion control measures must be installed to achieve the required vegetative coverage. Storm Water Pollution Prevention Plan (SW3P) addresses temporary erosion and sediment control measures for construction sites, ensuring that adequate controls are in place to manage erosion and sedimentation. TxDOT emphasizes the importance of training for inspectors and contractors to ensure that erosion control measures are implemented effectively.

2.2.7 Focused Areas

Specific areas like rest stops, picnic areas, and urban intersections demand a higher level of maintenance to remain both visually appealing and safe for public use. Turf establishment and upkeep are crucial in these locations such as regular mowing, trimming, and selective application of herbicides to a well-groomed appearance. Focused areas are generally under separate landscape maintenance contracts, characterized by higher-level landscape and ornamental plantings. Focused areas can be found in both urban and rural settings, with maintenance practices varying based on the surrounding land use and requirements. While these areas are maintained separately, they should still align with the overall vegetation management strategies, which emphasize safety, environmental protection, and the preservation of native wildlife habitats.

2.2.8 Wildlife Habitat and Native Plant Conservation

Efforts are made to protect wildlife habitats and conserve native plant species. This includes identifying non-mow areas adjacent to conservation lands and employing vegetation management practices that support habitat preservation. Human intervention is identified as a significant factor in environmental changes affecting native species. Native species, having adapted to local conditions, provide essential habitat for various wildlife species. The use of native plants enhances biodiversity and ecological stability in roadside environments. Establishing native vegetation improves ecological conditions, benefiting wildlife, as these plants have evolved alongside local fauna, offering food and shelter that non-native species may not provide. The integration of native plants into roadside management not only addresses erosion control and aesthetic concerns but also plays a significant role in wildlife habitat conservation (Li et al. 2007). Native grasses have evolved over time to withstand harsh environmental conditions, making them essential for creating stable vegetation communities. Local plants are best suited to thrive in their specific environments, which is crucial for maintaining local biodiversity, including native insect, bird, and mammal populations. TxDOT has been incorporating native grass species into its vegetation establishment programs for many years. The feasibility of using an all-native species seeding mix for roadside vegetation highlights the advantages of native plants in restoration and habitat enhancement. The use of native plants not only supports wildlife but also helps preserve the botanical and aesthetic heritage of the region. Native plants are recognized for their ability to stabilize soil, prevent erosion, and improve water quality by reducing nutrient leaching. Various trials comparing native and standard seed mixes indicate that while both mixes can achieve good vegetative cover, the composition of species and their performance can vary significantly (McFalls et al. 2006). TxDOT's roadside vegetation management practices aim to preserve and enhance wildlife habitats. This includes the strategic planting of native species that provide food and shelter for various wildlife. Roadsides serve as important habitats for many species, offering corridors and refuges in otherwise fragmented landscapes. Proper management can significantly contribute to biodiversity conservation (TxDOT 2018).

2.2.9 Threats and Degradation of Habitat

The successional processes of plant species on roadsides are complex, involving competition for resources among various species. While native species often possess characteristics that enhance their competitive abilities, habitat changes have diminished their dominance in these areas. Organizations like TxDOT are implementing sustainable management strategies, such as using mowing and herbicides to control invasives species and promote native plants. Maintaining native vegetation is crucial to restoring ecological balance and providing better habitats for local wildlife. Overall, threats to habitat and ecosystem degradation are closely tied to the balance between native and non-native species (Li et al. 2007).

2.2.10 Invasive Species Management

TxDOT actively manages invasive species to prevent them from displacing native vegetation and disrupting ecosystems. This involves identifying and targeting invasive species through both mechanical and chemical means (TxDOT 2018). Invasive species can significantly threaten the integrity and function of ecosystems by reducing species diversity. To address this, TxDOT utilizes native plant seeds in roadside management to prevent the introduction and spread of invasive species. Overall, the management of invasive species is framed within the broader context of promoting native plant establishment and maintaining biodiversity in roadside environments (Li et al. 2007).

2.3 Other DOTs Practices

In addition to TxDOT's roadside vegetation management practices, various state DOTs have developed strategies to improve vegetation management along roadways. These practices address the unique challenges faced by each state and highlight best practices and tailored solutions for specific tasks. The following sections provide a detailed overview of the areas where each state is focusing its roadside vegetation management efforts:

2.3.1 Washington State Department of Transportation (WSDOT)

The Washington State Department of Transportation (WSDOT) provides detailed and comprehensive ecological-based practices for roadside vegetation design and management that aim to create low-maintenance, self-sustainable vegetation conditions, using native plants planted in the right locations along the roadways (WSDOT 2023). WSDOT provided a roadside policy manual that promotes the protection and conservation of resources for sustainable roadside vegetation and supports pollinator habitat and restoration by focusing on planning, program management, project development, construction, and maintenance (Hartwig 2022). The proposed Roadside Classification Plan by WSDOT provides guidelines on roadside character classifications and suitable treatment levels for vegetation and revegetation plans. The inclusion of a WSDOT landscape architect in the design development process can aid the design process and improve the environmental and visual quality of Washington's roadsides. In addition to the Roadside Manual, the WSDOT also provides an IRVM program, which enables maintenance crews to apply proper techniques and appropriate timing to take care of the soil and vegetation alongside highways, primarily for:

1. Mowing and trimming

2. Herbicide use

3. Release of weed-eating insects

4. Soil improvement

5. Planting native plants

Furthermore, WSDOT developed a Maintenance Accountability Process (MAP) tool, which measures and quantifies the outcomes of maintenance activities, including vegetation-related tasks, based on a 5-scale rating system (Dye and Rus 1997). This system reports the condition of roadside activities and maintenance, ranging from 1.0 as the best condition to 5.9 as the worst condition. An illustration of the roadside and landscape based on Level of Service (LOS) is shown in Figure 2.

Service Level – **A** – Roadside has minimal visible litter, no noxious weeds, nuisance vegetation, or vegetation obstructions. Ditch lines, guardrail, signs and sight lines are completely visible.

Service Level – **B** – Roadside has a minor amount of visible litter, noxious weeds, nuisance vegetation, or vegetation obstructions. Ditch lines, guardrail, signs, and sight lines are slightly obscured by encroaching vegetation.

Service Level – **C** – Roadside has a moderate amount of visible litter, noxious weeds, nuisance vegetation, or vegetation obstructions. Vegetation is starting to encroach on the pavement edge, moderately obscuring ditch lines, guardrail, signs, and sight lines.

Service Level – **D** – Roadside has a significant amount of visible litter, noxious weeds, nuisance vegetation, or vegetation obstructions. Vegetation is encroaching on the pavement edge, significantly obscuring ditch lines, guardrail, signs, and sight lines.

Service Level – **F** – Roadside has a extensive amount of visible litter, noxious weeds, nuisance vegetation, or vegetation obstructions. Vegetation has encroached on the pavement, extensively obscuring ditch lines, guardrail, signs, and sight lines.

Figure 2. WSDOT Roadside and landscape Maintenance LOS Matrix (Dye and Rus 1997)

2.3.2 Ohio Department of Transportation (ODOT)

The Ohio Department of Transportation (ODOT) is dedicated to controlling noxious weeds and invasive grasses along Ohio roadways. The manual, "*Guide for Roadside Integrated Vegetation*

Management (RIVM) of Prohibited Noxious Weeds in Ohio," serves as a practical field guide designed to assist in the identification and control of noxious weeds and invasive plants (ODOT 2023). It includes detailed instructions on herbicide application and provides worksheets for effective management. This manual offers both visual and practical recommendations to ensure proper vegetation control practices.

The Ohio Department of Transportation (ODOT) has identified and assessed various vegetation management strategies to enhance the effectiveness and efficiency of roadside maintenance tasks. These strategies aim to improve worker safety, promote safe highway use for the public, and enhance roadside aesthetics. The research project by Gulick et al. involved 25 different field tests, categorized into four management zones as illustrated in Figure 3. Some tests were repeated in various environments to develop a management matrix that improves productivity, effectiveness, and cost-efficiency, as shown in Figure 3 (Gulick et al. 2017).

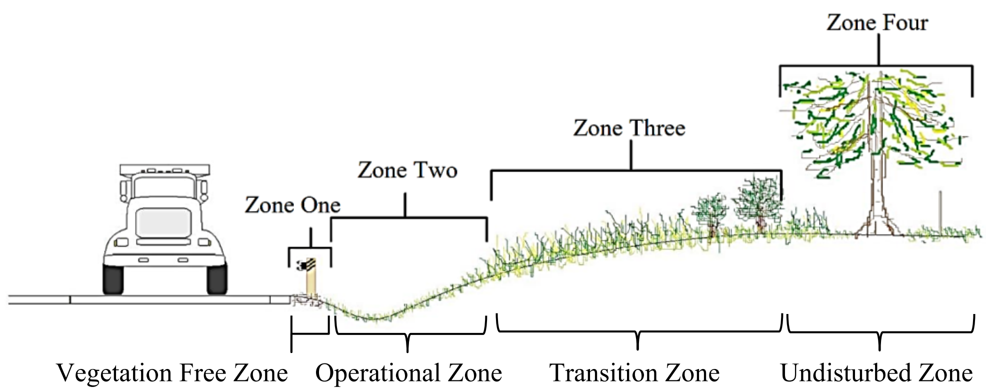

Figure 3. Diagram of ODOT's Roadside Management Zone (Gulick et al., 2017)

The additional objectives of this research include:

1. Increasing worker and road user safety.
2. Enhancing environmental stewardship by using eco-friendly pesticides to control invasive and illegal plants, thereby reducing the need for mechanical maintenance and lowering fossil fuel use and emissions.
3. Evaluating the use of novel chemical techniques for vegetation management.
4. Improving workforce proficiency with tools and pesticides.

5. Reducing the number of invasive species and hazardous weeds in the right-of-way (ROW).
6. Extending maintenance cycles for woody and herbaceous plants.

This manual provides comprehensive instructions and visual aids to implement these strategies effectively (Gulick et al. 2017), as depicted in Figure 4.

Brush/Shrub/Small Tree (< 6" Diameter) Maintenance & Removal

Current ODOT Process

Description: Brush, shrubs, and trees under 6" diameter are not maintained by a standardized procedure. In general the work involves mowing with a flail or rotary mower and no herbicide treatment regardless of the vegetation composition.
ODOT's Presented Challenges: Vegetation Encroachment has out-paced vegetation management activities. Crews would like to catch up but are faced with manpower time and equipment constraints.
Davey's Observations: Small trees and shrubs are left to grow larger and larger in diameter making their removal require greater effort. Often trees are maintained when they should be removed to provide a long-term solution to the vegetation on a site. Rotary and flail mowers do not leave proper cuts thus leaving vegetation susceptible to disease, pests, failure, and fast growing water sprouts that are poorly attached.
Recommendations: Tall growing vegetation that requires continued maintenance and is incompatible with ODOT's maintenance abilities should be removed. No or low maintenance vegetation should be planted to prevent competition by unwanted species. Small trees should be removed while still small to avoid vegetation encroachment and to reclaim the right of way. Herbicide should be applied by an appropriate method either before or after removal to prevent regrowth.

Goal	Approach	Recommended Improvement	Timing / Frequency	Notes / Considerations	Potential Benefit	Herbicide Cost (not included in the Purchase Price)	Purchase Price of * Equipment	Operational Cost Per Hour	Personnel Scale	Return on Investment	IVM Follow Up
Preservation & Enhancement (Maintenance through Selective Removal of Non-Desirable Vegetation) *OR* Encroachment Prevention (Removing All Vegetation)	Herbicide Treatment *BEFORE* Selective Removal	2 Backpack Sprayers* Foliar Application of Non-Selective Herbicide* Tractor and Flail Mower[1] String Trimmer Truck with Trailer	**Mechanical:** Any time of year. **Chemical:** Foliar Applications must be done during the active growing season. Basal Bark Applications can be applied anytime of year when temperatures are above freezing.	If non-desirable vegetation is well distributed, use a Skid Sprayer with Hose Reel and 4x4 Truck, if it is sparse, consider more precise, spot treatments with a Backpack Sprayer. They can also be used together in mixed areas. Allow at least one week between herbicide application and removal. It may be advisable to allow desirable grass species to establish for purposes of having ground cover until the shrub layer becomes dominant. Monitor brush for site distance or hazard potential. Standard Hand Tools for these operations include chainsaws, lopping shears and pruning saws.	Tractors, Flail, and Rotary Mowers are standard equipment in ODOT garages. Rotary mowers allow for mowing on slopes and ditches. Builds upon an already common vegetation management process. The cost of additional *Mechanical* equipment should be very low. Basal Bark and Foliar Applications allow for flexibility in timing.	Glyphosate $17/gallon (3.8 liters)	$$	$$$	🧍🧍🧍🧍	★★★	1. Prepare site for planting desired vegetation as needed. 2. Replant area with low maintenance vegetation. 3. Monitor for undesirable plant species. 4. Employ cultural practices to enhance desirable vegetation as needed. 5. Apply selective herbicides to control unwanted vegetation as needed.
		Skid Sprayer with Hose Reel* and 4x4 Truck Foliar Application of Non-Selective Herbicide* Tractor and Flail Mower[1] String Trimmer Truck with Trailer					$$$$$	$$$$	🧍🧍🧍🧍🧍	★★★★	
		2 Backpack Sprayers* Basal Bark Application with Non-Selective Herbicide* Tractor and Flail Mower[1] String Trimmer Truck with Trailer				Glyphosate $17/gallon (3.8 liters) Imazapyr $168/gallon (3.8 liters) Triclopyr $64/gallon (3.8 liters)	$$	$$$	🧍🧍🧍🧍	★★★	
		2 Backpack Sprayer* Foliar Application of Non-Selective Herbicide* Tractor and Rotary Mower[1] String Trimmer Truck with Trailer				Glyphosate $17/gallon (3.8 liters)	$$	$$$$$	🧍🧍🧍🧍	★★★★★	
		Skid Sprayer with Hose Reel* and 4x4 Truck Foliar Application of Non-Selective Herbicide* Tractor and Rotary Mower[1] String Trimmer Truck with Trailer					$$$$$	$$$$	🧍🧍🧍🧍🧍	★★★★	
		2 Backpack Sprayers* Basal Bark Application with Non-Selective Herbicide* Tractor and Rotary Mower[1] String Trimmer Truck with Trailer				Glyphosate $17/gallon (3.8 liters) Imazapyr $168/gallon (3.8 liters) Triclopyr $64/gallon (3.8 liters)	$$	$$$	🧍🧍🧍🧍	★★★	
		2 Backpack Sprayers* Foliar Application with Non-Selective Herbicide* Forestry Mulcher on Skid Steer[1] String Trimmer Truck with Trailer			For brush over 1" in diameter a forestry mulcher is extremely effective. Will reduce the need for multiple vegetation control methods. Will save time due to its ability to control a wide range of brush sizes and types, including vines and small trees. Basal Bark and Foliar Applications allow for flexibility in timing.		$$	$$$	🧍🧍🧍🧍	★★★	
		Skid Sprayer with Hose Reel* and 4x4 Truck Foliar Application with Non-Selective Herbicide* Forestry Mulcher on Skid Steer[1] String Trimmer Truck with Trailer					$$$$$	$$$$	🧍🧍🧍🧍🧍	★★★★★	
		2 Backpack Sprayers* Basal Bark Application with Non-Selective Herbicide* Forestry Mulcher on Skid Steer[1] String Trimmer Truck with Trailer					$$	$$$	🧍🧍🧍🧍	★★★	

Figure 4. Maintenance Matrix Based on Field Tests (Gulick et al. 2017)

2.3.3 Oklahoma Department of Transportation (ODOT)

The Oklahoma Department of Transportation (ODOT) developed an IRVM program, which is a collection of techniques and processes designed to satisfy the department's environmental and economic vegetation goals (Montgomery et al. 2010). The ODOT Roadside Vegetation Manual primarily follows these goals:

1. Enhance safety for both travelers and employees by reducing roadside vegetation hazards and minimizing driver fatigue.
2. Manage highway vegetation with environmental sensitivity and consistency by protecting and reintroducing native grasses, controlling invasive and harmful weeds, and maintaining or improving water quality and wildlife habitats.
3. Deliver economic benefits by efficiently using taxpayer dollars to protect and extend the life of infrastructure, fostering sustainable vegetation communities.
4. Develop or maintain visually appealing roadsides.

2.3.4 Virginia Department of Transportation (VDOT)

The Virginia Department of Transportation (VDOT) emphasizes specific mowing practices and guidelines (VDOT 2010). Mowing is performed and quantified based on service levels A, B, C, D, and E:

Service Level A:

- Mow up to 18 feet from the pavement/paved shoulder edge or to the centerline of the ditch, whichever is less.
- No more than four cycles annually.
- Litter pickup and removal before and during each mowing cycle in all visible non-wooded areas.

Service Level B:

- **More than two lanes**: Mow up to 18 feet from the pavement/paved shoulder edge or to the centerline of the ditch, whichever is less, no more than three cycles annually.
- **Two lanes**: Mow up to 9 feet from the pavement/paved shoulder edge no more than three cycles annually.
- Litter pickup and removal before and during each mowing cycle in all visible non-wooded areas.

Service Level C:

- Mow up to 9 feet from the pavement/paved shoulder edge no more than two cycles annually.
- Litter removal services may be contracted out or managed through Adopt-A-Highway, Community Service, or other means based on available resources.

Service Level D:

- Mow up to 9 feet from the pavement/paved shoulder edge no more than one cycle annually.
- Litter removal services may be managed through Adopt-A-Highway, Community Service, or other means based on available resources.

Service Level E:

- Mowing occurs only to address sight distance problems.

Guardrail Policy:

- Annually, mow a minimum of 5 feet behind guardrails unless the vegetation is predominantly no-mow type turf grass.

VDOT also developed and implemented a pollinator habitat program in 2014 to establish naturalized areas featuring nectar-producing and pollinator-friendly plants (VADOT 2019). The program objectives can be summarized as follows:

- **Lower Maintenance Expenses**: The program aims to reduce maintenance costs by decreasing the frequency of mowing and cutting down on other vegetation management expenses, such as invasive species control and herbicide applications.
- **Naturalized Planting Areas**: Establishing zones with nectar and pollinator species to support pollinator health and biodiversity.
- **Cost Reduction**: Minimizing the need for regular maintenance and associated costs, while enhancing environmental benefits.

By creating these naturalized areas, the program seeks to balance cost savings with ecological responsibility, contributing to a more sustainable approach to roadside management.

In other practices, VDOT developed the "*BMP Inspection & Maintenance Manual*" and the "*VDOT Maintenance Best Practices*" for roadside and field inspections and maintenance (VDOT 2021a; b). These manuals offer recommendations to address primary and common issues related to stormwater management, mowing, tree removal, brush cutting, pesticide management, and animal-related concerns.

2.3.5 Colorado Department of Transportation (CDOT)

The Colorado Department of Transportation (CDOT) implements roadside vegetation management to maintain a safe driving environment by: (1) establishing and maintaining clear sight distances, (2) ensuring road signs are visible and free of vegetation, (3) keeping roads clear of shade that slows ice melting in winter, and (4) preserving the structural integrity of roads (Kohlhepp et al. 1995). The Roadside Vegetation Management protects the investment in Colorado roads by preventing damage from unchecked vegetation growth, enhances the visual appeal of roadways, controls noxious weeds, reduces fire hazards, and promotes the establishment of native plants, which lowers maintenance costs and creates attractive roadsides. This Roadside Vegetation Manual is designed for district maintenance sections, providing specific procedures, guidelines, and recommendations for effective roadside vegetation management. Hence, this manual is designed to provide valuable information on:

1. Categorization of state and county highways based on traffic volume and adjacent property use, along with management practices for each category.
2. Detailed descriptions of available mechanical management techniques, including hand labor, mowers, brush cutters, special situations, and special precautions.
3. Detailed descriptions of available chemical management techniques, including types of herbicides, types of control, types of plants to be controlled, and factors contributing to effectiveness.
4. Comprehensive guidance on developing and implementing a weed management plan, with specific control measures for Colorado's four designated weeds.
5. Specific guidelines on the control, removal, and disposal of trees and brush.
6. The effects of vegetation management techniques on wildlife habitats and wetlands.

2.3.6 North Carolina Department of Transportation (NCDOT)

The North Carolina Department of Transportation (NCDOT) has developed an extensive roadside vegetation management program (NCDOT 2017). This program covers a wide range of soil-related issues and maintenance methods, including: (1) identifying soil types and problems, and implementing corrective actions, as well as ensuring soil fertility; (2) selecting and managing various vegetation types, focusing on turfgrasses, ornamental plants, and wildflowers; and (3) integrated roadside vegetation management, which is categorized into natural areas, where vegetation grows naturally, and managed areas, where vegetation is strategically designed, planned, and maintained to achieve specific objectives. The primary goal for the vegetation manager is to maintain safe transportation corridors by ensuring hazard-free safety zones, low-growing vegetation in the operational area, and unobstructed sight distances.

NCDOT conducted a detailed cost analysis and interviews to evaluate the mechanical, chemical, and cultural aspects of vegetation management, comparing their practices with Alabama, Kentucky, and Texas (Martin et al. 2017) and the key findings include:

- NCDOT’s annual budget for roadside vegetation management is comparable to Texas, with Alabama and Kentucky having smaller budgets due to less extensive road networks.
- Replacing one mowing cycle with an additional Plant Growth Regulator (PGR) application could save $2.5 million annually, with $1.4 million savings from reduced mowing on secondary roads.
- Coordination of PGR applications and mowing is crucial for maximizing benefits.
- While secondary roads are mowed more frequently, PGR applications are more common on interstates and primary roads, typically applied from March to July.
- There are inconsistencies in purchase order data and fiscal records, indicating potential cost reporting issues.
- Barriers to increasing PGR applications include personnel shortages, budget restrictions, insufficient equipment, and limited time windows for application.

2.3.7 Indiana Department of Transportation (INDOT)

Herold et al. proposed an IRVM for Indiana by investigating and comparing use of herbicide and mowing treatments for weed and height control, and evaluated native seed mixes for use as alternative to traditional non-native roadside vegetation (Herold et al. 2014). It was found that significant cost savings can be achieved by reducing the mowing cycles by implementing other approaches including herbicide and native plants. Furthermore, over 40% cost saving was achieved through one application of herbicide in lieu of one mowing cycle.

2.3.8 Iowa Department of Transportation (IDOT)

Brandt et al. provided a technical report for implementing IRVM at the county level, native seed and seeding, erosion control, weed control, prescribed burning for Iowa (Brandt et al. 2015). Since expenditures on herbicide application and making no or less control on roadside weeds are not sustainable, the manual proposed guidelines for policy makers and engineers for adopting IRVM for existing roadside vegetation and developed use of native prairie grasses and wildflowers for erosion control.

2.3.9 Oregon Department of Transportation (ODOT)

Oregon's roadside vegetation management manual primarily addresses design principles to guide project stakeholders in the design and functionality of landscapes within ODOT right-of-way (ODOT 2020). It aims to balance safety, economy, ecology, aesthetics, sustainability, and compatibility with operational and maintenance needs across various transportation project types, from urban to rural. This manual provides guidance on roadside development, including plants and planting, concerns specific to ODOT regarding roadside development, irrigation design, development of contract documents for projects, construction and inspection guidance, and maintenance issues for roadside development projects.

2.4 Related Research

Due to the complexities associated with specific aspects of roadside vegetation management and the critical nature of vegetation-related tasks, numerous studies have been conducted from various perspectives. These studies highlight the need for greater attention to certain areas of roadside vegetation. Below is a summary of key studies that align with the objectives and scope of this research.

2.4.1 Sustainable Vegetation Management and Planning

Public transportation and land use laws and practices increasingly promote sustainable development patterns by encouraging expansion in urban areas along important transportation corridors (Sobel et al. 2013). Landscape ecology and urban forestry provide information on the additional benefits and drawbacks of using vegetation to improve air quality. In addition to enhancing air quality, vegetation in urban areas can also improve the aesthetics, reduce noise levels, carbon sequestration, storm water runoff and regulation, temperature regulation, improving soil quality. These additional advantages are often referred to as ecosystem services. By taking into consideration of the several criteria like urban form, improve air quality, visibility and aesthetics, and site characteristics can help in integrating sustainable transportation in the process of land use laws and practices (Form and Quality 2013).

Sustainable vegetation seeks to establish vegetation that requires little to very less supplemental water and no use of chemical fertilizers. The fundamental concept behind this is that the land use increases, surface water runoff increases and the capacity of the soil to absorb and retain water decreases. Hence, there is a need for alternatives that will help in achieving increased soil moisture retention and increase recycling of the nutrients. The purpose of having sustainable vegetation is develop self-sustaining and self-sufficient vegetation have been shown to significantly reduce and restore the impacts on soil quality, lower peak storm water flows, and boost infiltration (Jones et al. 2006). According to Cooperband, L. (2002) in Building Soil Organic Matter with Organic Amendments and NRCS, organic matter is a vital component of soils because it serves many purposes (Cooperband 2002). These include: (1) provides a carbon source for the soil; (2) provides an energy source for soil microbes; (3) assists plant growth by improving the ability of the soil to store and transmit air and water which is measured by the features like improved porosity, water holding capacity, and resistance against drought; (4) improves soil fertility and plant productivity by enhancing the soil's ability to store .and supply nutrients, water, and air thoroughly; (5) increase cation and anion exchange capacities; (6) improves porosity, infiltration and root penetration by binding the soil particles together into stable aggregates; (7) reduces compaction, water runoff and soil erosion; (8) carbon sequestration; (9) minimizes the deleterious effects of pesticides, heavy metals, and other pollutants on the vegetation and the environment by chemically capturing the pollutants on leaf surfaces.

Vegetation is a vital component of roadside management. A sustainable roadside landscape lowers the maintenance costs. It provides enhanced safety for vehicles and roadway users, preserves the quality of the roadside surface, puts a limit on the responsibility of the government and enhances overall driving experience. Johnson, A. M. (2008)'s Best Practices Handbook on Roadside Vegetation Management has provided guidelines for the effective management of roadside vegetation for the Minnesota Department of Transportation. The seven best management practices fall into 7 categories based on different criteria. They 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 noxious weeds, (6) Manage living snow fences, and (7) Use integrated construction and maintenance practices. The handbook also discusses the appropriate management techniques for vegetation depending on the several factors such as the desired appearance of the roadside, the type of vegetation desired, soil conditions, roadway location, roadway use and visibility, roadway traffic, adjacent land use, and topography. Washington State DOT (WSDOT)'s State Roadside Manual lists some of the significant ecosystem services that include stress reduction, shading for pedestrians, easy transit-oriented roadways, stream-bank stabilization, wetland mitigation, water quality improvement, water retention, smoother flow of water, air and noise pollution reduction, wildlife habitat and visual quality, quality of life, and corridor continuity (WSDOT 2023).

Research was conducted to identify and quantify the costs, safety implications, and environmental impacts of routine mowing versus managed succession of vegetation management specifically for Zone 3. Guidelines for recommended roadside vegetation management practices were developed as the primary goal. The project's goals were achieved through two primary objectives:

- **Assessment of Current Practices**: Conducted a thorough evaluation of roadside vegetation management in the U.S. This included research on environmental sustainability, wildlife habitat, safety for drivers and maintenance workers, and the cost differences between reduced mowing/managed succession and routine mowing.

- **Development of Guidance Tools**: Created tools to help agencies decide if a managed succession program is suitable for a specific location. These tools include guidelines and an interactive web-based tool that considers site-specific conditions to evaluate the feasibility of implementing managed succession. The research focused on existing vegetation, impacts of changing maintenance and mowing protocols, and effects on adjacent properties and land uses. Key areas of emphasis include:

- Safety implications
- Ecosystem services
- Wildlife habitat
- Agency mowing protocols
- Cost differentials of managed succession vs. routine mowing
- Institutional obstacles to reduced maintenance
- Cooperative opportunities
- Invasive species/noxious weed issues
- Ongoing maintenance requirements
- Adjacent land use concerns
- Wildfire considerations
- Roadway context
- Public perception, outreach, and stakeholder involvement
- DOT performance metrics
- Snow, ice, and wind concerns

Based on the findings, a matrix of challenges and benefits regarding safety, management, environmental sustainability, and costs for routine mowing and managed succession is proposed. It is recommended that roadside vegetation maintenance focuses on:

- Maintaining the safety clear zone
- Encouraging or preserving native or low-maintenance vegetation to inhibit the spread of noxious or invasive plant species
- Managing wildlife and pollinators
- Reducing fire hazards by minimizing roadside fuel
- Preventing soil erosion and invasive plants to preserve infrastructure
- Using vegetation for stormwater quality and quantity control
- Ensuring compatibility with adjacent land uses
- Complying with environmental regulations
- Enhancing roadside aesthetics

Johnson developed a comprehensive set of guidelines for the Minnesota Department of Transportation to aid local agencies in effective roadside vegetation management (Johnson 2008). These guidelines discuss BMPs identified through research, literature reviews, surveys, and discussions with industry experts. The BMPs are categorized as follows:

- Develop an integrated roadside vegetation management plan.
- Develop a public relations plan.
- Develop a mowing policy and improved procedures.
- Establish sustainable vegetation.
- Control prohibited and restricted noxious weeds.
- Manage living snow fences.
- Use integrated construction and maintenance practices.
- Manage roadside vegetation for wildlife and vehicle safety.

Effective roadside vegetation management depends on an integrated approach, which involves assessing and comparing existing conditions with the desired roadside environment. Additionally, other construction operations such as proper seeding techniques, selecting appropriate plants for specific areas, using salt-tolerant species when necessary, and implementing erosion control measures significantly impact roadside conditions.

A research report conducted for the Massachusetts Department of Transportation assesses how the presence of roadside vegetation and the design of clear zones affect motorist speed, lateral placement, and visual scanning patterns (Knodler & Fitzpatrick, 2016).The study found that driving simulation results and field observations are correlated. Specifically, drivers tend to move toward the center of the road when negotiating left turns due to the size of the clear zone. Eye-tracking data revealed that drivers scan from the middle of the road to its edge, and their horizontal scan patterns did not vary significantly with changes in clear zone size or vegetation density. This lack of statistical significance suggests that drivers frequently use their peripheral vision to check the clear zone for hazards. In another study conducted for Georgia, Specific efforts were made to investigate the effectiveness of roadside vegetation management, including: (1) reducing mowing to enhance ecological benefits, and (2) keeping the pavement edge near the roadside clear to ensure safe water drainage. The possible planting techniques considered were: (1) pollinator meadows, (2) native plant seed production, (3) plantings for carbon sequestration, (4) canola or other biodiesel crops,

(5) crops for hay or other fiber production, and (6) on-road solar installations (outside of the designated clear zone with safety fencing).

2.4.2 Public Perceptions on Road and Vegetation

The role of vegetation in roadway landscapes extends far beyond aesthetics, serving as a critical factor in improving safety and environmental sustainability. Well-managed vegetation along highways can influence driving behavior, mitigate accidents, and enhance the overall travel experience. From reducing glare to serving as physical barriers, landscaping features can play a vital role in accident prevention and traffic management. Various studies have explored how specific vegetation strategies—such as managing plant height, density, and species composition—can shape driver performance, reduce roadway monotony, and support sustainable design practices. While landscaping projects for roadways are frequently only considered from an aesthetic standpoint, landscaping can be a functional and essential part of a transportation corridor by constructing visual barriers to block light from approaching vehicles' headlights, particularly on curves on median divided highways. Where highways pass through densely inhabited regions, trees and plants can act as auditory and visual barriers.

The environment at the side of the road will influence drivers' choices, either favorably or unfavorably. The component that makes the travel more enjoyable than the interstate highway alternative and may also help to increase levels of alertness is well manicured roadside borders with enough features to be fascinating. In other words, streets with a landscaped center strip or a planted median may change how drivers perceive lane width and thereby slow down driving speeds linked to an increase in accident severity.

- Vegetation Height

Zartman examined the effects of mowing height and frequency of managing the highway rights-of-way (HROW) vegetation height as a function of annual precipitation at four locations in Texas in order to determine vegetation height as a function of precipitation and mowing treatment and evaluate the effect of the interrelationship of precipitation and mowing treatment (Zartman et al. 2013). When strategically placed, shrubs or tall grasses can reduce headlight glare from approaching cars, although larger plants like trees can reduce solar glare at specific times of the day. According to recent studies, shrubs can lessen the risk of human damage or death by absorbing some of the kinetic energy produced by wayward cars. The monotony of mowed turf roadsides is lessened by a variety of woody plant kinds (Lucey and Barton 2010)

- Plant Species Composition

Studies provided evidence that drivers on highways frequently encounter a variety of plants with a wide range of compositional and aesthetic traits. This complies with the idea that successive scenic visual sequences should be provided by the spatial distribution and landscape variations along the roadside environment (Fathi & Masnavi, 2014)

- Vegetative buffers

According to research findings, roadside vegetation areas that weren't particularly created or managed for stormwater treatment significantly reduce the number of contaminants in highway runoff. According to research done on Texas's vegetated strips and swales, the majority of pollutant removal takes place on the side slopes rather than the length of the strips.

- Recovery/clear zones

A study by Fitzpatrick investigates the relationship between the size of the clear zone and the presence of roadside vegetation in relation to vehicle speed and lateral position (Fitzpatrick et al. 2014). With the intention of demonstrating the relationship between clear zone design and driver behavior, thereby enhancing clear zone design practices and thereby enhancing roadway safety.

- Driver's Speed and Lane Positioning

A study evaluating the effects of roadside trees on drivers' performance in terms of speed and lateral position along a narrow two-lane rural road lined with trees was conducted to understand the safety implications of existing tree-lined roads by analyzing the relationships between driving performance and the characteristics of the trees along various geometries of the roadway alignment. And to evaluate the viability of planting new trees along the roadside as a speed-reduction technique that could reduce the possibility of run-off-the-road incidents and head-on collisions (Calvi 2015).

- Driver's Roadside Behavior

Using simulation during light traffic conditions, (Cackowski and Nasar 2003) examines the effect of the parkway design versus the traditional highway on anger and frustration, and, within traditional highways, examines the effects of variations in the ratio of built to natural material alongside the road.

- Driver's Performance

According to a study, drivers frequently see a variety of plants beside roadways, each with unique compositional and ornamental traits. This complies with the idea that successive scenic visual sequences should be provided by the spatial distribution and landscape variations along the roadside environment. Furthermore, driving through natural scenery is less stressful and frustrating, the same vegetation may worsen run-off-the-road collisions. A study assesses the effects of clear zone design and the presence of vegetation along the roadside on driver speed, lateral placement, and patterns of visual scan (Fitzpatrick et al. 2014).

2.4.3 Public Perception on Aesthetics

The visual appeal and functionality of roadside vegetation play a critical role in shaping public perception and enhancing the driving experience. Studies have shown that vegetation design, plant selection and scenic beauty directly influence how drivers and pedestrians perceive the road environment. From preferences for native plants to the impact of greenery on safety and aesthetic value, research explores how different vegetation arrangements affect not only visual enjoyment but also the ecological and social dimensions of urban and suburban landscapes.

- Space Visual Preference and Perception

Wolf conducted a national study in the United States to learn more about public preferences and perceptions of forest and vegetation planning and management in urban freeway roadsides, as well as public opinions towards roadside functions, uses, and public support for roadside management expenditures (Wolf 2003). Results show that older drivers have a strong preference for trees as visual screening, but they are more likely to perceive trees as safety hazards. Furthermore, the visual preference for roadsides increases with both increased quantities of vegetation in the image and increased height and density of trees in comparison to commercial views. In another study Wolf conducted two survey studies in order to offer an empirical basis for decision making regarding vegetation in transportation corridors and to develop strategies for eliciting stakeholder input through design visualization approaches (Wolf 2006). The existence of considerable community greening was connected with positive consumer inferences and a greater willingness to pay for goods and services.

- Landscape Perception

A study by Weber investigates the variety of roadside vegetation and associated ecosystem services perceived by city residents in highly populated inner-city districts, as well as the value of roadside vegetation that has grown wild (Weber et al. 2014). Results indicated that city people see a variety of cultivated and "wild" green components in addition to trees, associating a wide range of meanings and values with roadside vegetation and awareness of associated ecosystem services. Lucy and Barton also investigated the perception of limiting non-native turf grass and incorporating sustainably managed roadside meadows of native warm season grasses and flowering perennials, native shrubs, and trees, and concluded that acceptance could be increased by increasing knowledge of the associated benefits (Lucey and Barton 2011).

- Scenic Beauty Assessments

Akbar et al. conducted a questionnaire survey of road users' perceptions of current roadside vegetation's scenic beauty and their perceptions of roadside vegetation with improved scenic value, resulting in a greater preference for the re-establishment of native species in roadside verge re-vegetation (Akbar et al. 2003). Clay and Smidt investigated whether descriptor variables used by agencies to assess scenic quality along roads in their jurisdiction could produce results indicative of public preference for highway conditions when applied in an expert assessment (Clay and Smidt 2004). Only variety had a significant relationship to preference and was most correlated with the construct scenic beauty.

- Native Versus Non-Native Plants Vegetation Design

The utilization of native plants is one of the fundamental tenets of sustainable landscape design and implementation in roadside re-vegetation. This justification has two parts: first, native plants are better suited to the region's geophysical and climatic circumstances, improving their chances of long-term growth. Second, local identity and regionalism are preserved by native flora, and these factors are linked to societal problems and the maintenance of regional culture (McDonald, 2012).

- Plant Selection, Ornamental Characteristics and Preference

Studies provided evidence that drivers on highways frequently encounter a variety of plants with a wide range of compositional and aesthetic traits. This complies with the idea that successive scenic visual sequences should be provided by the spatial distribution and landscape variations along the roadside environment (Fathi and Masnavi 2014)

- Vegetation types, height, and Sustainable Solutions

TxDOT's planting recommendations are as follows: Vegetation beside roads should be arranged or maintained to achieve the following objectives: sight distance, obstruction visibility, erosion control, and aesthetics. No vegetation should be grown in a way that could obscure traffic signs, sightlines, or driver visibility. Allowing a minimum of 3 feet of open space on frontage roads between the back of the curb and any area that needs to be maintained for maintenance workers. Only low-growing plant species should be used at junction areas. Plants must not be planted close to lanes that merge. Enhancements to the landscape must not put drivers or maintenance staff in danger (Mok et al., 2006).

- Maintenance-Related Activities Affecting Scenic Beauty

Ojeda conducted qualitative research to measure main landscape attributes and visual scale characteristics through a fieldwork along the Pargua highway (Alto Bonito Area) utilizing a scale of attributes, the type of vegetation through an environmental inventory (phytosociological analysis), and the degree of management of the highway taking into account its maintenance and human intervention (Ojeda 2018). Using the Naturalism index, which ranges from 1 to 5, for each landscape with the idea that the higher the naturalism, the higher the scenic beauty. A roadside environment that is aesthetically pleasant is mostly dependent on vegetation. To achieve the intended aesthetic, careful plant material selection and placement—either individually or in groups—can be crucial. The project's aesthetic objectives should be established, particularly if there are any spots that call for screening or views that may be emphasized and framed by flora (J. Mok et al., 2003).

2.4.4 Cost and Economic Analysis

Hagen et al. employed cost-benefit analysis to evaluate cost-effectiveness usage of soil bioengineering in three different projects as an alternative to traditional roadside management approaches. This study found that utilizing soil bioengineering method is significant in terms of cost savings and environmental benefits compared to traditional methods. Moreover, compared to the traditional methods, the benefits of soil bioengineering would increase as the pollutant uptake effectiveness increases. Furthermore, soil bioengineering significantly improves air quality and runoff reduction in urban and industrial areas rather than in rural areas (Hagen et al. 2002).

Buffington investigated the costs of two primary vegetation control approaches in Texas including increasing use of the contract mowing and increasing use of chemical over spraying, The findings showed that contract mowing is significantly more cost-effective than in-house mowing. Furthermore, chemical over spraying is more cost-effective than mechanical mowing. Overall, it is suggested that chemical over spraying with a minimal amount of contract mowing is the most suitable vegetation control strategy in Texas (BUFFINGTON 1988).

In another study, Vogt et al. reviewed the literature on the "Costs of Not Maintaining Trees" including maintenance costs for types of tree care considered in municipal budgets such as planting, pruning, removal, pest and disease management, and less-studied types of tree care such as tree risk management, fertilizing and nutrient management, watering, mulching, cabling, staking, tree protection, and infrastructure repair (Vogt et al. 2015). It was found that managers in the municipality level should make decision to care / not care of trees which can lead to cost much later in a tree's life span that was not predicted. Moreover, it was concluded that not caring for trees in early establishment, not managing for diseases or pests, and not maintaining the urban forest as a whole by not planting trees would result in loss of net benefits.

Harrison estimated the economic value and benefits of ecosystem services such as carbon sequestration, runoff prevention, pollination, invasive species resistance, and aesthetics for Florida Department of Transportation (FDOT) roadside right-of-way ecosystem. This study concluded that the total value of these benefits was estimated at about half billion dollars and even doubles when implementing sustainable vegetation practices and consequently would lead to reducing vegetation management costs around 30 percent (Harrison 2014).

Nowak et al. developed a cost-effectiveness evaluation matrix to compare herbicide and non-herbicide alternatives for managing roadside vegetation for New York State Department of Transportation (NYSDOT) using Delphi method. As shown in Table 2, this study provided a matrix based on direct and indirect costs and benefits of herbicide and non-herbicide alternatives by applying and comparing two different zones as shown in Figure 5 (Nowak et al., 2005). According to the results and the suggestion of the experts, it is concluded that conventional herbicide treatment methods are more cost effective than non-herbicide ones.

Effectiveness/Environmental Externalities	Physical						Cultural			Biological/ Ecological		Chemical
	Mechanical		Thermal									
	Mowing	Hand-cutting	Prescribed burn	Steam	Direct flame	Radiant/Infrared	Planting	Grazing	Fertilizing	Interference	Mycoherbicide	Bioherbicide
Cost-Direct												
Labor	---++	----0	----0	----0	----0	----0	----0	----+	0--0+	-+-+0	0--00	-0-00
Equipment	-----	0----	----+	-----	-----	-----	+--00	+--0+	0--00	++-++	0--00	00-00
Materials	+0--0	+0+-0	00-+?	+0--0	00--0	00--0	---0-	-----	0--0?	++-+0	00-00	-0-00
Waste disposal	+0---	+0+--	+00++	+0-00	+0-00	+0-00	+0-++	+0-++	00-++	+0-++	00-00	00-00
Cycle length	----+	----0	---++	----0	----0	----0	++-++	-0-++	-0-++	++-++	00-0+	-0-00
Cost-Indirect												
Safety	----0	-----	-----	----0	----0	----+	+0-++	0--++	00+0+	++0++	00000	00000
Air Quality	0----	--+--	-----	+---+	0---+	+---+	+0+++	000++	00+++	+00++	00000	00000
Noise	-----	--+--	00000	-0---	-0---	00---	+0+++	+000+	0000+	+00++	00000	00000
Aesthetics	++++-	++++0	-0---	000-0	000-0	000-0	++++-	+0+?-	0+++-	++0+-	+0000	00000
Water	-0+-0	--+-0	-0---	+00-+	000-+	+00-+	+0+++	-0--+	-----	++0++	++00+	00000
Soil	0-+--	00+ 00	-0---	+00-0	00+-0	+00-0	+++++	-0---	0++++	++0++	+0000	00000
Wildlife	-++--	00+-0	-0+--	-0--0	-0--0	000-0	+++++	+-+-?	0++++	++0++	00000	00000
Biodiversity	--+--	00+-0	--+--	0---0	0---0	0-0-0	+++-+	0-+-?	0++-+	++0-+	+0000	00000
Benefit-Direct												
Effectiveness	----+	----0	-----	-----	----+	-----	----+	----+	----+	+0--+	----0	----0
Benefit-Indirect												
Aesthetics	+-++-	+0++0	--0--	--0-0	--0-0	--0-0	+++++	+0+?-	+++++	++0++	00000	00000
Wildlife	--+--	+0+-+	--+--	0-0-+	--0-+	0-0-+	+++++	+-+-?	+++++	++0++	00000	00000
Biodiversity	+-+--	+0+-+	0-+--	+-0-+	0-0-+	+-0-+	+++++	0-+-?	+++-+	++0-+	+0000	00000

Figure 5. Matrix for comparing cost effectiveness of different non-herbicide methods for Zone 2 (Nowak et al., 2005)

As depicted in Table 2, Kahn quantified the multiple ecosystems monetary values mainly on four roadside types: minor arterial roadways with no tree setback, major arterial roadways, collector streets, and a local residential street setting (Kahn 2016).

Table 2. 50-Year (2015-2065) ecosystem services projection in 4 locations (Kahn 2016)

Location	Pounds of Carbon Sequestration	Gallons of Rainfall Interception	Savings in Air Quality Improvements
State Street	$217,845	$1,576,716	$1,622
Union Street	$229,857	$1,724,691	$1,845
Pine Street	$232,860	$5,232,454	$4,801
Cedar Street	$255,435	$1,360,042	$1,383

The Kentucky Transportation Cabinet (KYTC) has released a study exploring the economic and environmental benefits of reduced mowing (Van Dyke et al. 2021). Many state departments of transportation (DOTs) are implementing conservation mowing programs to reduce the frequency of roadside mowing while expanding pollinator habitats.

This report synthesizes best practices for conservation mowing, based on a review of landscape management policies, programs, and procedures used by 15 state DOTs. An economic analysis of various mowing strategies indicates that KYTC can save between $9 million and $24 million over five years through reduced mowing. Additionally, eliminating a single litter cycle can generate another $5 million in savings over the same period. To facilitate communication with the public, a proof-of-concept marketing document has been developed to explain how KYTC is adjusting its landscape management practices.

In October 2019, the reduced roadside mowing plan was circulated among various districts and compared to the best practices synthesis. Although largely congruent, KYTC was subsequently recommended to:

- Eliminate routine mowing of median interiors if medians exceed a certain width.
- Consider less frequent complete mow-outs of rights of way.
- Use selective herbicide treatments in areas mowed less frequently to control undesirable plant species.

In 2021, the Cabinet introduced mowing strategies focused on improving pollinator habitat along rural interstates, parkways, and other selected routes.

2.4.5 Operations and Maintenance

Allen and McCully performed several experiments for vegetation establishment of grass turf for erosion control and control unwanted plants by developing methods for controlling unwanted plants growing and determining habitat restrictions with biological treatment requirements. This study mainly focused on vegetation establishment by modification of soil physical and chemical problems, and vegetation control through controlling perennial weeds and maintenance of plants (Allen and McCully 1976). It was found that landscape plantings can be maintained using selected pre-emergence herbicides, acid soil materials should be removed once vegetation is going to established.

Li et al. investigated whether standard seed mix of TxDOT requires modifications for better addressing invasive species where erosion control can still be perceived. The report was performed by focusing on (1) the effects of mowing on grass establishment, (2) erosion control properties of standard, and non -standard TxDOT seed mixes, and (3) successional process of using TxDOT seed mixes and seeding for roadside vegetation. It was concluded that mowing maintenance may not necessarily reduce plant diversity and less mowed areas make TxDOT seed mixes hardly noticeable. Furthermore, there are no or little data regarding the economics and cost analysis of maintaining native plant roadsides since less mowing and less herbicide are required for them (Li et al. 2008).

Fedler et al. investigated whether application of compost as mulch can improve establishment of highway vegetation compared to the traditional methods. They evaluated 10 different treatment methods on soils of 3 different Texas counties. It was found that 2 inch or great layer of mature compost mulch preventing annual and invading plants from reestablishing, soil moisture and temperature can be enhanced using 3 proposed treatment alternatives, 1.5 inch of extra irrigation per month provides no beneficial effects on roadside vegetation establishment (Fedler et al. 2003).

Furthermore, factors affecting soil quality and erosion control such as pH and nutrients were proposed for better understanding of erosion control actions. For example, soil nutrients can be improved by correcting its pH level, where applications of lime can increase soil pH (decrease acidity). However, applications of sulfur can decrease soil pH level. Johnson outlined preventive methods to deal with salty soils such as use of salt-tolerant grasses and sods, effective turf establishment practices, and use of native grasses and wildflowers for Minnesota. Moreover, maintenance methods to protect soil from salt and ice including vacuuming and sweeping, soil treatments, and design and construction strategies were proposed (Johnson 2000).

Arnold and Griffin investigated and performed several experiments for maintenance and establishment of woody and herbaceous plants and turf grasses for use in the roadside. The study mainly focused on the various techniques of planting and control of vegetation, plant materials, and growth inducing materials (Arnold and Griffin 1967). For example, the planting experiments includes weed control around roadside plantings and chemical control of weeds in rest areas, and turf-related experiments includes evaluation of various herbicides for the control of brushy, weedy vegetation, and aluminum sheeting, and herbicide and herbicide additives.

Armstrong presented an integrated approach for facilitating and improving the establishment of pollinator habitat and native plants along roadsides. This guideline was provided through a comprehensive process including (1) initiating, (2) planning, (3) implementing, and (4) monitoring and managing a roadside revegetation (Armstrong et al. 2017). The report also provided operation and maintenance procedures for successful maintaining revegetation including (1) decision process for treating unwanted vegetation, (2) vegetation treatment options, (3) prevention approach, (4) protection (Armstrong et al. 2017).

CHAPTER 3 – RESEARCH OBJECTIVES AND FRAMEWORK

The primary objective of this research project is to develop an evaluation toolkit that effectively quantifies the benefits of roadside vegetation across five key modules: environmental benefits, operations and maintenance, lifecycle costs, public perceptions of roads and vegetation, and public perceptions of the aesthetics of roadside vegetation projects. Given the extensive research projects conducted within TxDOT and other DOTs, this research primarily incorporated TxDOT's reports, manuals, and policies aligned with the research objectives. However, it also integrated certain criteria from other DOTs and related publications across five modules. Additionally, the benefits are calculated using a combination of federal standards and academic research, which detail the various components of the RVET. These calculations are automated and interact with user inputs and outputs, as illustrated in Figure 6.

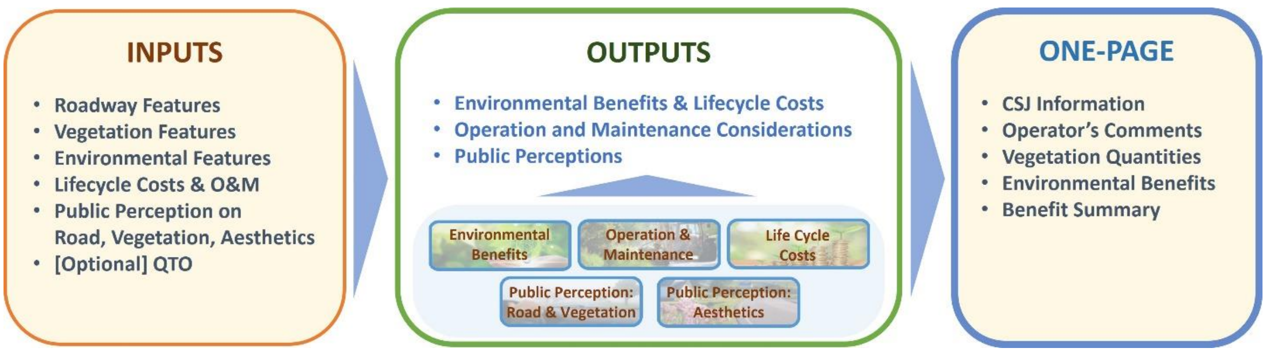

Figure 6. Overview of the RVET Framework and Assessment Modules

3.1 Environmental Benefits

The Environmental Benefits section is divided into five parts: Carbon Capture, Heat Island Mitigation, Soil Loss Reduction, and Runoff Reduction. Each section uses a variety of inputs from the TxDOT roadway inventory system to estimate benefits for operators in terms of sustainability. The overall objective of this section is to give operators a rough approximation of both quantitative and monetary benefits from roadside vegetation from various environmental aspects.

The carbon capture submodule focuses on one specific aspect of CO2 and carbon capture. This submodule's primary goal is to determine the amount of carbon that is sequestered in the trees planted with the assumption that the carbon primarily comes from plant respiration in which CO2 is exchanged for energy and carbon and O2 is expelled. This process results in carbon sequestration.

As this process has many factors it has been simplified for easy operator use and gives rough estimates. The submodules' goals were to determine carbon capture from a green mass that can be calculated on average tree dimensions that the operator inputs. This green mass can ultimately give an approximation of the carbon currently present in a tree through stoichiometry.

The heat island mitigation submodule's goal is to calculate the potential heat reduction benefits for a localized area. Many factors influence the urban heat island and as such many of the results from this section are left as conservative calculations. This subsection's goal is to provide a simple calculation that relates canopy coverage to temperature reduction to keep calculations within a spreadsheet.

The soil loss submodule's goal is to calculate a rough estimation of soil loss that can be prevented by vegetation that is planted. The submodules' objective was to contain the RUSLE equation that is used to calculate soil loss inside of a spreadsheet to keep inputs simple and easy for operators. The submodule does not examine impervious surfaces and the various changes that can change from site to site as total GIS integration was not possible. It compares the worst-case scenario to evenly spaced vegetation with trees and grasses being planted. This submodule does not consider the potential maintenance costs of soil erosion on roads, rather it investigates the cost to society in cleanup costs to city and municipal utilities. Thus, this submodule's objective is to give both monetary and a rough order of magnitude of soil loss mitigated.

The Runoff Reduction section calculates the runoff volume savings and curve number based on precipitation and vegetation coverage at the location. It compares the worst-case scenario with the proposed condition using the selected coverage in the general inputs.

3.2 Operation and Maintenance

Operations and maintenance are critical components of roadside vegetation management. It is essential not only to evaluate and improve these activities from various aspects, such as cost, crew management, and environmental impact, but also to develop balanced management approaches that benefit roadside users, the vegetation itself, and the adjacent wildlife habitats.

The goal of operations and maintenance module is to facilitate the evaluation of critical roadside vegetation tasks and activities, while also providing recommendations based on integrated factors and parameters for best management practices. This module designed to deliver valuable information and solutions, considering both internal and external factors associated with each task, allowing vegetation management staff to assess activities based on both qualitative recommendations and quantitative cost-related analyses.

This module primarily offers recommendations and cost calculations for operations and maintenance tasks, including mowing, herbicide application, wildflower management, and litter removal. For each activity, the RVET calculates the total cost based on the area under consideration, the unit cost of the activity, and miscellaneous costs. It provides three cost items for each activity, indicating minimum, average, and maximum total costs, giving a comprehensive view of operational costs applicable across the state of Texas. By offering these cost ranges, users are given an approximate quantitative measure of each activity, applicable to various areas.

For each of the operations and maintenance activities, detailed quantifications and recommendations are provided, along with the aforementioned cost calculations:

- Mowing: Mowing is a key component of roadside vegetation operations. This section provides recommendations and considerations based on three types of mowing as defined by TxDOT: full-width mowing, strip mowing, and spot mowing. Depending on the location and type of mowing, users can better understand the conditions and associated costs of the selected mowing practice.
- Herbicide Application: This section evaluates the safety, cost, and conditions of using herbicides, specifically in relation to invasive grasses and weeds. The module provides recommendations on suitable herbicides for specific invasive species, enabling users to compare various herbicides and understand their total costs. It also covers application rates, mixtures, toxicity levels, and the quantity of herbicides required for effective treatment.
- Litter Removal: Litter removal is an essential task in roadside maintenance, particularly before mowing operations commence. Various states have implemented programs for litter removal, and this module quantifies litter conditions based on the number of 4x4 objects per centerline mile of a project. It also provides monetary estimates for litter removal activities, factoring in the number of cycles required annually.
- Seeding for Erosion Control: To promote sustainable vegetation and improve erosion control along Texas roadways, this section provides recommendations for wildflower and grass species suitable for erosion control, considering factors such as soil type, district, location, and urban/rural conditions. Monetary quantification for seeding activities is also included,

calculating the total cost for the designated vegetation area.

- Wildflower Program: The wildflower program enables users to select and receive recommendations for suitable wildflower species based on their district. This allows users to select, review, and compare different wildflower species for a single project, following the guidelines of the TxDOT Wildflower Program.

3.3 Life Cycle Costs and Benefits

Life-Cycle Cost Analysis (LCCA) is a subset of benefit-cost analysis (BCA), an economic evaluation technique used to compare the benefits of different project alternatives. By examining all costs associated with the lifecycle of an asset—both agency-related and user-incurred—this method enables roadside vegetation staff to identify the most cost-effective option. Furthermore, LCCA offers a systematic approach that considers how agency actions impact transportation users, while also helping to balance these impacts with the system's construction, maintenance, and preservation requirements. Lifecycle cost calculations generally are performed for a period of 20, 30, or 50 years through initiating, construction, operation and maintenance, and disposal phases of projects (Carson et al. 2011; Hagen et al. 2002). Lifecycle cost analysis steps including (1) establishing design alternatives, (2) determining activity timing, (3) estimating costs (agency and user), (4) computing life-cycle costs, and (5) analyzing the results (Transportation and Administration 2002). Equivalent uniform annual cost analysis, Future value, present value, and net present value are among the most important cost calculations associated with life cycle cost estimation and analysis (Transportation and Administration 2002). This technique accounts for the total expenses involved in constructing, operating, maintaining, and eventually decommissioning infrastructure and its materials. These costs are calculated across the infrastructure's entire lifespan, requiring assumptions about factors like inflation or discount rates. By using life-cycle costs, decision-makers can better compare alternatives, particularly during the planning stages of green infrastructure projects. In sustainability research specifically implementation of LCCA in roadside vegetation, it's important to consider both monetary and non-monetary values. While some results can be quantified in monetary terms, many significant environmental outcomes are difficult to measure in dollars. Evaluating both monetary and non-monetary outcomes during the planning phases of roadside vegetation projects enables decision makers to weigh the trade-offs among these areas. In the context of roadside vegetation, it is important to consider LCCA as an essential tool for long-term planning and management. Roadside vegetation requires a significant investment in terms of initial planting, frequent maintenance. By performing LCCA, agencies can optimize the allocation of resources over the asset's entire lifespan, thereby minimizing overall costs while ensuring that the vegetation provides the intended benefits such as erosion control, improved aesthetics, and enhanced ecosystem services. One of the primary considerations in LCCA for roadside vegetation is the cost of maintenance, which includes activities such as mowing, herbicide application, wildflower program, and seeding for erosion control. These costs can vary depending on factors such as frequency of an activity, crew, soil type, and the types of plants selected. LCCA allows decision-makers to evaluate these trade-offs and select vegetation strategies that offer the best balance between upfront and ongoing costs.

This module aims to provide lifecycle costs and benefits various environmental attributes over a 20-year projection. It can calculate various attributes of proposed projects based on installation, operation, maintenance, and environmental benefits factors which enables TxDOT roadside vegetation staff to make suitable decisions regarding vegetation projects that not only provides valuable insights over a 20-year projection, but also facilitate the best option regarding the vegetation alternatives for each project. By evaluating both monetary and non-monetary factors considering discount and inflation rates over a 20-year roadside vegetation project, decision makers can implement solutions that provide long-term value to both the agency and the public.

3.4 Public Perception on Road and Vegetation: Road Experiences

This module is designed to assess the desirability of road experiences through different combinations of roadside vegetation from the perspective of drivers. It aims to analyze the overall desirability of various road and vegetation parameters.

The module considers various road features including road function, number of lanes, speed limit, and clearing width. For example, clearing width, or the width of the clear zone around the road, is a critical factor, with wider clear zones generally enhancing safety and visibility.

In addition to road features, the module evaluates vegetation characteristics including tree height, grass height, vegetation types, densities, and landform features. Vegetation that is well-maintained and appropriately scaled for the road environment tends to receive higher grades, reflecting better safety and visibility.

The evaluation employs a 5-point Likert scale, ranging from highly desirable (5) to highly undesirable (1), to assess each parameter. Higher ratings on this scale signify overall desirability, while lower ratings indicate areas needing improvement.

By analyzing the grades assigned to different parameters, the module highlights specific features that require attention and improvement. This systematic evaluation aids in decision-making processes and helps identify where enhancements can be made . Overall, the module provides valuable insights into how roadside vegetation and road features interact to influence driver perceptions and experiences.

3.5 Public Perception on Road and Vegetation: Aesthetics

This module is designed to assess the desirability and aesthetic perception of various roadside vegetation combinations from the driver's perspective, using a range of parameters. It aims to provide insights into how different elements contribute to the visual appeal and overall experience of highways.

The aesthetics of highways are influenced by a combination of road features, vegetation characteristics, and cultural and landscape features. This module focuses on evaluating these critical aesthetic factors to understand their impact on the overall highway experience. Higher ratings are assigned to more desirable aesthetic features, while lower ratings indicate less favorable elements. The goal is to provide valuable insights that can guide decision-making and design considerations, ultimately enhancing the aesthetic quality of highways.

The module evaluates road features such as road type, number of lanes, speed limit, and clearing width in terms of their aesthetic contributions. Higher ratings are given to road features that enhance the visual appeal and overall aesthetic quality of the highway, whereas lower ratings are assigned to features that detract from the highway’s attractiveness.

Similarly, the module assesses vegetation features including the height of trees and shrubs, grass height, types of vegetation, placement, density, and the use of native plant species. Higher ratings are given to vegetation characteristics that positively contribute to the highway’s visual appeal, while lower ratings reflect less desirable aspects.

Additionally, the module considers cultural and landscape features to provide a more comprehensive understanding of aesthetics. This includes evaluating how elements like regional or native plant species, suitability for wildlife habitats, natural landforms, and the presence of water features along the roadside contribute to the overall visual experience and integration with the surrounding environment. These attributes help shape a sense of place, reflect regional identity, and enhance the aesthetic coherence between the road and its surrounding landscape. By focusing on these aesthetic factors, the module aims to enhance the design and planning of highways, ensuring they offer both functional and visual benefits to drivers.

CHAPTER 4 – INTEGRATED ROADSIDE VEGETATION DATABASE

The evaluation toolkit is developed to provide automated and semi-automated results based on the data implemented into the toolkit. Integrated data incorporation is required for the evaluation toolkit, which serves as the foundation for the calculations. The incorporated dataset in the evaluation toolkit comprises the TxDOT roadway inventory as the primary and base layer, TxDOT control sections, and precipitation and soil condition data. The incorporated data in the evaluation toolkit is processed and integrated using ArcGIS and Python scripting with the GeoPandas library due to the large size of records and geometry processing. A summary of the integrated dataset incorporated into the toolkit is provided in Table 3.

Table 3. Overview of integrated datasets in RVET

Source	Dataset Name	Description	Ref.
TxDOT Open Data Portal	Roadway Inventory	GIS polyline layer of TxDOT's roadway network, including key inventory attributes.	TxDOT RI
TxDOT Open Data Portal	Control Sections	Polyline layer of TxDOT Control Sections for on-system and off-system road	TxDOT CS
National Resources Conservation Service (U.S. Department of Agriculture)	1991-2020 Annual Average Precipitation	1991-2020 Annual Average Precipitation Raster for state of Texas	NRCS
Oak Ridge National Laboratory (NASA)	Global Hydrologic Soil Groups	Raster of hydrologic soil groups (HSGs) with a geographical resolution of 1/480 decimal degrees for four standard classes: A, B, C, and D	ORNL

The following provides explanation of the data integration to understand the underlying incorporated layers in the evaluation toolkit:

4.1 TxDOT Roadway Inventory

The TxDOT roadway inventory GIS layer is initially and primarily utilized as the base layer for data integration. The roadway records, using the record-type variable, are limited to incorporate the necessary roadway segments for the evaluation toolkit, restricting it to values between 0 and 5. This resulted in the elimination of non-essential roadways, reducing the records from 901,324 to 514,604. These records consist of on-system roadways under the control of TxDOT. Finally, a total of 514,604 roadway segments were selected for data integration as shown in Figure 7.

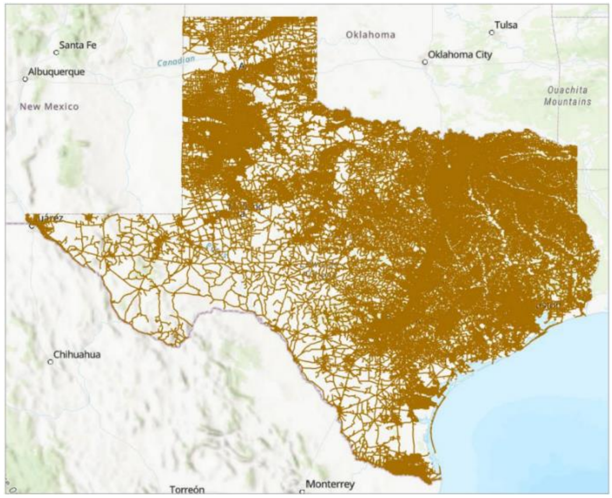

Figure 7. TxDOT Roadway Inventory Map

The evaluation toolkit is designed to automatically present and display roadway-related information in the input tab for user convenience based on the user's roadway selection. The results will then be used in various modules for automated calculations and quantifications of different roadside vegetation sections.

4.2 TxDOT Control Sections

To make the roadway selection easier, the filtered TxDOT roadway inventory is intersected with the control section GIS layer, as shown in Figure 8. Given the restricted coverage of the control section segments, which only includes the centerlines of the TxDOT roadway inventory, buffers are created over the control section maps to encompass both the westbound and eastbound of the roadways.

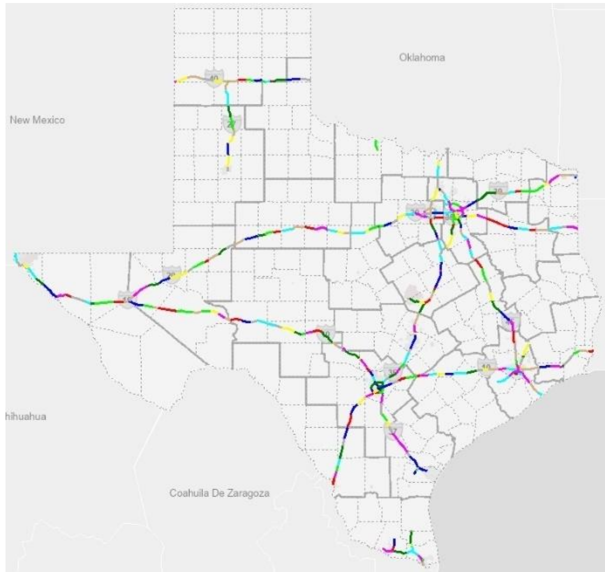

Figure 8. TxDOT Control Section GIS Layer

4.3 Precipitation Data

The toolkit also provides precipitation data for each roadway segment, implemented through the intersection of the annual average precipitation raster map (USDA NAIP 1991-2020) with all previously intersected layers. This involves computing the average precipitation points along each road segment. The resultant joined layer in this section now incorporates the average annual rainfall for each road segment, as illustrated in Figure 9.

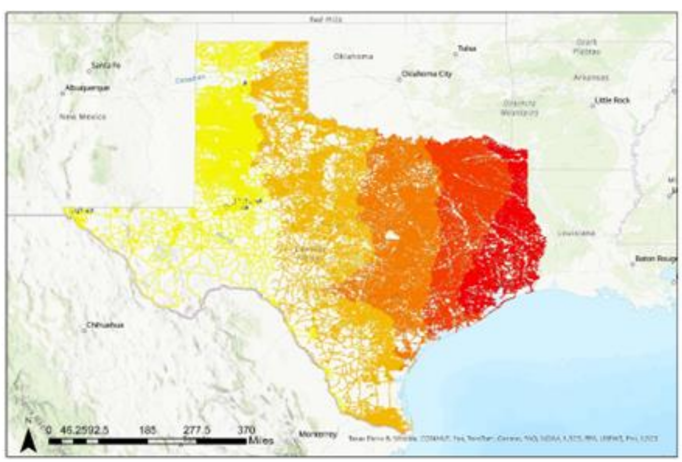

Figure 9. Average annual precipitation over TxDOT roadways

4.4 Hydrologic Soil Groups

All the previously integrated GIS layers are additionally intersected with geological soil group data sourced from ORNL DAAC (2018). This raster data was incorporated into the intersected layers, as illustrated in Figure 10. Subsequently, three classifications of soil groups were extracted for each road segment, encompassing the dominant, maximum, and minimum identified soil types. Furthermore, the soil types are classified based on runoff potential along the road segment, as detailed in Table 4. Finally, the related soil information for each segment of the selected roadway is presented in the input tab.

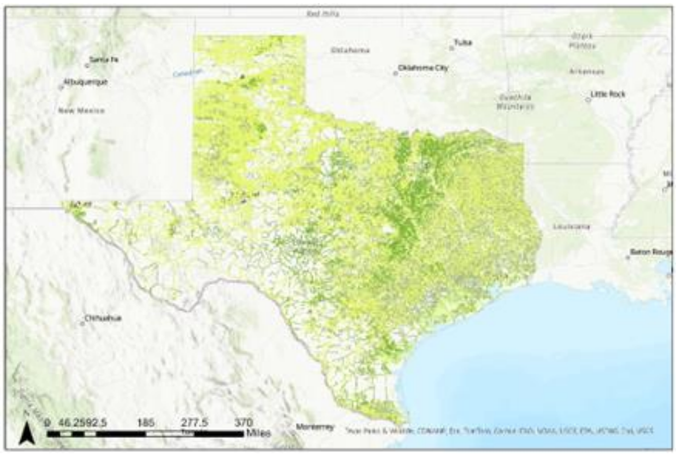

Figure 10. Intersected soil data over the TxDOT roadways

Table 4. Soil Group Classifications within the dataset

HSG	Soil texture class	Runoff potential
A	Sand	Low
B	Sandy loam, Loamy sand	Moderately low
C	Clay loam, Silty clay loam, Sandy clay loam, Loam, Silty loam, Silt	Moderately high
D	Clay, Silty clay, Sandy clay	High
A/D	Sand	High
B/D	Sandy loam, Loamy sand	High
C/D	Clay loam, Silty clay loam, Sandy clay loam, Loam, Silty loam, Silt	High
D/D	Clay, Silty clay, Sandy clay	High

According to the incorporated dataset, the detailed explanations of the soil considered soil groups in the evaluation toolkit are as follows:

Group A: These soils have high infiltration rates even when completely saturated. They mainly comprise deep, well-drained sands and gravels, allowing for rapid water transmission with final infiltration rates exceeding 0.30 inches (7.6 mm) per hour. They typically contain over 90% sand and less than 10% clay.

Group B: These soils exhibit moderate infiltration rates when fully saturated. They are mostly moderately deep to deep soils that are moderately well drained to well drained, featuring moderately fine to moderately coarse textures. The water transmission rate for these soils ranges from 0.15 to 0.30 inches (3.8 to 7.6 mm) per hour, and they typically contain 50-90% sand and 10-20% clay.

Group C: These soils show slow infiltration rates when thoroughly saturated. They primarily include soils with a layer that hinders water movement downward or soils with moderately fine to fine textures. Their water transmission rate ranges from 0.05 to 0.15 inches (1.3 to 3.8 mm) per hour, and they generally contain less than 50% sand and 20-40% clay.

Group D: These soils have very slow infiltration rates when completely saturated. They primarily consist of clay soils with high swelling potential, soils with a permanent high water table, soils with a claypan or clay layer near the surface, and shallow soils over nearly impervious materials. Their water transmission rate is less than 0.05 inches (1.3 mm) per hour, typically containing less than 50% sand and more than 40% clay.

CHAPTER 5 – ASSESSMENT METHODS FOR MODULES

This chapter presents the evaluation criteria and calculations conducted for each module for quantification of roadside vegetation based on proposed five key modules: environmental benefits, operations and maintenance, lifecycle costs, public perceptions of roads and vegetation, and public perceptions of aesthetics. Each of these modules is discussed in detail below.

5.1 Environmental Benefits

This section outlines the descriptions and criteria used in the RVET to quantify environmental benefits.

5.1.1 Carbon Sequestration

The RVET considers the impacts the vegetation will have on carbon capture and their equivalent cost. This calculation is not affected by the level of traffic but instead calculated by stoichiometric ratios as demonstrated by (University of New Mexico 2010). Considering the intention of the toolkit is for high level analysis only, an average carbon content per lb is used for all trees. The tree biomass volume is calculated with the average diameter at breast height (DBH) and height. An average tree height and DBH are taken from all the proposed tree vegetation is taken with the number of trees and the total green mass is calculated by an equation provided by the US Forestry Service. The equivalent cost in savings is calculated using values from numerous studies as well as USDOT proposal guidelines (Carmela Falci Dechen 2011; Pimentel et al. 1995; Randle and Timothy J 2019) and climate change mitigation costs are calculated as equivalent control costs.

The calculation assumes that all trees in a project are of varying species and as such creates a 'hybrid' tree that is a weighted average of all the trees in a project regarding trunk diameter size and tree height. This method of averaging is only used for the sequestration part for green mass calculations. The hybrid tree dimensions are then used to calculate the total amount of starting and potential green mass at the end of the project lifetime. To keep calculations streamlined, the leafy biomass is not considered and as such the cyclical nature of carbon capture is not investigated. Only the carbon sequestration that occurs from wood biomass is considered, this biomass only grows with the tree growth and does not have a life cycle like tree leaves and needles do.

5.1.2 Heat Island Effect

Vegetation in general has been shown to have a significant effect on ambient air temperature within the canopy area covered for several reasons. The two main reasons are the evaporative cooling effect that live vegetation has in cooling the surrounding area and the shelter of radiative heat from the sun's rays. This solar radiation shelter doubles by keeping the ground cooler and resulting in a lower ambient air temperature and direct shelter from heat impact from solar heating. The toolkit primarily investigates the effects of temperature reduction via the shelter from radiative heat. The models used here are derived from academic papers. (Knight et al. 2021) The toolkit modulates the amount of reduction via the amount of canopy coverage the vegetation provides with diminishing returns at higher amounts. RVET calculates the temperature reduction as a local area temperature reduction (project scale) with an emphasis on the lowest temperatures found in shaded areas.

Rates of reduction are calculated using a reducing effect formula with empirical data found from studies performed in the state of Washington (Knight et al. 2021) that link the canopy coverage to ambient air temperature. The toolkit has provisions to be able to calculate the amount of potential summer electricity savings to local consumers. This calculation only considers the homes that are added in RVET; however, the home parameters are not adjustable as they are built on a thermal simulation model that is not run within the excel document. The equation used in RVET adjusts the home cooling usage by the local air temperature only, it does not include any benefit that could occur from shading the house from solar radiation. In addition, RVET only examines the dry bulb temperature of the area and does not consider the increase in humidity that can occur from an increase in vegetation.

5.1.3 Soil Loss

The RVET toolkit considers the effect rooted plants have on soil integrity and resistance to storm erosion. This portion of the toolkit will only consider the effect of erosion from water-based sources, primarily storm-based erosion. As such the toolkit uses the Revised Universal Soil Loss Equation (RUSLE) with manual calculations. Most of this equation is factored by the one variable within the equation for vegetation coverage, the C factor. The amount of soil loss mitigated is effectively modulated by this C factor, which is controlled by the level of vegetation planted, trees and grass alike. The toolkit then calculates the amount of soil erosion mitigated by calculating the worst-case scenario and then subtracting the projects scenario from it to determine the amount of soil preserved.

Calculating the equivalent cost of soil loss is much more complex due to every area handling soil erosion differently and the potential impacts ranging greatly. The RVET does not consider the effects of structural degradation of roadways and bridges due to soil loss and only estimates the cost to society in cleanup costs. As such this value of soil erosion prevented should be quite conservative and used for high-level analysis. This module uses a comprehensive study (Carmela Falci Dechen 2011) that analyzes the different costs in different areas of the world in different assets, this project specifically uses the cost to society in the United States. The coverage factor is calculated using modulated values from USDA Ag. Handbook no. 537 for pasture coverage of grass and trees.

5.1.4 Runoff Reduction

This section calculates runoff reduction and the runoff curve number, which measures direct runoff volume based on rainfall. To achieve this, the section primarily makes assessments based on site conditions and compares pre- and post-development based on CN values. Additionally, other factors to consider include geological soil types ranging from A, B, C, and D. Generally, the curve number ranges from 30 to 100, with lower values indicating low runoff potential and higher values indicating greater runoff potential (Hjelmfelt, 1991; USDA, 1986; Woodward et al., 2003).

To quantify runoff reduction, the RVET automatically identifies the soil type for each roadway segment, allowing for accurate curve number assignment. It also provides the precipitation volume for each segment for the user’s reference. However, the precise calculation of runoff reduction is based on the input of 24-hour rainfall data in inches. The RVET then automatically calculates the runoff reduction and savings for the intended future condition of the project, as well as the runoff reduction volume by subtracting the runoff volume of proposed project condition from the existing condition.

5.2 Operation and Maintenance

Given the critical role of operations and maintenance in managing roadside vegetation, this toolkit provides a comprehensive analysis and quantification of essential tasks. These tasks include mowing, controlling invasive grasses and weeds through herbicide application, managing wildflower programs, and removing litter. The goal is to offer cost-related metrics and recommendations to optimize roadside vegetation projects. The detailed quantification of these key operations and maintenance tasks is as follows:

5.2.1 Mowing

Mowing is considered one of the critical tasks associated with roadside vegetation operations and maintenance. The type, costs, condition of the mowing varies based on the TxDOT district level, type of species, location, and urban/rural condition. The RVET is equipped with a dashboard that enables the quantification of mowing operations with respect to costs and types of mowing. It provides recommendations based on the type of mowing and calculates the total cost based on acreage and mowing frequency per year. The RVET categorizes mowing operations into three major types conducted by TxDOT, which are as follows:

- **Modified Full-Width Mowing:** Modified full-width mowing involves cutting all vegetation in the unpaved right-of-way areas, excluding designated non-mow or natural zones.
- **Spot Mowing:** Spot mowing will be conducted as needed to ensure clear sight distances in critical areas.
- **Strip Mowing:** Strip mowing involves cutting vegetation 14 to 15 feet from the shoulder edge, regardless of whether the shoulder is paved or unpaved.

5.2.2 Herbicide Application

The RVET provides essential information on using herbicides to control invasive grasses and weeds. The tool automates recommendations based on the specific grasses and weeds present at a site. This information is sourced from the Herbicide Operations data provided by TxDOT (TxDOT 2020a). RVET offers detailed recommendations on herbicide types and application methods tailored to target species, including:

- Alternative treatments for a target species
- Application rate
- Optimum treatment period considering type of herbicide

- Considerations regarding usage and location where herbicide will be used
- Bare ground and Guardrail Policies
- Half-Life of herbicide in contact with soil
- Formulation
- Total herbicide application considering the frequency/cycle and acreage of application

5.2.3 Litter Pickup

TxDOT conducts litter removal through various methods, including the Adopt A Highway Program. Given the significance of keeping roadways clear of litter, these operations are prioritized before mowing. To assess the condition of roadway segments and project locations, the RVET quantifies roadway in terms of the litter condition based on the amount of litter present in the project. This assessment is adapted from a survey conducted by the GDOT (Dye and Rus 1997) that measures roadway's condition in terms of litters, classifying them from minimal, with fewer than 125 items per centerline mile, to extensive, with over 1,000 items. This quantification provides decision-makers with valuable insights for optimizing cleaning operations, reducing mowing budgets, and improving the accuracy of operational cost estimates. Additionally, the RVET calculates the total cost of litter removal per acre per year, based on the frequency of these operations.

5.2.4 Seeding for Erosion Control

Erosion control based on planting wildflowers and grasses is considered in the RVET by recommending grasses and wildflowers suitable for erosion control based on various factors, including soil type, district, and urban/rural conditions (TxDOT 2020b). The RVET also proposes the appropriate seeding rate and calculates the total cost of seeding based on the acreage.

This section primarily provides recommendations on the use of suitable grasses and wildflowers based on various local factors and attributes. Given the importance of erosion control in roadside vegetation operations, this can assist TxDOT decision-makers in making a comparative, fast, and accurate assessment of the appropriate species to mitigate the effects of erosion on sites.

5.2.5 Wildflower Program

The Wildflower Program has been incorporated into the RVET for operations and maintenance. To recommend suitable wildflower species for each district, the RVET utilizes the Grass, Weed, and Wildflower Guide provided by TxDOT (TxDOT 2020b). This guide helps propose various species and outlines considerations for planting each species based on the location of the vegetation project. Notably, the RVET excludes Johnsongrass and Bermudagrass, as these species will no longer be considered in Texas. The RVET also provides recommendations, considerations, and an estimate of the total cost of seeding based on the project's acreage.

5.3 Lifecycle Costs

Lifecycle cost analysis has been incorporated into the RVET to assess the monetary and non-monetary values and benefits of a project over a 20-year projection. This analysis includes considering the associated installation costs, as well as operation and maintenance costs. Considering life cycle cost equations and concepts, the RVET calculates the life cycle costs and environmental benefits over a 20-year projection, focusing on three primary sections: 1) Life cycle costs of installation, operation, and maintenance, 2) Monetary values of environmental benefits, and 3) Environmental benefits from quantity reductions. The calculations are based on the provided discount rate, inflation rate, and the initiation of operations for the roadside vegetation project.-

The dashboard is designed to automatically calculate lifecycle costs, considering factors such as the time value of money, inflation rate, discount rate, escalation, and net present value (NPV) (Curran 2006). It incorporates previously calculated environmental factors, including carbon sequestration, temperature reduction, soil loss reduction due to water, and runoff reduction. These projections account for both monetary and non-monetary values. This quantification of benefits allows users to assess the economic value and potential returns. Together, these projections provide a holistic understanding of both costs and benefits, supporting informed decision-making and long-term planning.

5.4 Public Perception on Road and Vegetation: Road Experiences

The toolkit provides important insights into road, vegetation, and landform features that shape public perception on road experiences, based on extensive literature reviews and 34 surveys. The evaluation is done through selecting the conditions from a drop-down list that helps assess the desirability of various combinations of roadside vegetation from the driver's perspective, using a range of parameters for grading on a 5-point Likert scale, making a total of 20 points for each sector. The overall score is calculated based on averaging the scores according to the selected features, with the definition of scales and ratings for public perception. This score determines the sector's recommendation as either highly desirable (score of 5), desirable (score of 4), neutral (score of 3), undesirable (score of 2), or highly undesirable (score of 1). The module also highlights features that require attention based on the calculated gradings.

Survey: A public survey was conducted to evaluate the public perception towards roadside vegetation. The primary objective of this study was to measure users' perceptions of roadside vegetation based on their experiences on highways in Texas. The survey acts as an empirical study involving actual users (drivers) of highways in Texas. The survey questionnaire primarily asks survey subjects to rank their preferences among presented images. Likert scale is also used depending on questionnaire types. It delves into user perception of roadside vegetation affecting road experiences using visual simulation in images. These images depict various roadside settings along urban and rural highways, with configurations including four-lane divided and eight-lane (or more) divided roads. The images showcase different types of vegetation, ranging from grass/prairies to high-density areas with medium-sized trees and it asks for user rankings for various highway landforms. In addition, other questions include frequency of highway usage, evaluation of the current state of highways, demographic information, and more to study users' background and perception toward existing highways. Throughout the survey, participants were asked to rate the images based on their perspectives on road experiences, considering the specific context depicted in each image.

Table 5. Road Design Standards for Clear Zones (Roadway Design Manual, 2022)

Location	Functional Classification	Design Speed (mph)	Avg Daily Traffic	Clear Zone Width (ft) Minimum	Clear Zone Width (ft) Desirable
Rural	Freeways	All	All	30 (16 for ramps)	
Rural	Arterial	All	≤ 750	16	30
Rural	Collector	≥ 45	All	10	
Rural	Local	All	All	10	
Suburban	All	≤ 8,000	All	10	20
Suburban	All	8,000 - 12,000	All	10	20
Suburban	All	12,000 - 16,000	All	10	25
Suburban	All	> 16,000	All	20	30
Urban	Freeways	All	All	30 (16 for ramps	

				and collector-distributor)	
Urban	All (Curbed)	≥ 50	All	Use above suburban criteria insofar as available border width permits	
Urban	All (Curbed)	≤ 45	All	4 from FOC	6 from FOC
Urban	All (Uncurbed)	≥ 50	All	Use above suburban criteria	
Urban	All (Uncurbed)	≤ 45	All	10	

5.4.1 Road Features

The road features (qualitative) explore how different road types and characteristics influence public perception towards road experiences, focusing on aspects such as road function, number of lanes, speed limits, and clearance widths. Road classifications are based on national standards for urban and rural roadways (California and Carolina 2000), with different categories. Lane configurations and speed limits vary by road type (Rawson 2015), and clearance guidelines follow established design standards (Ramthun 2022). The clear zone requirements are shown in Table 5.

5.4.2 Vegetation Features

The vegetation features assess how different types and arrangements of roadside vegetation impact public opinion regarding road experience. It explores factors like the tree height, grass height, vegetation type and vegetation density. Tree heights are categorized based on established guidelines (Macdonald et al. 2006). Vegetation types encompass a range of options, determined by 34 public survey results. Grass height typically varies (Johnson 2008), Click or tap here to enter text.while vegetation density is recommended based on visibility needs (Jia et al. 2022).

5.4.3 Landform Features

The landform features section investigates how topography and landform characteristics impact public perception. It involves user rankings of various highway landforms, including flat terrain, uphill inclines, and downhill declines. Participants rated their perceptions of roadside experiences through images of these landforms, helping to understand how different topography influence the quality of roadside environments. This approach provided valuable insights into user perspectives across diverse highway settings, with the results graded accordingly.

5.5 Public Perception on Road and Vegetation: Aesthetics

The toolkit offers valuable insights into how road, vegetation, cultural, and landscape features influence public perception of aesthetics. This is derived from extensive literature reviews and surveys. The evaluation process involves selecting conditions from a drop-down menu to assess the desirability of various roadside vegetation combinations from the driver's perspective. The assessment uses a 5-point Likert scale across a range of parameters, totaling 20 points per sector. The overall score is calculated based on averaging the scores according to the selected features, with the definition of scales and ratings for public perception. This score determines the sector's recommendation as either highly desirable (score of 5), desirable (score of 4), neutral (score of 3), undesirable (score of 2), or highly undesirable (score of 1). The module also highlights features that require attention based on the calculated gradings.

Survey: A total of 34* public surveys were conducted to evaluate the public perception towards roadside vegetation. The primary objective of this study was to measure users' perceptions of roadside vegetation based on their experiences on highways in Texas. This study focuses on actual highway users (drivers) in Texas. The survey primarily asks participants to rank their preferences among various presented images, with some sections utilizing a Likert scale based on question types. It assesses user perceptions of roadside vegetation for aesthetics using visual simulations, displaying images of different highway settings, including urban and rural roads with four-lane, eight-lane or more configurations. These images feature a range of vegetation types, from grasslands/prairies to densely vegetated areas with medium-sized trees and ask users to rank different highway landforms. Additional questions cover highway usage frequency, evaluation of current conditions, demographic information, and more to capture users' backgrounds and perceptions of existing highways. Participants rated the images based on their aesthetic views within each depicted context.

5.5.1 Road Features

* Public survey conducted was a small sample focus group from a local community and may not be representative of other regions.

The qualitative aspects of road features explore how different road types and characteristics impact public perceptions of aesthetics. This includes factors such as road function, type, number of lanes, speed limits, and clearing width (Rawson 2015). The number of lanes and the designated speed limits significantly influence driver experience, highlighting different levels of concerns and risks (Forbes 1999). Roads are categorized into various types, and these classifications help determine their features like lane count and speed limits. The tool uses these classifications to automate inputs based on the specified clearing width (Ramthun 2022).

5.5.2 Vegetation Features

The vegetation features evaluate how various types and arrangements of roadside vegetation influence public perception of aesthetics and visual appeal, including tree height, grass height, vegetation type, and density. Trees are categorized by height (Macdonald et al. 2006), while vegetation types are evaluated based on public survey results. The tool adjusts grass height and vegetation density according to user inputs, adhering to guidelines for visibility and roadside conditions (Johnson 2008a; Jia et al. 2022).

5.5.3 Cultural and Landscape Features

This section evaluates factors influencing public perception on roadside environments, including the use of native plants and trees, wildlife habitat suitability, topography, and water features. Assessments consider if habitats meet the needs of various species (Grebner et al. 2013) and the impact of topography on environmental and climate factors. These elements together shape the overall aesthetic and ecological quality of roadside areas.

CHAPTER 6 – CONCLUSIONS

The development of the RVET mark a transformative milestone for the TxDOT in managing roadside vegetation. By addressing the previously unmet need for a cohesive, data-driven approach, the RVET provides transportation planners, environmental practitioners, and landscape designers with a comprehensive tool for informed decision-making. This integrated toolkit aligns with the directives of Executive Order 1-92 and supports TxDOT's mission to create and maintain environmentally sensitive and aesthetically pleasing roadside landscapes across Texas.

The RVET's evaluation framework is designed to tackle a range of critical aspects associated with roadside vegetation management. The toolkit includes modules that evaluate environmental benefits, operational and maintenance considerations, lifecycle costs, and public perceptions of road experiences and aesthetics. This holistic approach ensures that vegetation projects are assessed from multiple perspectives, promoting not only environmental sustainability but also cost efficiency and public satisfaction. The main contributions of the RVET per module are as follow:

Environmental Benefits: The RVET's environmental benefits module provides a preliminary yet valuable assessment of how roadside vegetation impacts soil erosion, carbon sequestration, and runoff reduction. The integration of geospatial data, including TxDOT's roadway inventory, precipitation records, and soil group information, allows for a context-specific analysis of these benefits. Despite the current use of simplified models and available data, the module lays the groundwork for future enhancements. Advanced modeling techniques and localized field studies based on district-level analysis should be pursued to refine assessments, particularly for heat island effects, to provide more precise and actionable insights.

Operational and Maintenance Considerations: The RVET's operational and maintenance module offers a detailed analysis of key activities including mowing, herbicide application, seeding for erosion control, wildflower program, and litter removal. By providing cost estimates and recommendations for each activity, the toolkit helps streamline maintenance practices and improve resource allocation. Future enhancements could include integrating real-time monitoring and adaptive management strategies to further optimize maintenance practices and respond dynamically to changing conditions.

Lifecycle Costs: The lifecycle cost analysis (LCCA) module within the RVET is instrumental in evaluating the long-term financial implications of roadside vegetation projects. By projecting costs and benefits over a 20-year period, this module supports decision-makers in selecting the most cost-effective and sustainable vegetation strategies. Future developments could focus on expanding cost factors and exploring alternative scenarios, including the impact of emerging technologies and materials, to offer a more comprehensive view of long-term costs and benefits.

Public Perception on Road Experiences: The RVET's module on public perception of road experiences provides critical insights into how roadside vegetation and road features affect driver safety and satisfaction. By assessing factors such as road function, number of lanes, speed limits, and vegetation characteristics, this module highlights areas for improvement in road design and vegetation placement. Expanding public engagement efforts and conducting more extensive surveys can further refine these perceptions and ensure that the toolkit remains aligned with evolving public expectations and safety standards.

Public Perception on Aesthetics: The aesthetics module evaluates how different combinations of roadside vegetation impact the visual appeal of highways. By analyzing road and vegetation features, cultural elements, and landscape integration, this module offers valuable guidance for enhancing the visual quality of transportation corridors. Future research could explore additional aesthetic factors and public preferences to ensure that vegetation designs not only meet functional requirements but also resonate with diverse visual expectations.

The insights gained from the RVET are poised to support the statewide implementation of improved roadside vegetation management practices. By integrating environmental, operational, economic, and perceptual data, the toolkit promotes a comprehensive approach to vegetation management that benefits both the environment and the public. The RVET stands as a testament to TxDOT's commitment to fostering a greener, safer, and more visually appealing transportation network.

Future Directions: The continued development of the RVET should focus on several key areas. First, expanding the scope of environmental benefits to include more detailed modeling and localized data will enhance the accuracy and applicability of the toolkit's assessments. Second, integrating advanced technologies and real-time data collection methods into operational and maintenance modules will improve the efficiency and effectiveness of vegetation management practices. Third, broadening public engagement and refining aesthetic evaluations will ensure that roadside vegetation projects align with community preferences and enhance overall road experiences. Fourth, compliance with various state and federal policies such as NEPA for accurate yet reliable statewide measurements. Finally, ongoing collaboration with research institutions, technology developers, and other stakeholders will be crucial in advancing the RVET's capabilities and ensuring its relevance in the evolving landscape of roadside vegetation management.

In conclusion, the RVET represents a significant advancement in roadside vegetation management and serves as a model for similar initiatives in other regions. By providing a comprehensive, data-driven approach to evaluating and managing roadside vegetation, the toolkit supports TxDOT's goals of enhancing environmental quality, road safety, and aesthetic value. The continued refinement and expansion of the RVET will further strengthen its impact, fostering a more sustainable and visually appealing transportation network for all Texans.

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APPENDIX: VALUE OF RESEARCH

Value of Research (VOR)

TxDOT Project 0-7162, Quantifying Benefits of Roadside Vegetation

Introduction

Many transportation agencies and Departments of Transportation (DOTs) have developed roadside vegetation programs aimed at promoting sustainability, improving quality of life, and enhancing the visual appeal of infrastructure. However, Texas has lacked a comprehensive tool for assessing the benefits and potential risks associated with different types of roadside vegetation and their applications. To fill this gap, this research introduces the Roadside Vegetation Evaluation Toolkit (RVET) for Quantifying Benefits of Roadside Vegetation. This toolkit equips TxDOT planners, environmental specialists, and landscape architects with the means to effectively evaluate roadside vegetation. The RVET, supported by extensive geospatial data, addresses five key areas: environmental benefits, operational and maintenance efficiency, lifecycle costs, public perception of roadways and vegetation, and aesthetics. The insights gained from RVET will support the statewide implementation of enhanced roadside vegetation strategies within TxDOT, contributing to the well-being of Texans. This study offers a thorough evaluation framework, delivering important information for stakeholders across its five core modules.

Benefit Areas

The development of the RVET addresses several critical benefit areas that align with TxDOT's goals for sustainability, cost-effectiveness, and public satisfaction. The primary benefit areas include:

- **Environmental Benefits:**
  The RVET offers tools to evaluate the environmental impacts of roadside vegetation. These include carbon sequestration, urban heat island mitigation, soil erosion control, and runoff reduction. By quantifying these benefits, the toolkit provides transportation planners with a clearer understanding of how roadside vegetation contributes to environmental sustainability and ecosystem services, while estimating economic savings in these areas.
- **Operational and Maintenance Efficiency:**
  The toolkit assists in streamlining maintenance operations, such as mowing, herbicide application, litter removal, and erosion control. By providing detailed cost estimations and recommendations for managing these tasks, the RVET helps optimize resource allocation,

reduce costs, and promote effective roadside vegetation management practices across various projects.

- **Lifecycle Cost Management:**

The RVET integrates a 20-year lifecycle cost analysis to evaluate long-term financial and environmental benefits. This aspect allows TxDOT to make informed decisions regarding roadside vegetation investments, ensuring that projects are cost-effective over time while delivering ongoing ecological and operational advantages.

- **Public Perception and Aesthetic Enhancement:**

Public perception is a key component of roadside vegetation projects. The RVET assesses how different combinations of vegetation, road features, and cultural elements influence public views on road aesthetics and safety. By providing insights into these perceptions, the toolkit helps enhance road user experience, contributing to improved public satisfaction and a more visually appealing transportation infrastructure.

In summary, the RVET equips TxDOT with the capability to evaluate roadside vegetation comprehensively, from environmental impacts to operational efficiency, lifecycle costs, and public perception. These benefit areas contribute to a more sustainable and economically sound approach to roadside vegetation management.