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16. ABSTRACT

This research was conducted to analyze the lifetime costs associated with concrete barriers, steel guardrails, and wooden versus metal guardrail posts and signposts. In this study, a comprehensive lifecycle cost analysis and cost-benefit evaluation framework was developed that can be used to facilitate decision-making processes to mitigate safety risks and reduce overall operational expenses. The researchers reviewed the practices of other Departments of Transportation (DOTs) in selecting roadside barriers, conducted interviews with Caltrans maintenance personnel, and used available analytical models and data extracted from Caltrans databases to conduct the cost-benefit analysis. The methodology incorporated several factors, such as construction and maintenance costs, exposure risk during maintenance operations, and the cost imposed on public in terms of traffic delays and accidents outcome. The results of this research are presented in the form of a software tool named CalBarrier, designed to calculate and compare the life-cycle costs of concrete barriers and steel guardrails. The study findings underscore the complexity of selecting the most cost-effective barrier, necessitating the consideration of many factors, including construction cost, maintenance cost, exposure risks, and public costs, while accounting for many variables, such as traffic mix, economic factors, and road geometry. The CalBarrier serves as a valuable resource for evaluating and comparing the life-cycle costs of concrete barriers and steel guardrails. Furthermore, this research has revealed that the wooden guardrail posts and signposts, despite their lower initial costs, incur elevated maintenance and disposal expenses, which makes them less cost-effective over their lifetime.

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Cost-Benefit Analysis for Concrete vs. Metal Guardrails and Wood vs. Metal Posts for Signs and Guardrails

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Executive Summary

This research was conducted to study the lifetime cost of concrete barriers, steel guardrails, and wooden and metal guardrail posts and signposts. Another objective of this research was to develop a software tool to perform cost-benefit analyses of various barrier options using the information gathered in this research.

Findings from previous research at the Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center revealed that maintenance work on guardrails, barriers, and end-treatments incurs the highest average cost per work order compared to other roadside features. This finding underscored the urgent need to evaluate these costs for enhanced efficiency. Therefore, this study aimed to develop a comprehensive life-cycle cost analysis and cost-benefit evaluation to assist the decision-making processes and reduce safety risks and overall operational costs. The objectives of this research encompassed computing and comparing the lifecycle cost of concrete barriers versus steel guardrails, as well as wooden versus steel guardrail posts and signposts. Additionally, the study aimed to develop a software tool for calculating and comparing the lifetime costs of these barriers that incorporated their maintenance costs and their impact on public expenses.

This research included an overview of available studies on the selection procedure of barriers and posts conducted by other Departments of Transportation (DOTs). Furthermore, Caltrans staff were interviewed to obtain their perspective and useful experience about the subject of this project. This research also extracted relevant information from Caltrans databases, including Integrated Maintenance Management System (IMMS), to compute the lifetime cost of barriers and posts. Construction and maintenance costs, as well as the risk of exposure during maintenance of barriers, were also reviewed under the objectives of this project. The cost imposed on the public by the barrier type in the form of traffic delays due to the necessary maintenance and crash into the barriers were also computed in this research. Finally, a software tool, CalBarrier, was developed to calculate the lifetime cost of various barrier types and compare them against each other.

The results of this research showed that selecting the most cost-effective barrier requires the inclusion of many parameters, such as construction, maintenance, exposure, and public costs, while carefully considering factors like traffic mixture, economic factors, and road geometry. CalBarrier was

developed to incorporate all these factors in computing and comparing the lifetime cost of concrete barriers versus steel guardrails, as a part of this study. Analyzing the lifetime cost of wooden vs. steel guardrail posts and signposts revealed that, while wooden posts have a lower initial cost, they incur higher maintenance and disposal costs, making them less cost-effective over their lifetime. Moreover, interviews with Caltrans staff highlighted that wooden posts are not a suitable choice in fire-prone and rocky regions.

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Acronyms and Abbreviations

Acronym	Definition
AHMCT	Advanced Highway Maintenance and Construction Technology
Caltrans	California Department of Transportation
COTS	Commercial Off–The-Shelf
DOT	Department of Transportation
DRISI	Caltrans Division of Research, Innovation and System Information
PM	Project Manager
IMMS	Integrated Maintenance Management System
VSL	Value of Statistical Life
VTTS	Value of Travel Time Saving
RSAP	Roadside Safety Assessment Program
AADT	Annual Average Daily Traffic
NCHRP	National Cooperative Highway Research Program
AASHTO	American Association of State Highway and Transportation Officials
FHWA	Federal Highway Administration

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Chapter 1: Introduction

1.1 Problem

The California Department of Transportation (Caltrans), through its Division of Research, Innovation, and System Information (DRISI), completed research conducted by the Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center at UC Davis. This research revealed that maintenance work on guardrails, barriers, and end-treatments has the highest average cost per work order compared to the maintenance cost of all other roadside features considered. This finding highlighted the need to evaluate these costs to improve efficiency. Additionally, in certain situations, such operations expose highway workers to live traffic for an extended duration, increasing safety risks. The equipments' exposure to high-speed traffic and the potential for crashes and equipment downtime decrease productivity and increase maintenance/construction costs. Therefore, there was a need for both safety and efficiency considerations in developing a lifecycle cost analysis and cost-benefit evaluation, which could assist decision-making regarding best practices to reduce both safety risks and the cost of such operations.

1.2 Objectives

The purpose of the current research was to compute and compare the lifecycle costs of concrete barriers vs. steel guardrails, as well as wooden vs. steel guardrail posts and signposts. Another objective of the study was to develop a software tool that could calculate and compare the lifetime costs of these barriers, taking into account their construction, maintenance, and public costs, as well as the risks associated with exposure of the workers to live traffic during maintenance activities.

1.3 Scope

The project involved a series of tasks aimed at evaluating the life-cycle cost of concrete barriers versus guardrails, as well as the steel vs. wooden signposts and guardrail posts. These tasks encompassed project management, assessment of practices in other State Departments of Transportation (DOTs), evaluation of unit costs, assessment of maintenance requirements, analysis of public costs, evaluation of traffic exposure risks, consideration of site and environmental factors, and synthesis of data to conduct a cost-benefit analysis.

Each of these tasks played a crucial role in understanding the best practices, cost factors, and safety considerations associated with roadside infrastructure.

Task 1 focused on project management, including quarterly progress reports and the formation of a Project Panel to oversee project work and progress. Task 2 involved researching practices in other State DOTs to gain insights into material selection for barriers and signposts. Task 3 was about establishing unit cost bases for various barrier and guardrail components. Task 4 included assessing maintenance requirements and conducting virtual meetings with Caltrans personnel. In Task 5, the project evaluated public costs associated with roadside barrier choices, considering traffic delays and crash probabilities.

Task 6 assessed traffic exposure risks during the maintenance of barriers by considering the collision history and labor times. Task 7 incorporated site and environmental considerations that can impact costs, particularly in challenging locations like median barriers. Finally, Task 8 synthesized data from Tasks 2 to 7 to determine life cycle costs and perform a cost-benefit analysis, helping to determine the most cost-effective solutions. Task 9 involved the integration of data and findings into a final report, summarizing the project outcomes.

1.4 Research Methodology

The AHMCT Research Center employed a Project Panel (panel), including the Caltrans Project Manager (PM), Caltrans project customers, and other stakeholders to guide this research. Data from the Integrated Maintenance Management System (IMMS) were integrated with data from best practices of other state Departments of Transportation (DOTs), along with data obtained from Caltrans Districts and field operational personnel, to establish the baseline necessary for performing the cost-benefit analysis.

1.5 Overview of Research Results and Benefits

The benefits of this project include improved safety for maintenance/construction workers and cost savings in certain high-cost maintenance operations associated with barriers, guardrails, and signposts. This research may assist in the decision-making process when:

- Choosing between concrete versus metal guardrails.
- Replacing wooden versus metal guardrail posts and signposts.

A method was developed to estimate the cost of lane closures, considering factors like reduced traffic speed and Value of Travel Time Savings (VTTS). For concrete barriers, this cost is approximately $0.1101 per foot per year per AADT, whereas for Thrie-Beam and W-Beam barriers, it's $0.7234 and $4.298 per foot per year per AADT, respectively.

The total exposure cost of equipment and workers to high speed traffic during maintenance of the barrier is approximately $4.80 per person-hour of work.

In roadways with high AADT and high crash probabilities, concrete barriers have proven to be more cost-effective than guardrails, with lower maintenance costs.

Guardrail Posts: Wooden guardrail posts have an average cost of $28.57 each, while steel posts average $63.87. However, considering construction, disposal, and maintenance costs, steel posts are more cost-efficient by at least $2.40 per foot, accounting for 7% of the construction cost.

Wooden signposts cost around $20.82 each, whereas steel signposts average $38.46. When considering disposal and maintenance costs, wooden signposts prove to be slightly more expensive over their lifetime. The main factor for higher life-cycle cost of wooden signpost is the disposal cost of treated wood waste. These findings suggest that, despite higher initial cost, steel guardrail posts, and steel signposts offer cost savings and better durability when compared to their wooden counterparts. Moreover, steel posts address other challenges, such as storage space, installation in mountainous terrains, and fire-prone regions, which makes them more practical choices for roadside infrastructure.

Chapter 2:
Literature Search

This chapter includes a literature search on publicly available documents, including reports, instruction manuals, and software, that are related to barrier and signpost selection, installation, maintenance, and lifecycle analysis.

ROADSIDE SAFETY ANALYSIS PROGRAM (RSAP) (https://rsap.roadsafellc.com/)

Roadside Safety Analysis Program (RSAP) is a software tool that evaluates the cost-effectiveness of roadside safety features. RSAP was first developed under the National Cooperative Highway Research Program (NCHRP) Project 22-9(1) and was updated and improved under different NCHRP projects, including 22-9(2) and 22-27. Different releases of RSAP are distributed with the American Association of State Highway and Transportation Officials (AASHTO) Road Design Guide. RSAP computes the expected cost-benefit ratio for different roadside designs by employing a series of conditionally independent probabilities on vehicle roadside encroachment, the probability of a crash given roadside encroachment, and the probability distribution of the severity of a crash if an encroachment has occurred. RSAP version 3, which is the latest release of the tool, is structured into the following four modules:

- Encroachment module
- Crash prediction module
- Severity prediction module
- Cost-benefit module

The first three modules compute the conditional probability of each event, and the last module computes the expected cost-benefit of the safety feature according to the results from the other modules.

Procedure to Quantify Consequences of Delayed Maintenance of Guardrails, NCHRP, Report 859, 2017 (http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_859AppendixF.pdf)

This report is an appendix of the final NCHRP Project 14-20A report and presents a procedure for quantifying the financial consequences of delayed maintenance on guardrail systems. The presented approach uses performance models to predict the guardrail future condition and compares the agency cost with different maintenance scenarios, including on time maintenance, no maintenance at all, maintenance delayed by budget, and maintenance delayed by policy by a certain number of years.

Manual for Assessing Safety Hardware (MASH), AASTHO, 2016 (https://safety.fhwa.dot.gov/roadway_dept/countermeasures/reduce_crash_severity/aashto_guidancecfm.cfm)

This document presents uniform guidelines for crash testing highway safety features and provides evaluation criteria for assessing test results. Different performance metrics that are considered by the Manual for Assessing Safety Hardware (MASH) include the structural sufficiency of the barrier, the risk of injury to occupants of the impacting vehicle, the post-impact behavior of the vehicle and the trajectory of debris resulting from the impact, and the exposure of structures and people behind the safety feature. Factors, such as cost or durability of the safety features, are not included in MASH standard.

Highway Safety Manual (HSM), AASTHO, 2014 (https://safety.fhwa.dot.gov/rsdp/hsm.aspx)

The Highway Safety Manual (HSM) is published by the AASHTO and provides tools for quantitative safety analyses on an existing or a proposed roadway. HSM can be used for developing successful roadway safety management programs and evaluating existing programs and policies. Furthermore, HSM presents tools to predict crash frequency and severity at a site. It also provides methods to identify factors contributing to crashes and potential countermeasures to make improvements. Finally, HSM offers a catalog of crash modification factors (CMFs) for a variety of geometric and operational treatment types that can estimate the change in probability of a crash or crash outcome due to installing a specific treatment.

Risk Management and Assessment of Upgrading and Standardizing Guardrail, Indiana DOT, 2009 (https://docs.lib.purdue.edu/cgi/viewcontent.cgi?article=2646&context=jtrp)

This report studied the current use of guardrail systems in Indiana and examined different factors necessary for performing a cost-benefit analysis of guardrail systems. The researchers examined two years of run-off-the-road (ROR) crash data to develop a database that could be used in the cost-benefit analysis and decision-making process regarding roadside guardrails. Different aspects of ROR crashes that were investigated included frequency, location, road geometry, season, traffic volume, and crash outcome. The main findings demonstrated that 96% of ROR crashes involved a single vehicle, and the overall rate of ROR crashes were lower than the reported number in the AASHTO Roadside Design Guide. Other aspects of vehicle-guardrail crashes, such as impact position, encroachments rate, crash probability, and severity probability, were also investigated in this research.

This study also evaluated different costs related to guardrail repair and maintenance, such as parts cost, equipment cost, and the labor cost. The authors reported that for end treatment and crash cushion repairs, the parts cost had the highest share, while the labor had the highest costs for regular guardrail repairs.

Highway Design Manual (HDM), Caltrans, 2019 (https://dot.ca.gov/-/media/dot-media/programs/design/documents/hdm-complete-12312020a11y.pdf)

This manual presents procedures and guidelines for efficient and safe design of highways. This document includes various aspects of highway design from application of design standards and basic design policies to minute details such as highway shoulder standards and storm water management. Although the necessity of guardrails and other roadside barrier installation for safety is mentioned several times, this manual refers to "*Traffic Safety Systems Guidance*" for details about guardrail installation.

W-Beam Guardrail Repair: A Guide for Highway and Street Maintenance Personnel, FHWA, 2008
(https://safety.fhwa.dot.gov/local_rural/training/fhwasa08002)

This document provides guidance and instructions on repairing W-beam guardrails. It classifies three levels of damage: "guardrail no longer reasonably functional", "guardrail should function adequately under a majority of impacts", and "should not impair the guardrail's ability to perform". The document also provides instructions on the procedure for appropriate repair for each damage category. An estimation of the parts, materials, work crew, and equipment necessary for the guardrail repair task is also presented.

Guardrail Installation Training Manual, Virginia DOT, 2019
(https://www.virginiadot.org/business/resources/locdes/grit_manual.pdf)

This manual outlines the design and installation procedures for different guardrail systems. The document includes an introduction to roadside safety, standard guardrail systems and standard guardrail transitions, guardrail terminals, special guardrail treatments, and barrier delineation. A list of guardrail installation references is also provided in this document.

Criteria for Restoration of Longitudinal Barriers, NCHRP, Report 656, 2010 (https://ntrl.ntis.gov/NTRL/dashboard/searchResults/titleDetail/PB2010110793.xhtml)

This report offers a comprehensive guideline to determine the level of damage and deterioration of W-beam roadside barriers. This report first reviews the state of practice in the U.S. and Canada for criteria on repairing damaged flexible or semi-rigid longitudinal barriers. Then, different methods used by the research team for evaluation of the crash performance of barriers with minor damages is discussed, including pendulum testing, finite element modeling, and full-scale crash test. Finally, the document provides repair criteria for different type of damage to longitudinal barriers.

Guardrail, Cable Barrier, and Crash Attenuator Inspection and Repair Guidelines, South Carolina DOT, 2016
(https://www.scdot.org/business/pdf/GuardrailInsp_RepairGuide.pdf)

This document provides guidelines for inspection and maintenance of barrier systems and crash attenuators. For example, it states that the guardrails and end treatments on the interstate system must be inspected every three years if no damage is reported, and the inspection must be performed every five years for all non-interstate roads. The document provides a step-by-step guide to inspect different parts of a barrier/end treatment. The document also provides some instructions for repairing the barriers; however, it does not include any guidance on upgrading an existing or a damaged barrier.

Guardrail Replacement and Maintenance Guidelines, Minnesota DOT, 2010
(https://www.lrrb.org/pdf/2010RIC13.pdf)

This document provides guidelines for replacement and maintenance of roadside barriers including W-beam and Thrie-beam guardrails, cable barriers, bull nose rail systems, and concrete barriers. The document also includes an overview of end treatments used in Minnesota along with the state DOTs maintenance and inspection procedure. The state and national standard and resources on the subject are reviewed in the final part of this document.

Cost-Effective Treatment of Existing Guardrail Systems, Nebraska DOT, 2013 (https://digitalcommons.unl.edu/civilengdiss/57)

This report uses RSAP to evaluate W-beam guardrail systems in the State of Nebraska. Field condition, guardrail geometry, and deviations from state-of-the-art practices were documented during field investigations and then entered into the RSAP software. The results of cost-benefit analysis by RSAP were used to determine which guardrails comply with current safety standards, which ones need to be upgraded, and which ones have to be removed. This document also provides cost-effective upgrade recommendations for existing barrier systems.

Roadside Safety Pocket Guide, Pennsylvania DOT (PennDOT), 2018 (https://www.dot.state.pa.us/public/pubsforms/Publications/Pub 652.pdf)

This pocket guide summarizes the information in different standards and manuals, including Part 2, "Highway Design", of PennDOT's Pubication13M; Publication 72M, *Standard for Roadway Construction*; and Publication 23, *Maintenance Manual*. The document provides instructions to guide decision-making on how to install and when to terminate roadside barriers.

Selection of a Certified Barrier (https://www.roadsidepooledfund.org)

The Roadside Safety Pooled Fund is a roadside safety research program sponsored by several state DOTs to carry out crash testing in accordance with Federal Highway Administration (FHWA) adopted standards. Different types of barriers (guardrail and concrete) are tested by the Roadside Safety Pooled Fund, and the reports on barrier performance under different conditions can be found on their website. There are hundreds of reports available in this database regarding concrete barriers and guardrails. Some of these reports are discussed below.

- **Guardrails**
  - Design and Testing of a MASH TL-3 Thrie-Beam System for Roadside and Median Applications (614341)
  - Thrie/W-Beam/Tubular Barrier Gap Rail for MASH TL-3 (610461)
  - Placement of Guardrail on Slopes — Phase IV (609301)
  - W-Beam Guardrail with Steel and Wooden Posts in Concrete Mow Strip (608551)
  - MASH Full-Scale Crash Testing of a 31-inch Buried-in-Backslope Terminal Compatible with an MGS Guardrail System (608431)

- MASH TL2 31-inch W-Beam Guardrail (602921)
- Guardrail Deflection Analysis – Phase I (405160-24)

- **Concrete Barriers**
  - MASH Evaluation of F-Shape and Single-Slope Concrete Barriers with Drainage Scuppers (612831)
  - MASH TL-4 Concrete Median Barrier with Fence Mounted on Top (613131)
  - MASH TL-4 Investigation and Testing of Critical Flare Rate for Cast-In-Place Concrete Barrier Flaring around a Fixed Object (611901)
  - TL-4 Design and Analysis for Sloped Median Wall for Grade Separations (405160-35)
  - Single Slope Half Size Concrete Barrier Wall (405160-27)
  - Concrete Barriers for Slopes or MSE Walls (405160-13)
  - Anchored Concrete Barrier (405160-3)

The participating states and agencies are Alabama, Alaska, California, Colorado, Connecticut, Delaware, Florida, Idaho, Illinois, Iowa, Louisiana, Maryland, Massachusetts, Michigan, Minnesota, Mississippi, Missouri, New Mexico, Ohio, Oregon, Ontario, Pennsylvania, Tennessee, Texas, Utah, Washington, West Virginia, Wisconsin, Texas A & M Transportation Institute, and the Federal Highway Administration.

Life Cycle Economic Comparison of Common Signpost Materials and Types, Kansas DOT, 2005
(https://journals.sagepub.com/doi/10.1177/0361198105191100102)

This report is a lifecycle analysis for signposts. The objective was to determine the most cost-effective signpost type by considering different factors, including labor, material cost, time requirements for installation, and maintenance needs. Four single-post systems and three double-post systems were considered. This study showed that although the material cost is lower for wooden posts, their installation and maintenance costs are higher. Consequently, among the considered single signposts, the Poz-Loc Socket system, which uses a metal post, was determined to be the most cost-effective option over the lifecycle of the sign. Among the double-post systems, the Poz-Loc Slipbase system was found to be the most cost-effective solution. This study showed that wooden posts only become a competitive option if the price of steel steeply increases over the upcoming years.

Manual on Uniform Traffic Control Devices, FHWA, 2009 (https://mutcd.fhwa.dot.gov)

The Manual on Uniform Traffic Control Devices (MUTCD) is published by FHWA and defines standards for installing and maintaining traffic control devices, including highway signs and traffic signs.

Maintenance of Signs and Sign Supports: A Guide for Local Highway and Street Maintenance Personnel, FHWA, 2010 (https://safety.fhwa.dot.gov/local_rural/training/fhwasa09025)

This document is a guide on sign maintenance. Different topics are covered, including sign types, material, installation, support (signpost), inspection, repair and replacement, and preventive maintenance. Although this report briefly discusses different types of signposts (supports) and points to different standards for signpost selection, it does not provide a guideline for selecting between different signpost materials or types.

Sign and Delineator Design Guidelines for Local Roads, South Dakota DOT, 2018 (https://dot.sd.gov/media/documents/SignDelineationDesignManual.pdf)

This manual reviews the design and installation of highway signing devices. It has different sections allocated to sign placement, sign application, delineation, sign assembly, inspection, and standard plates.

User Guide to Standard Plans Section, Roadside Signs, Appendix A, Post Type Selection, Caltrans, 2018 (https://dot.ca.gov/-/media/dot-media/programs/engineering/documents/standardplanuserguides/signsohstructures/201810-ug-spsectrsappxa-roadsidesigns-posttypeselection-a11y.pdf)

This document presents guidelines and standard plans for the design of wooden post roadside sign structures, including six post type designations. It considers the basic dimensions and guides users to verify the basic dimensions meeting several limitations.

Evaluation of Wood Species and Preservatives for Use in Wisconsin Highway Sign Posts, Wisconsin DOT (WisDOT), 2013 (https://www.fs.usda.gov/treesearch/pubs/46200)

This study focuses on three main areas:

- Properties of wood species that are found in the State of Wisconsin and can be used in signposts.
- The different wood preservatives for use in the treatment of signposts manufactured from Wisconsin wood species.
- Current WisDOT post storage practices and recommendations for mitigating warp during storage and use.

The report concludes that the current WisDOT practice of using wooden posts made from southern pine or red pine and treated with Chromated copper arsenate (CCA) is the best option among available alternatives. The justification for these findings is that red southern pines are prevalent in the State of Wisconsin, and they are strong among softwood species, with relatively large and treatable sapwood zones. Moreover, CCA is proven to be an effective preservative and is compatible with aluminum signs.

Chapter 3:
Practices of Other DOTs

In early 2022, a survey was distributed to state DOTs to gather information related to signpost materials, guardrail post materials, and concrete barriers vs. guardrails. A total of 17 responses were received from the states listed in Table 3.1

Table 3.1. The states that responded to the survey.

Alaska	Michigan	North Carolina
Colorado	Minnesota	Ohio
Connecticut	Nebraska	Tennessee
Illinois	New Jersey	Washington
Indiana	New York	Wisconsin

The survey used four descriptors to describe the frequency of use, and they are listed in Table 3.2. The same nomenclature is used in this report. For example, when "often" is used to describe how common a practice is, then this correlates to 40% to 80% of the time.

Table 3.2. Survey categories to quantify percent of usage for a specific practice.

Descriptor	Usage Percentage
Rarely	0%-10%
Occasionally	10%-40%
Often	40%-80%
Mostly	80%-100%

The results of the survey are summarized according to the following topics:

- 3.1 – Signpost material selection, replacement, and guidelines
- 3.2 – Guardrail post material selection and replacement
- 3.3 – Concrete barrier usage instead of guardrail

3.1 Signpost Material Selection and Replacement

All 15 states provided answers in this category of questions. Their results are summarized below in four groups:

- 3.1.1 – Utilization of wooden vs. metal signposts during initial installation

- 3.1.2 – Replacement of wooden signposts with metal signposts
- 3.1.3 – Guidance or written specification for material selection of signposts
- 3.1.4 – Factors considered when selecting signpost material
- 3.1.5 – Lifecycle cost analysis of wooden vs. metal signposts

3.1.1 Utilization of wooden vs. metal signposts during initial installation

The majority of respondents utilized metal for signposts. Only WisDOT mostly used wood, and Alaska and Illinois often used wood. These three respondents did not provide explanations for their responses. Figure 3.1 captures the distribution of responses that show the tendency to not use wood. Seven respondents elaborated on their rationale for using wood, and of these, the most common reason was for temporary signage during construction or after an accident (until a steel signpost could be installed). Wooden signposts are also used rarely in New York for aesthetic reasons. Michigan, Indiana, and Wisconsin DOTs responded that wooden signposts are used for larger signs. Michigan DOT explained what wooden signposts are used when the sign exceeds #3 U-channel capacity and falls under W 8 x 13 support capacity.

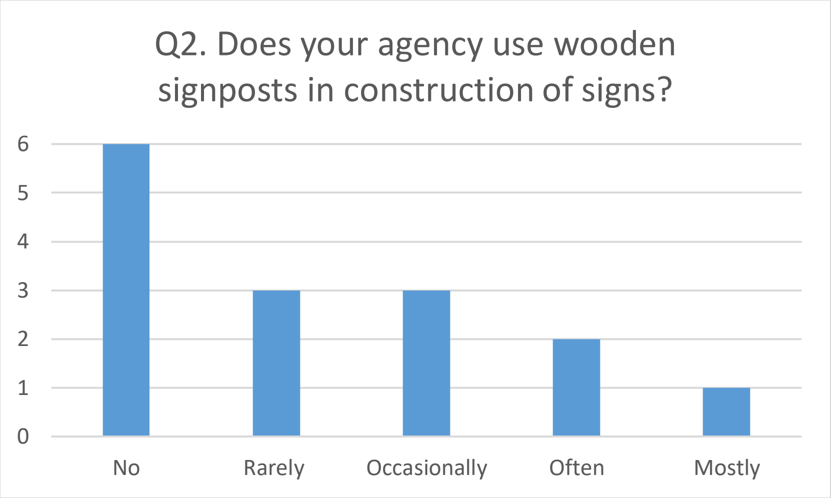


Figure 3.1. Survey responses to the question, “Does your agency use wooden signposts in construction of signs?”

3.1.2 Replacement of wooden signposts with metal signposts

Wooden signposts are typically replaced due to failure in performance or an accident. The survey showed that six of the 15 DOTs did not replace damaged wooden signposts with metal signposts. Of the remaining nine DOTs, the frequency of replacement was nearly equal from rarely to frequently. See Figure 3.2 for the distribution of responses.

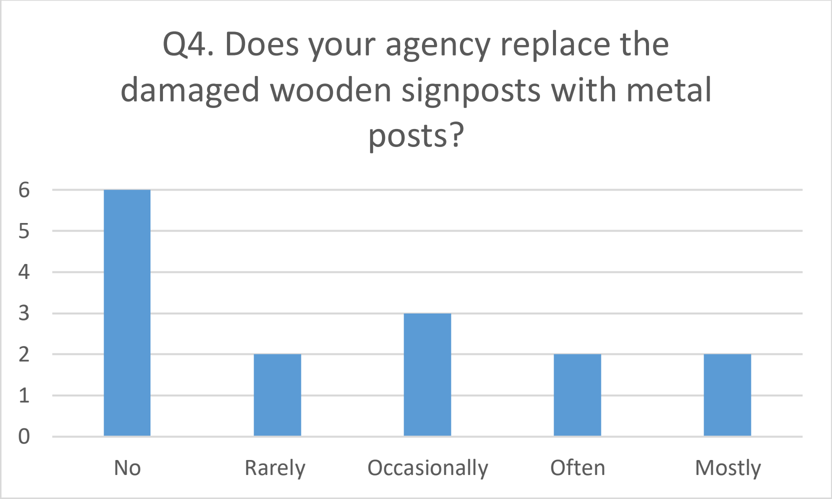


Figure 3.2. Survey responses to the question, "Does your agency replace the damaged wooden signposts with metal posts?"

3.1.3 Guidance or written specification for material selection of signposts

Fifty percent of states have guidance or written specifications regarding the selection of signpost material. Most states (9 out of 15) responded that they do not have agency guidelines related to choosing between wooden vs. metal signposts. However, two states with no agency guidelines explained that they do have general recommendations that are followed; therefore, we included those two states into the "yes" group.

3.1.4 Factors considered when selecting signpost materials

The most common factor in choosing wooden vs. metal signpost material for seven of 15 respondents was location (environment) and maintenance (see Figure 3.3). Both New York and Illinois DOTs indicated that location is their main factor in choosing signpost material. However, the rationale is either for aesthetics or for ease of installation, depending on the underlying soil conditions. Seven agencies also specified that maintenance was an important factor. Colorado and Minnesota stated that steel is cheaper over time, while Michigan said wood was cheaper because it is easier to pull out. The initial cost was specified by six state DOTs, and wood was typically referenced as slightly cheaper. Another common factor mentioned by five respondents was crash safety. Several agencies reported that they are attempting to comply with MASH standards or will comply once more non-proprietary options are available. Only Minnesota DOT stated that they prefer not to use treated materials in the ground.

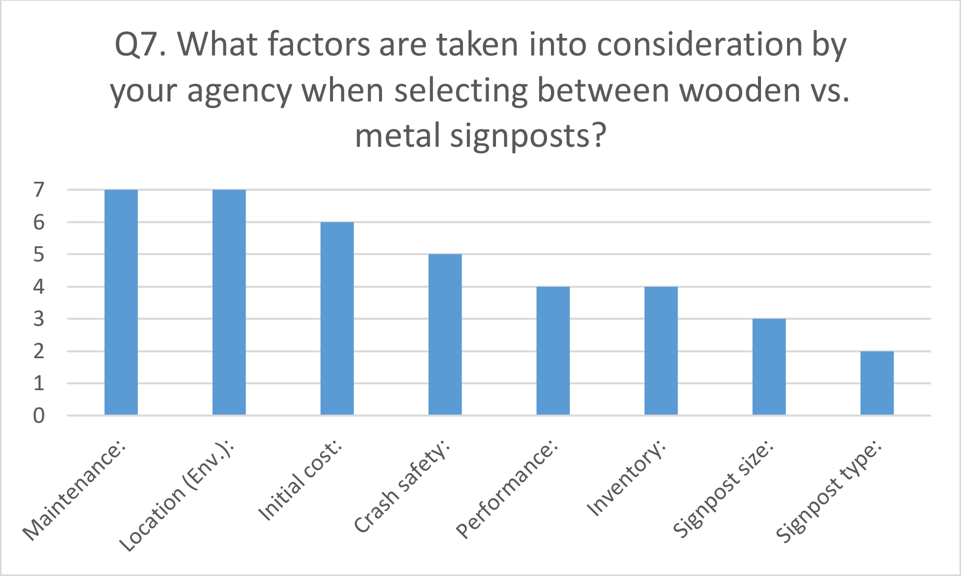


Figure 3.3. Survey responses to the question, "What factors are taken into consideration by your agency when selecting between wooden vs. metal signposts?"

3.1.5 Life-cycle cost analysis of wooden vs. metal signposts

Respondents typically had not conducted a lifecycle cost analysis of wooden vs. metal signposts. Only the Illinois DOT had performed an informal study, in which they found the two choices in signpost material have similar lifecycle costs. This informal report supported their rationale to leave the material choice up to the crews onsite, based on the subsurface conditions.

3.2 Guardrail Support Material Selection and Replacement

Twelve states provided answers to this category of questions. Their results are summarized below in four groups:

- 3.2.1 – Utilization of wooden posts in guardrails
- 3.2.2 – Replacement of wooden guardrail posts with metal posts
- 3.2.3 – Guidance or written specification for material selection of guardrail posts
- 3.2.4 – Factors considered when selecting guardrail post material
- 3.2.5 – Lifecycle cost analysis of wooden vs. metal guardrail posts

3.2.1 Utilization of wooden posts in guardrails

Steel posts were more commonly used by the respondents, as shown in Figure 3.4. Only the Washington, Ohio, and Illinois DOTs reported using wooden posts often. The Illinois DOT was the only one to further explain they allowed contractors to decide the material. Of the seven states that provided an explanation, three states permitted the contractor to decide. This decision appeared to be based on cost, with one respondent referencing an increase in wood prices affecting the decision. The three main reasons stated for use of wooden posts were aesthetic treatment, previous designs, and specific performance requirements.

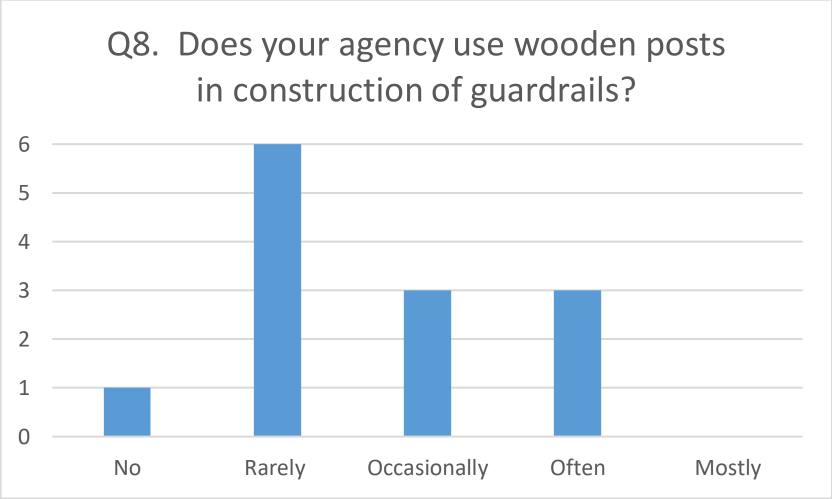


Figure 3.4. Survey responses to the question, "Does your agency use wooden posts in construction of guardrails?"

3.2.2 Replacement of wooden guardrail posts with metal posts

As shown in Figure 3.5, DOTs usually replace guardrails using similar materials. Their explanations show that they favor in-kind replacement, since the performance requirements or initial design drove that decision. Of eight states respondents that explained further, half stated that mixing wood and metal is not preferred. Minnesota DOT was the only state that mostly replaced wood with steel. They explained that the only time they replaced guardrails with wooden posts is if the crash-tested system was designed for wooden posts. There were two respondents who marked "often." These respondents explained that wooden guardrail posts were often replaced with steel in fire-prone areas, and wooden guardrail posts with extensive damage were also replaced with steel. Several states explained that if the damage is significant enough on a run of guardrails, then they will switch from wood to steel.

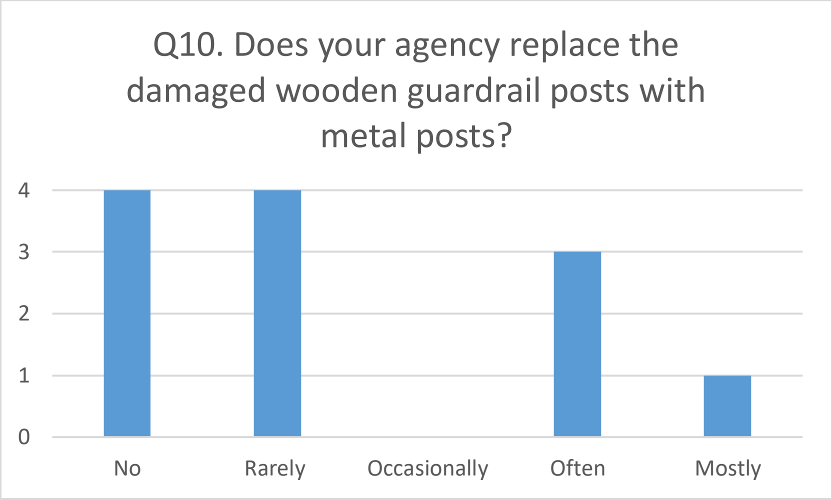


Figure 3.5. Survey responses to the question, "Does your agency replace the damaged wooden guardrail posts with metal posts?"

3.2.3 Guidance for material selection of guardrail posts

Most respondents (10 out of 12) did not have a guideline for choosing between wood or metal guardrail posts. Minnesota DOT stated that they have a standard of steel posts; however, if the system was crash tested with wooden posts, then rails are replaced with wooden posts. Nebraska DOT stated that straight runs are always steel post while short radius guardrail around an intersection are always wooden.

3.2.4 Factors considered when selecting guardrail post material

The initial cost was the most common consideration for selecting wood or steel posts for guardrails (see Figure 3.6). However, only nine states provided responses to this question. Maintenance and inventory were the next most common considerations. One respondent stated that the use of steel posts for guardrails is more prevalent in Indiana. Location was considered by two DOTs and included considerations of aesthetics or whether an area was fire prone.

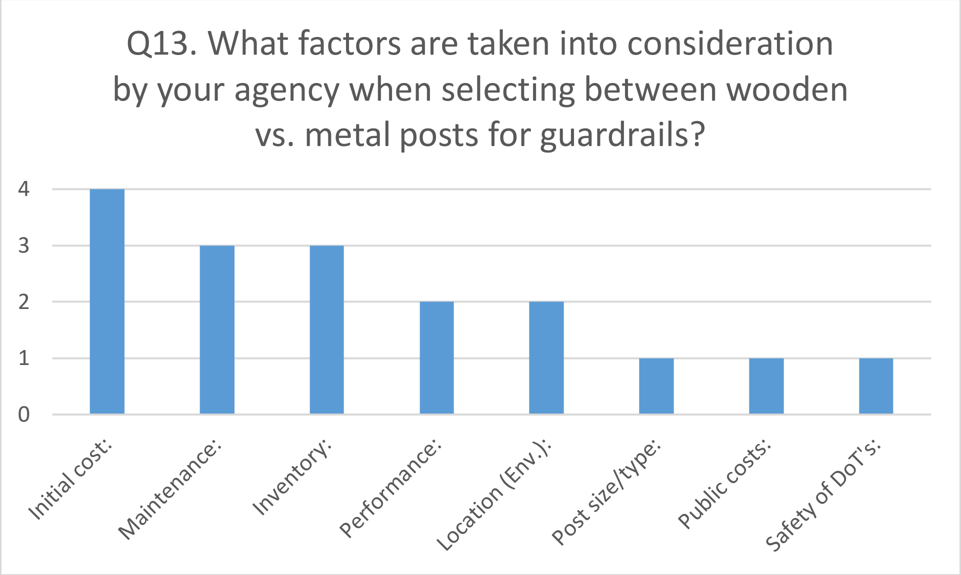


Figure 3.6. Survey responses to the question, "What factors are taken into consideration by your agency when selecting between wooden vs. metal posts for guardrails?"

3.2.5 Life-cycle cost analysis of wooden vs. metal guardrail posts

Almost all the 12 states DOT that responded to the question about a lifecycle cost-analysis stated they did not have one. One respondent stated that they did conduct a study in 2012 that determined the cost savings for steel, but the study was eventually set aside. Several other respondents mentioned that steel has a longer life cycle than wood, but they did not have a lifecycle cost study.

3.3 Concrete Barrier Usage Instead of Guardrails

Twelve states provided answers to this category of questions. Their results are summarized below in four groups:

- 3.3.1 – Replacement of guardrails with concrete barriers
- 3.3.2 – Guidance or written specifications related to new barrier types or replacement of guardrail systems with concrete barriers
- 3.3.3 – Factors considered when selecting between guardrails and concrete barriers
- 3.3.4 – Lifecycle cost analysis of guardrails vs. concrete barriers

3.3.1 Replacement of guardrails with concrete barriers

As shown in Figure 3.7, the majority of respondents reported rarely replacing guardrails with concrete barriers. Only one state DOT reported replacing them occasionally. There were six DOTs that provided an explanation. The most common motivation for replacement was a high-impact frequency. Safety concerns/performance needs were also stated as motivating factors by two DOTs. Replacement with concrete barriers can also be motivated by an increase in traffic volumes according to the Nebraska DOT.

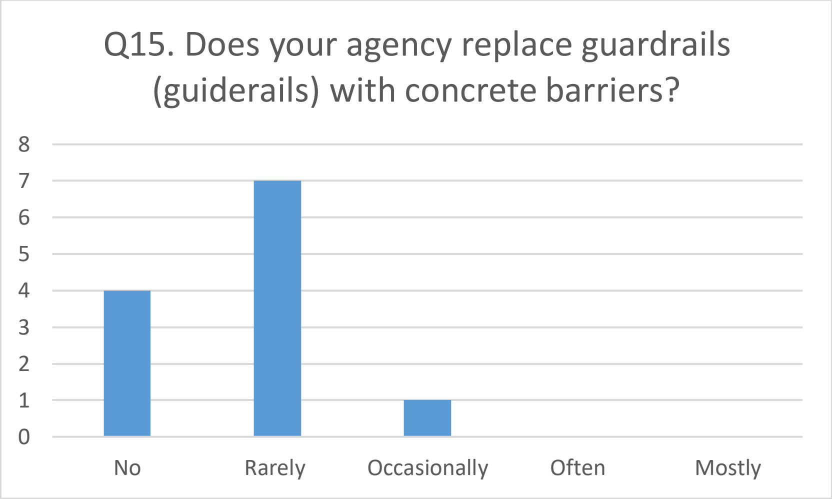


Figure 3.7. Survey responses to the question, "Does your agency replace guardrails (guiderails) with concrete barriers?"

3.3.2 Guidance or written specifications related to new barrier types or replacement of guardrail systems with concrete barriers

Half of the respondents reported that they have a guideline that provides guidance on barrier type and selection. After a brief review of the guidance provided by the states, it was found that concrete barriers are utilized to reduce crossover head-on crashes, due to their inherent lack of deflection. Other DOTs determined barrier type based on test level, with concrete barriers being utilized when higher test levels are desired. Only one state DOT reported that they have guidance for replacing guardrail systems with concrete barriers, and they use the AASHTO Roadside Design Guide. The AASHTO Policy on Geometric Design of Highways and Streets was also mentioned as a guideline by other respondents.

3.3.3 **Selection of guardrails and concrete barriers**

As shown in Figure 3.8, performance, maintenance, and initial cost were factors for six of the 10 respondents for selecting guardrails or concrete barriers. The performance of the system in meeting higher test level requirements, or the ability to redirect traffic, were common explanations for this factor. The lower future costs and the durability in high crash frequency areas were the most common maintenance explanation. Although the explanations for initial cost are more difficult to interpret than other responses, it appears that the higher initial cost is prohibitive. One DOT mentioned that they factor in the maintenance costs of guardrail systems during selection of a barrier, thus concrete barriers are not as cost prohibitive. The safety of DOT workers and equipment was a factor in choosing concrete barriers for five states. Concrete barriers were used as temporary barriers for work zones or in areas with high crash frequency to eliminate future exposure of maintenance workers and equipment to traffic.

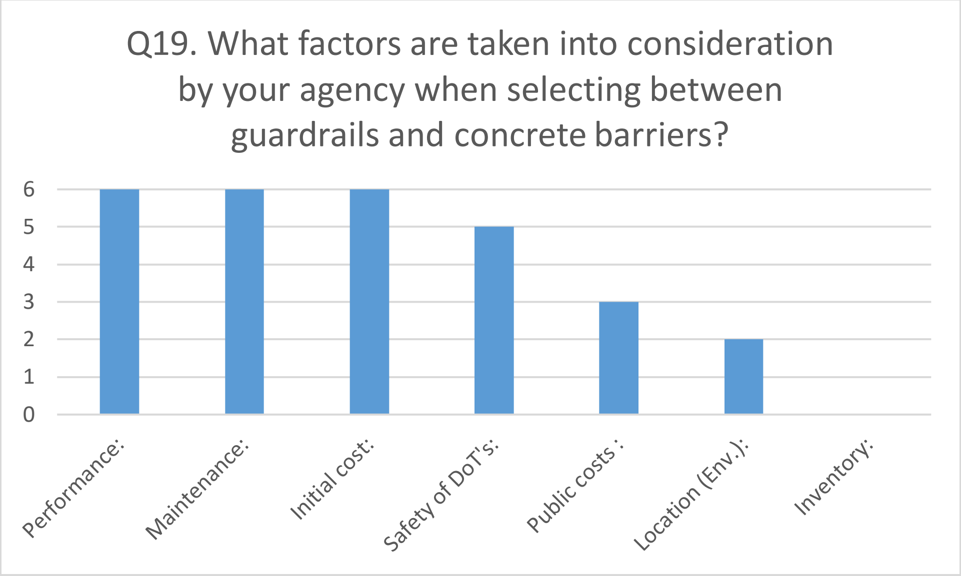


Figure 3.8. Survey responses to the question, "What factors are taken into consideration by your agency when selecting between guardrails and concrete barriers?"

3.3.4 Life-cycle cost analysis of guardrails vs. concrete

Results from the survey showed that there has not been a lifecycle cost analysis of guardrails vs. concrete barriers. Only three states provided explanations, all of which stated that concrete has a longer lifetime. One state mentioned that this decreases maintenance costs in areas with a high crash frequency.

Chapter 4:
Caltrans Practices

In May and June of 2022, interviews were conducted with Caltrans' district safety device coordinators and maintenance managers to gather information related to signpost materials, guardrail post materials, and concrete barriers vs. guardrails. Appendix A contains the survey questions that were utilized in the maintenance interviews. The interviews with the safety device coordinators followed a similar, less formal set of questions.

Safety device coordinators from Districts 3, 5, 7, 9, and 10, as well as a member from headquarters, responded to a request for an interview and then participated in an interview. Maintenance managers from Districts 1, 2, 3, 4, 5, 6, 7, 9, and 12 also responded to a request for an interview and then participated in an interview. The combination of rural and urban districts with various climates, annual average daily traffic (AADT), and geology has provided a variety of practices for the State of California. These practices are summarized in the following topic areas:

- Signpost material selection, replacement, and guidelines
- Guardrail post material selection and replacement
- Concrete barrier usage instead of guardrail

Several districts had multiple attendees to multiple interviews. The response of multiple respondents from the same district was identical when they were asked about the frequency of an item occurring. Therefore, we present the data based on the districts; the extra respondents in each district provided more insights into practice based on their responses to qualitative questions and are not counted multiple times in quantitative responses. The survey used four descriptors to describe the frequency of use, which are listed in

Table 4.1. The same nomenclature will be used in this report as the survey; for example, when "often" is used to describe how common a practice is utilized, it correlates to 40% to 80% of the time.

Table 4.1. Survey categories to quantify percent of usage for a specific practice.

Descriptor	Usage Percentage
Rarely	0%-10%
Occasionally	10%-40%
Often	40%-80%

Descriptor	Usage Percentage
Mostly	80%-100%

4.1 Signpost Material Selection and Replacement

Nine districts provided answers to the questions in this category of questions. The results are summarized below in five groups:

4.1.1 – Utilization of wooden vs. metal signposts during initial installation
4.1.2 – Replacement of wooden signposts with metal signposts
4.1.3 – Challenges when installing/replacing signposts
4.1.4 – Maintenance resource costs for wood and metal signposts
4.1.5 – Factors considered when selecting signpost material

4.1.1 Utilization of wooden vs. metal signposts during initial installation

In direct contrast to the survey results from other state DOTs, many districts in California use wood for signposts. Figure 4.1 illustrates the distribution of the responses, which shows the tendency to use wood most of the time. A lack of a metal signpost solution for signs larger than 36 inches was stated by several districts as a reason they did not use metal more frequently. The gore area was also discussed by many districts. Occasionally districts stated that they preferred wooden posts to allow for quick replacement, while other districts preferred metal for the same reason. This preference may be due to available equipment and should be further researched to be better understood. Districts that prefer wooden signposts also mentioned using a metal sleeve around the wooden signpost to make the signpost easier to replace.

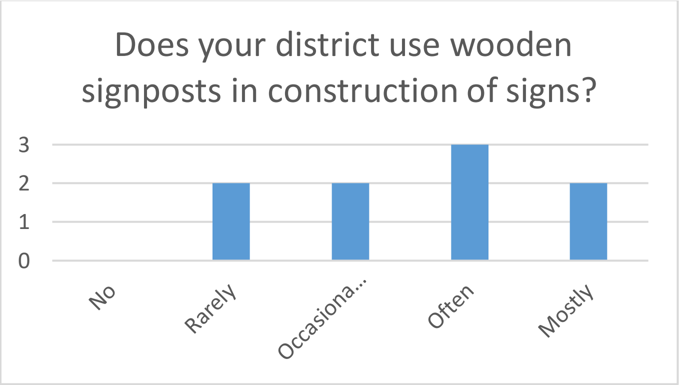


Figure 4.1. Survey responses to the question, "Does your district use wooden signposts in construction of signs?"

4.1.2 Replacement of wooden signposts with metal signposts

Most districts replace signposts in kind, except for certain circumstances, similar to survey results from other state DOTs. In California, it is typical for signposts in fire-prone areas to be replaced with metal signposts. Only one district is replacing wooden posts with steel most of the time; any 4 x 4 post is being replaced with metal, regardless of whether it is in a fire-prone area or not. Districts that occasionally change to metal signs referenced gore areas as a common reason to switch to metal signposts.

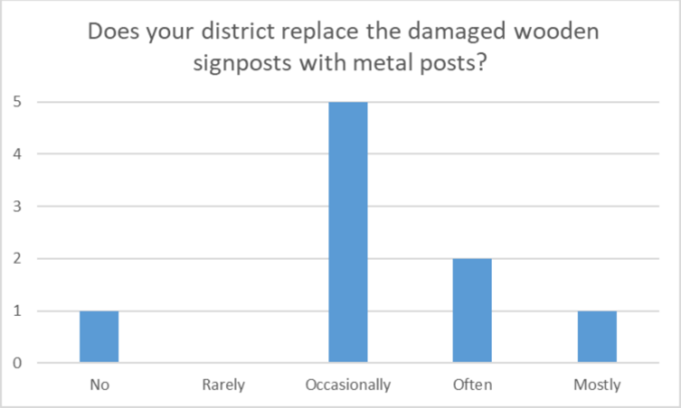


Figure 4.2. Survey responses to the question, "Does your district replace the damaged wooden signposts with metal posts?"

4.1.3 Challenges when installing/replacing signposts

The most common challenge while using wooden signposts is their classification as hazardous material. An associated cost with the disposal of a signpost and potential soil contamination must be addressed. Some districts mentioned that cutting the wooden posts triggers a special protocol that requires more resources than cutting a metal post. Another district also mentioned that wood could splinter apart during a collision, causing more clean-up time as all the hazardous material is retrieved.

An obstacle to replacing wood with metal is the total time involved. The metal replacement requires a base to be poured and the concrete to set. Usually, workers will have to return to the site to finish the replacement after the concrete has set. However, other districts stated the benefit of switching to metal for future repairs, since a new metal sign can be bolted into place. Regarding wooden signposts, some districts use a metal sleeve in the ground where the wooden signpost is placed, which allows for a quick replacement.

4.1.4 Maintenance resource costs for wood and metal signposts

Wooden signposts require several resources that add to the total cost of utilizing wood, such as the disposal cost, as previously mentioned. While there is still a cost of disposal, treated wood has now been lowered to a Class II or III landfill material, decreasing its disposal cost. Most districts have a bin where scrap treated wood is stored until it is ready for disposal. The storage of wooden signposts also takes more space and must be undercover, and undercover storage is at a premium in the state.

From interview responses, it was discovered that metal signposts appear to require fewer maintenance resources. In addition, metal can be recycled and creates a net income versus expense during disposal. The roadside exposure time to workers during replacement can be decreased with metal signposts. Finally, metal posts take up less space due to their size, and they can be stored outdoors, reducing the need for undercover storage.

4.1.5 Factors considered when selecting signpost materials

Similar to other state DOTs, California districts are most influenced by both environment and worker exposure when selecting signpost materials. Signs in gore areas are frequently hit, and the fastest replacement system is preferred in these locations. Typically, switching to metal or replacing wood with metal is preferred in these areas. Metal posts are preferred in all districts for fire-prone areas. Several scenic roadways are pressured to utilize wood for aesthetic reasons. Signs that are hit frequently are occasionally switched to metal posts to decrease the future repair time in some districts. The soil is also a factor for material selection; districts that prefer wood must occasionally use metal when the region is mountainous or rocky.

4.2 Guardrail Post Material Selection and Replacement

Nine districts provided answers to this category of questions. Their results are summarized below in six groups:

4.2.1 – Utilization of wooden posts in guardrails
4.2.2 – Replacement of wooden guardrail posts with metal posts
4.2.3 – Guidance on selection of guardrail posts
4.2.4 – Challenges when installing/replacing guardrail posts
4.2.5 – Maintenance resource costs for wooden and metal guardrail posts
4.2.6 – Factors for selecting guardrail post material

4.2.1 Utilization of wooden posts in guardrails

Similar to other state DOTs, Caltrans districts utilize metal posts more often than wooden posts. As shown in Figure 4.3, only three districts utilize wooden posts often, and two of these three mentioned that the current rate of change would soon have them using wood only occasionally. Districts that did not have the correct equipment for metal posts did not favor metal posts; otherwise, metal posts were preferred by respondents. Several districts stated that all new construction utilized metal posts. Districts that reported often using wooden posts did not use wooden posts in fire-prone areas, which required the work to be completed by contractors, since they did not have the equipment for working with metal post systems.

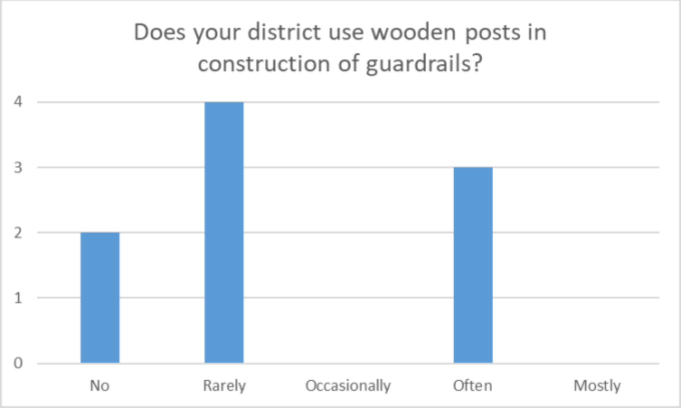


Figure 4.3. Survey responses to the question, "Does your district use wooden posts in construction of guardrails?"

4.2.2 Replacement of wooden guardrail posts with metal posts

Identical to other state DOTs, the replacement of guardrail posts is in-kind when a small number of posts need to be repaired. When a larger crash or a capital project occurs, a slight majority of districts occasionally replace wooden with metal guardrail posts, as shown in Figure 4.4. Districts that mostly replace wooden with metal posts choose to replace the system when only two posts require repair; these districts also mentioned that they are often concerned about fire-prone areas where wooden posts are not preferred. Districts that have the equipment to drive metal posts also stated that they are more likely to change any guardrails in an area where there has been an accident to metal posts.

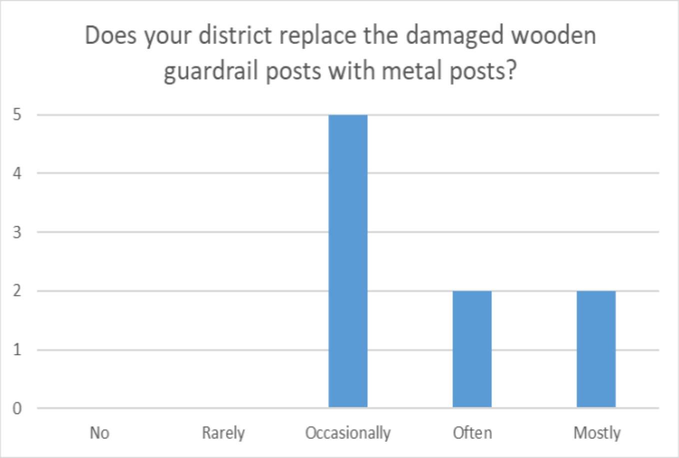


Figure 4.4. Survey responses to the question, "Does your district replace the damaged wooden guardrail posts with metal posts?"

4.2.3 Guidance on selection of guardrail posts

In 2021, a memo sent to all districts to use metal guardrails. About 10 years ago, there was another memo that recommended the replacement of wooden posts with metal posts in fire-prone areas. Some districts mentioned that having metal posts in the regions that are not frequently hit was advantageous, due to their longer lifespan. Wooden posts may rot and have a shorter service life, even if they are not impacted. Several districts also shared that it is always their goal to get a repair done as quickly as possible to reduce worker roadside exposure.

4.2.4 Challenges when installing/replacing guardrail posts

The most common challenge when installing or replacing guardrail posts, especially metal posts, is buried infrastructure. Several districts shared frustration with the inaccuracy of as-built drawings provided by some manufacturers, resulting in damage to culverts, water pipes, electrical systems, etc. Other districts noted that they have now adopted a policy of calling 811 before they begin a repair project. The actual frequency of these issues was not determined from the interviews; it is recommended that further research be conducted, due to the number of stories provided by the districts.

Soil type or rock formations can also present a problem when installing guardrail posts. The districts shared that in mountainous areas it is difficult to meet spacing requirements when using wood, since rock formations may prevent the installation of a wooden post. Those districts find metal posts to be advantageous.

A few districts shared that metal posts are more difficult to maintain if the district does not have the proper equipment. Therefore, they prefer wood since it is easier to remove and replace. One district also mentioned that they had preferred wood until they received the appropriate equipment to drive the metal posts; they now prefer metal guardrail posts.

4.2.5 Maintenance resource costs for wood and metal guardrail posts

The disposal cost for treated wooden posts was the most common reason cited for the cost of wooden posts. The cost is now slightly lower, due to the reclassification in August of 2021 of treated wood to Class II or III landfill, instead of Class I. Without the proper equipment for metal posts, some districts found metal posts to be too expensive. The initial material cost is higher, but the installation and roadside exposure time is also greater to install metal without the proper equipment.

Districts also mentioned that carrying wood and metal on a guardrail truck is challenging, due to limited space. They would prefer one standard that decreases the inventory space on their trucks and in the maintenance yards.

Both wooden and metal posts require weed control. Most districts did not prefer weed mats, stating that they are easily displaced by the wind even if staked down. Several districts mentioned that they slightly preferred the method of low-strength concrete as a weed barrier. However, they shared their concern that this approach can be challenging if not installed correctly. Further specifications or training to ensure that the concrete does not create problems for the removal of the post after an accident may be beneficial.

4.2.6 Factors for selecting guardrail post material

Fire resistance is a crucial factor favoring metal over wood for guardrail posts. Steel barriers withstand small fires without impact, and even moderate fires necessitate only the replacement of rubber spacers. In contrast, wooden posts may require replacement after even a small brush fire. Additionally, districts prefer metal when equipped for installation. It's worth noting from our discussions that in some cases, significant portions of galvanized steel in the rail might be replaced after large fires. This may be due to concerns about warping and potential damage to the galvanizing layer. While small brush fires pose minimal risk, larger forest fires might warrant comprehensive hardware replacement during rail upgrades in the field, considering the associated mobilization and setup costs.

Several districts also stated that the disposal costs for treated wood are a motivating factor to move towards metal guardrail posts. Although this question was related to guardrail posts, three primarily urban districts reported that they prefer concrete barriers to guardrail systems. This point will be discussed in further detail in the final section.

4.3 Concrete Barrier Usage Instead of Guardrail

Eight districts provided answers to this category of questions. Their results are summarized below in three groups:

4.3.1 – Replacement of guardrails with concrete barriers
4.3.2 – Guidance on replacement of guardrail with concrete barriers
4.3.3 – Challenges of using guardrails and concrete barriers

4.3.1 Replacement of guardrails with concrete barriers

Figure 4.5 shows that the majority of districts rarely replace guardrails with concrete barriers. However, three districts occasionally substitute guardrails with concrete barriers, and one reported often replacing guardrails with concrete barriers. Survey results from other state DOTs also showed that the replacement of guardrails with concrete barriers happens rarely or not at all. Several districts stated that they would like to use concrete barriers more frequently, but these are typically cost-prohibitive in a maintenance project and must be funded through capital projects. The high impact frequency is the most common motivation for replacing guardrails with concrete barriers, which is similar to other state DOTs. Some urban districts also stated that newer MASH standards can only be met with concrete barriers, due to constraints such as a tight radius curve on the roadway.

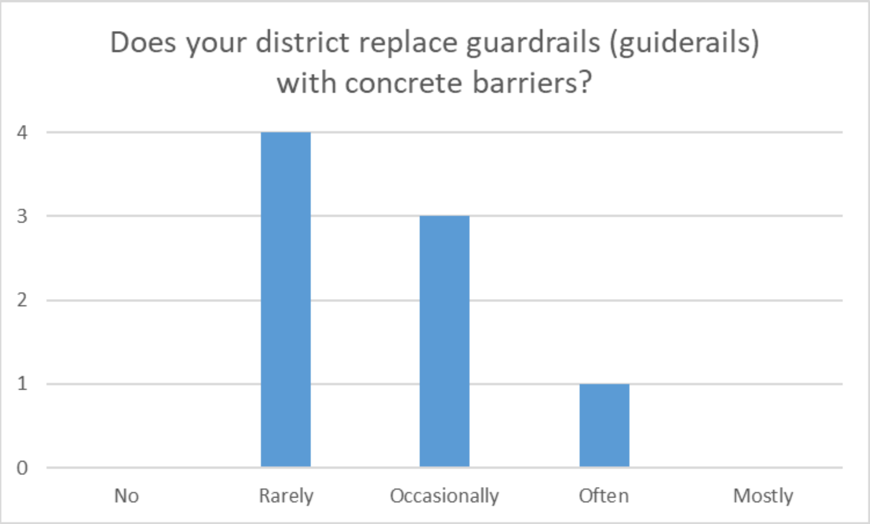


Figure 4.5. Survey responses to the question, "Does your district replace guardrails (guiderails) with concrete barriers?"

4.3.2 Guidance on replacement of guardrail with concrete barriers

As previously mentioned, a high impact frequency is the most common motivation for replacing guardrails. Different districts had different standards for the frequency of hits required before changing to concrete barriers, but three hits was reported as the most common. Only two districts mentioned the traffic safety system guidelines as a resource for decision-making.

4.3.3 Challenges of using guardrails and concrete barriers

Areas with high impact frequency require safety features that can be difficult to maintain, and many districts would prefer concrete barriers in those areas. The difficulty of repairing concrete barriers is due to worker exposure and lane closures on important roadways. Unlike guardrails, when a concrete barrier is hit, it does not typically require repair, eliminating worker exposure, lane closure, and the consequent public cost of traffic delays.

Cost is a crucial factor when considering concrete barriers. Districts mentioned that the initial cost is often prohibitive, far exceeding the price of a guardrail system. Water and wildlife are also significant environmental factors that must be considered when working with concrete barriers. Road surface runoff must be considered during the design process. Concrete barriers prevent the free flow of water and must be managed differently than a guardrail system. Districts mentioned that areas in flood plains prohibit the use of concrete barriers. Concrete barriers also present a formidable obstacle for wildlife.

Districts mentioned the need to have culverts for large animals and small holes or openings at the bottom of concrete barriers for smaller animals.

Chapter 5:
Assessment of Public Costs

In the following chapter, we describe the process of determining the public cost of each barrier option for segments of a road. We computed and included the cost of crashes to a barrier and cost of traffic delay during barrier maintenance as the public cost associated with barriers.

5.1. Crash cost

There are a few models available to compute crash cost; however, most of them have substantial drawbacks. In this research, we analyzed the Roadside Safety Assessment Program (RSAPv3) model [1], Zhu model [2], and Carrigan model [3]. The RSAPv3 model examines a particular segment of road and its roadside features to determine crash severity and cost. The Zhu model is too simple and is not able to determine differences in barrier types. Although the Carrigan model can evaluate differences in crash probability and severity for general highways, it does not examine specific roadway geometry. Relying on the methods used in the three studied models, we utilized the RSAPv3 model to calculate the crash cost associated with the barriers.

To determine which barrier alternative is more costly to the public, the crash cost of each alternative was computed. In Equation (1), $E(CC)_M$ is the expected crash costs for segment N of the road, which is defined as [1]:

$$E(CC)_N = ADT \cdot L_N \cdot P(Encr) \cdot P(Cr|Encr) \cdot P(Sev_s|Cr) \cdot E(CC_s|Sev_s) \qquad (1)$$

ADT is average daily traffic and L_N is the length of segment N. The probabilities are represented as:

- $\boldsymbol{P(Encr)}$: The probability a vehicle will encroach on the segment.
- $\boldsymbol{P(Cr|Encr)}$: The probability a crash occurs given an encroachment has occurred.
- $\boldsymbol{P(Sev_s|Cr)}$: The probability of crash of severity s given a crash has occurred.
- $\boldsymbol{E(CC_s|Sev_s)}$: The expected crash costs of a crash of s severity.

The encroachment probability, crash probability, crash severity, and crash costs must all be computed to choose the best barrier for a specific roadway section.

We employed the approach proposed by RSAPv3 to compute these factors and the crash cost associated with each barrier option. The RSAPv3 model is presented in the following sections.

5.1.1. Encroachment rate

RSAPv3 utilizes Cooper encroachment data to determine the model for computing the encroachment rate [1]. The Cooper data were collected from July to October 1978 by 12 teams from several Canadian provinces. The researchers monitored tire tracks and objects struck by vehicles on the roadside to determine rates of encroachment [4].

To determine the base encroachment rate from the Cooper data, a negative binomial (NB) or Poisson-gamma regression model was employed. This method describes the base encroachment rate (BER) for two- or three-lane undivided highways on the primary right and opposite right directions, as presented in Equation (2), where AADT is less than 15,000 vehicles per day.

$$BER_{PR,OR} = exp\,(0.8528 - 0.3531 \cdot I(PSL > 90) + 1.015 \cdot Rolling + 0.8194 \cdot Mountain - 0.2805 \cdot 3LN - 0.2902 \cdot \frac{AADT}{1000} + 0.6393 \cdot AD) \qquad (2)$$

As presented in Equation (3), the encroachment rate is considered constant when the traffic is more than 15,000 vehicles per day.

$$BER_{PR,OR} = 0.0715 \qquad (3)$$

In this mathematical model, the variables are defined as follows:

- $I(PSL > 90)$ = 1 if the posted speed limit is over 90 kph, or = 0 otherwise.
- $Rolling$ = 1 if the terrain is rolling, or = 0 otherwise.
- $Mountain$ = 1 if the terrain is mountainous, or = 0 otherwise.
- $3LN$ = 1 if the highway has 3 lanes, or = 0 if it has 2 lanes.
- AD = the density of major access points per kilometer.

The encroachment rate of divided highways with four or more lanes, is defined by Equation (4) when the AADT is less than 40,000 vehicles per day.

$$BER_{PR,OR} = exp\,(-0.2104 - 0.04128 \cdot \frac{AADT}{1000} + 1.145 \cdot AD) \qquad (4)$$

Finally, for AADT higher than 40,000 vehicles per day, this model considers a constant value for the encroachment as:

$$BER_{PR,OR} = 0.1554 \tag{5}$$

To convert the encroachment rate to the primary right encroachment frequency, Equation (6) is proposed.

$$BEF_{PR} = (1 - LB) \cdot FP \cdot C_{km,mi} \cdot \frac{365 \cdot AADT}{10^6} \cdot BER_{PR,OR} \tag{6}$$

where $C_{km,mi}$ is the conversion factor from kilometers to miles (1.6093), and FP is the fraction of traffic that flows in the primary direction, which is assumed to be a constant value of 0.50. LB demonstrates the fraction of encroachments that began as left side encroachments and crossed over to the right side.

In the two- and three-lane models, 21.6% of right encroachments began as left side encroachments of the opposite traffic direction, while for divided four-lane or wider highways, this number was only 6.7%. The base encroachment frequencies can then be modified with adjustment factors as their conditions vary from the standard. Such encroachment adjustment factors (EAF) include multi-lane adjustment, posted speed limit adjustment, access density adjustment, terrain adjustment, vertical grade adjustment, horizontal curve adjustment, lane width adjustment, shoulder width adjustment, and rumble strips adjustment factors.

A study of median crashes on highways of various lanes from Texas was analyzed to describe the effect of lane quantity on the encroachment rate. The adjustments to the encroachment factor for single and multi-lane highways are given in Table 5.1.

Table 5.1. Multi-lane adjustment factor [1].

Lanes	Undivided	Divided
1	1.000	1.000
2	0.755	1.000
3+	0.755	0.910

The base encroachment frequencies assume that the speed limit is 65 miles per hour, but if the studied section has a different posted speed limit, it is necessary to make an adjustment, as presented in

Table 5.2.

Table 5.2. Posted speed limit adjustment factor [1].

PSL (mph)	Undivided	Divided
< 60	1.423	1.179
60	1.423	1.179
65	1.000	1.000
> 65	1.000	1.000

The access density adjustment factors presented in Table 5.3 model the effect that major roads and highway access points have on encroachment frequency.

Table 5.3. Access density adjustment factor [1].

AD/mile	Undivided	Divided
0	1.00	1.00
1	1.49	2.05
2	2.22	4.18
3	3.32	8.56
4	4.94	8.56
5	7.73	8.56
6+	10.99	8.56

General highway terrain also affects the encroachment frequency, and the related adjustment factors are defined in Table 5.4.

Table 5.4. Terrain adjustment factor [1].

Terrain	Undivided	Divided	One-way
Flat	1.000	1.000	1.000
Rolling	2.579	1.661	1.661
Mountainous	2.269	1.506	1.506

The vertical grade of a highway section is directionally dependent, as the grade in one direction is the opposite in the other direction. The adjustment factor for a grade is described in Table 5.5, and a negative grade indicates a downhill slope.

Table 5.5. Vertical grade adjustment factor [1].

Grade (%)	Adjustment
< -6	2.00
-6	2.00
-2	1.00
> -2	1.00

The horizontal curvature adjustment is based on the radius of curvature, which is positive for curvature to the right and negative for curvature to the left. The factors for encroachment frequency adjustment are presented in Table 5.6.

Both the vertical grade and horizontal curve adjustments were adapted from the study performed by Wright-Robertson [5].

Table 5.6. Horizontal curve adjustment factor [1].

Radius (ft)	Adjustment
-1910	1.00
-950	4.00
0	4.00
0.1	2.00
950	2.00
1910	1.00

The default lane width in the encroachment analysis is 12 ft, but when the lanes are smaller, encroachments are more likely. This fact is reflected in the adjustment factors in Table 5.7, as developed in the Highway Safety Manual (HSM) [6].

Table 5.7. Lane width adjustment factor [1].

Width (ft)	Undivided	Divided
0	1.50	1.25
9	1.50	1.25
10	1.30	1.15
11	1.05	1.03
12+	1.00	1.00

Shoulder width is another influencing factor on the encroachments and can be an important tool to lower the frequency of vehicles leaving the lanes. The adjustments factors for various shoulder widths are listed in Table 5.8.

Table 5.8. Shoulder width adjustment factor [1].

Width (ft)	Undivided	Divided
0	1.000	1.000
1	0.935	0.980
2	0.870	0.960
3	0.820	0.940
4	0.770	0.920
5	0.720	0.900
6	0.670	0.880
7	0.625	0.880
8+	0.580	0.880

Rumble strips on divided highways tend to reduce encroachments, as presented in Table 5.9.

Table 5.9. Rumble strips adjustment factor [1].

Rumble Strips	Undivided	Divided
Yes	1.00	0.90
No	1.00	1.00

5.1.2. Crash Probability Models

To determine the probability of a crash in each segment, RSAPv3 maps the possible trajectories of a segment to check if any segment intersects a defined hazard. Then the model determines if a rollover might occur before a hazard is struck or on a path with no hazards. Finally, it calculates the probability of the barrier redirecting the vehicle. Figure 5.1 illustrates the flow of crash determination employed by RSAPv3 model [5].

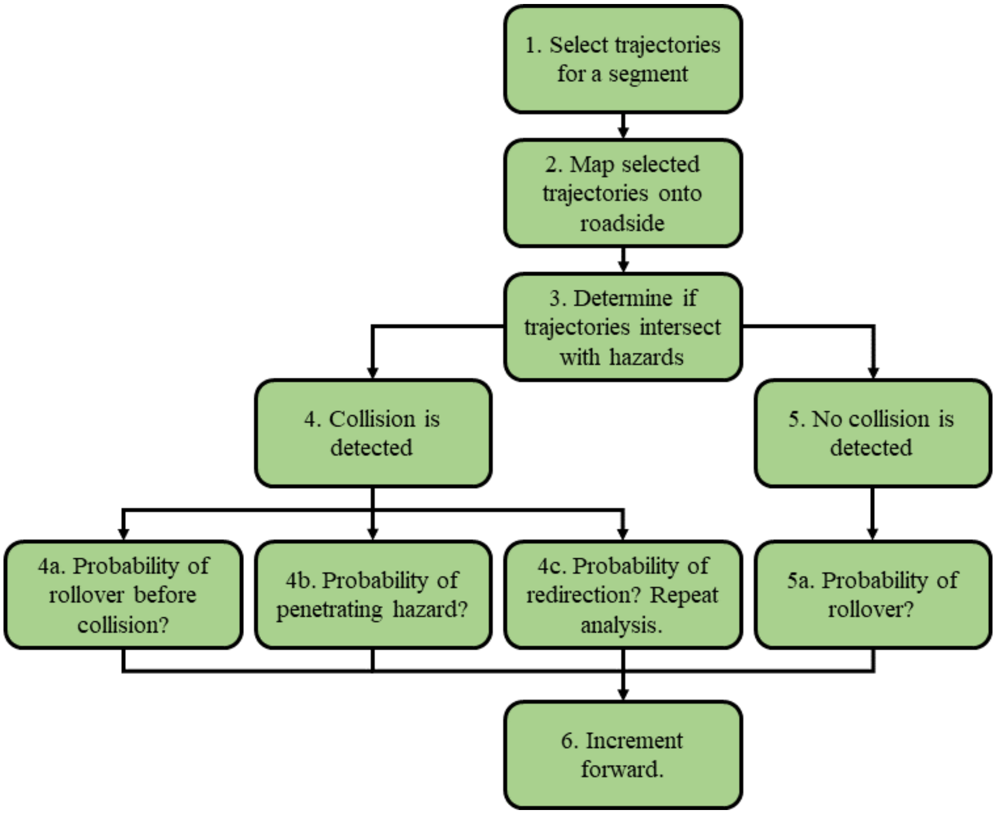


Figure 5.1. RSAPv3 crash prediction flow chart [5].

The following roadway and roadside trajectories are considered to have the most noticeable impact on crashes.

- Roadside cross-section profile
- Horizontal curve radius
- Highway vertical grade
- Posted speed limit

The roadside cross-section profile is measured to have the most significant impact on the trajectory, while the posted speed limit has the least-influence on trajectory. To select the trajectory, a score is created for each characteristic. A composite score is then calculated as a weighted average of the four scores for each trajectory from the database, and if the composite score is higher than 0.93, the trajectory is selected. These trajectories are mapped onto the given roadside to determine if a hazard is impacted.

The probability of vehicle rollover is determined based on the side slope, horizontal curve radius, and highway grade. There is little understanding of the other variables that affect rollovers as well as how all variables influence each other. The RSAPv3 model computes the probability of rollover at each increment employing Equation (7) and utilizing the data presented in Table 5.10.

$$P(R) = \frac{1}{L_{tot}} \sum_{i=1}^{n} P(R|Slope)_i \cdot \phi_{HC} \cdot \phi_{VG} \cdot L_i \qquad (7)$$

Table 5.10. Rollover probabilities by side slope [1].

Side Slope H:V	Rollover Probability
2:1	13.23%
3:1	8.99%
4:1	5.82%
Flat	3.61%
-10:1	5.03%
-6:1	5.82%
-4:1	6.82%
-3:1	12.04%
-2:1	18.52%

However, the calculated probability is adjusted according to the horizontal radius and vertical grade, as described in Table 5.11 and Table 5.12.

Table 5.11. Rollover adjustment by horizontal curve [1].

	Horizontal Curve Radius (ft)			
Side Slope	Baseline	1910 ft	955 ft	637 ft
Flat	1.00	1.08	1.18	1.25
10:1	1.00	1.01	1.06	0.96
6:1	1.00	1.06	0.95	0.85
4:1	1.00	1.30	1.45	1.35
3:1	1.00	1.21	1.14	1.06

Table 5.12. Rollover adjustment by vertical grade [1].

Vertical Grade (%)					
Side Slope	Baseline	-6%	-3%	3%	6%
Flat	1.00	1.50	1.12	0.72	0.63
10:1	1.00	1.15	1.07	0.72	0.54
6:1	1.00	1.58	1.09	0.96	0.76
4:1	1.00	1.78	1.53	1.01	0.80
3:1	1.00	1.30	1.29	0.66	0.62

The RSAPv3 model enables us to predict the probability of a vehicle rollover before, or instead of, a collision. When a vehicle's trajectory intersects a hazard, a collision is detected, and a few different outcomes can occur, such as:

- The vehicle is stopped in contact with the hazard.
- The vehicle penetrates the hazard due to structural failure.
- Vehicle rollover occurs.
- The vehicle vaults the obstacle, passing to the other side.
- The vehicle is redirected.
- The vehicle is redirected and then vehicle rollover occurs.

Two criteria are developed for cases in which the hazard's structural integrity is known or unknown to determine if a vehicle penetrates a hazard. The strength of the hazard is compared to the kinetic energy of the vehicle on impact.

- ***Criterion A:*** If the severity of the impact is greater than the known structural capacity, then the probability of penetration is determined based on a combination of the impact mechanics and a probabilistic model. In such a model, the probability is based on crash statistics and then increased up to 100% beyond the hazard capacity.

- ***Criterion B:*** If the impact severity is less than the strength of the barrier or if the structural capacity of the barrier is unknown, then the probability of penetration is based on crash statistics.

These criteria are developed to reduce the harsh change from not penetrating below the hazard structural capacity to a 100% chance of penetrating once that threshold is exceeded. Figure 5.2 illustrates the transition from Criterion A to B.

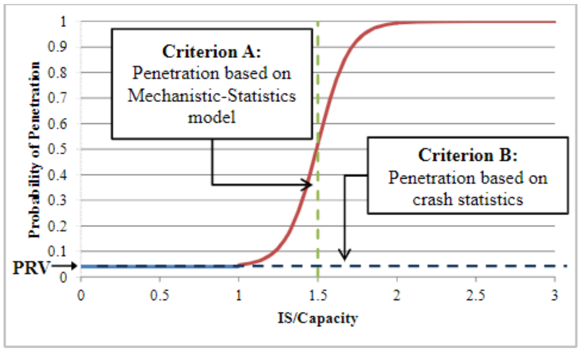


Figure 5.2. RSAPv3 hazard penetration probability [1].

For Criterion A, the probability function is described as follows:

$$P(P|Cr) = \frac{(1-s)}{2} \cdot \tanh\left[B\left(\frac{IS}{Cap} - A\right)\right] + \frac{(1+s)}{2} \qquad (8)$$

Parameter A defines the point of symmetry, and B controls slope of the curve. The variable s controls the lower value of the curve, IS is severity of the impacting vehicle based on its kinetic energy, and Cap is the known capacity of strain energy of the hazard. Once a penetration is detected, the model will continue the trajectory with a change in speed from the kinetic energy used to penetrate the barrier. The post-penetration velocity, v_P, is:

$$v_P = \sqrt{\frac{2}{M}(KE - Cap)} \qquad (9)$$

In Equation (9), M is the vehicle mass, and KE is the initial kinetic energy before penetration. If the vehicle is a truck, the rollover probability is determined based on the physical simulation. This methodology is based on the following four-step assessment of the rollover event:

Phase 1: Evaluating the initial impact between the front corner of the truck against the barrier using simple kinematics of the truck immediately before and after the impact.

- Phase 2: Evaluating the motion of the truck, assuming the front corner remains in contact with the barrier as the truck yaws toward the barrier.

- Phase 3: Second impact is evaluated as the side of the truck impacts the barrier.
- Phase 4: Conservation of energy is used to evaluate if the truck will rollover/vault the barrier.

This algorithm calculates the maximum roll angle to determine the probability of a truck rolling over. The preferred outcome of a collision with a barrier is that the vehicle is redirected. The probability of a redirection occurring is based on the probability that structural penetration or rollover of the barrier does not occur. It has been reported that the redirection angle for 80% of redirections is between 5 and 9 degrees [4]; therefore, the RSAPv3 model examines the trajectory for 5 and 9 degrees redirection.

Vehicle redirection will result in a speed change, which is calculated based on the change in kinetic energy. As presented in Equation (10), the kinetic energy after the redirection, KE_f, is approximated as a function of the kinetic energy before the redirection, KE_i, and the angle, θ

$$KE_f \approx KE_f\left(1 - \sin(\theta)\right) \quad (10)$$

Therefore, the velocity after the redirection, v_f, is defined by [6]:

$$v_f \approx \sqrt{\frac{2KE_f}{M}} \quad (11)$$

In the case of passenger vehicles, rollover event after a redirection is calculated statistically; however, for trucks, the rollover is based on the mechanics of the collision. Figure 5.3 shows an illustration of the RSAPv3 model's prediction of a rollover in the event of a crash.

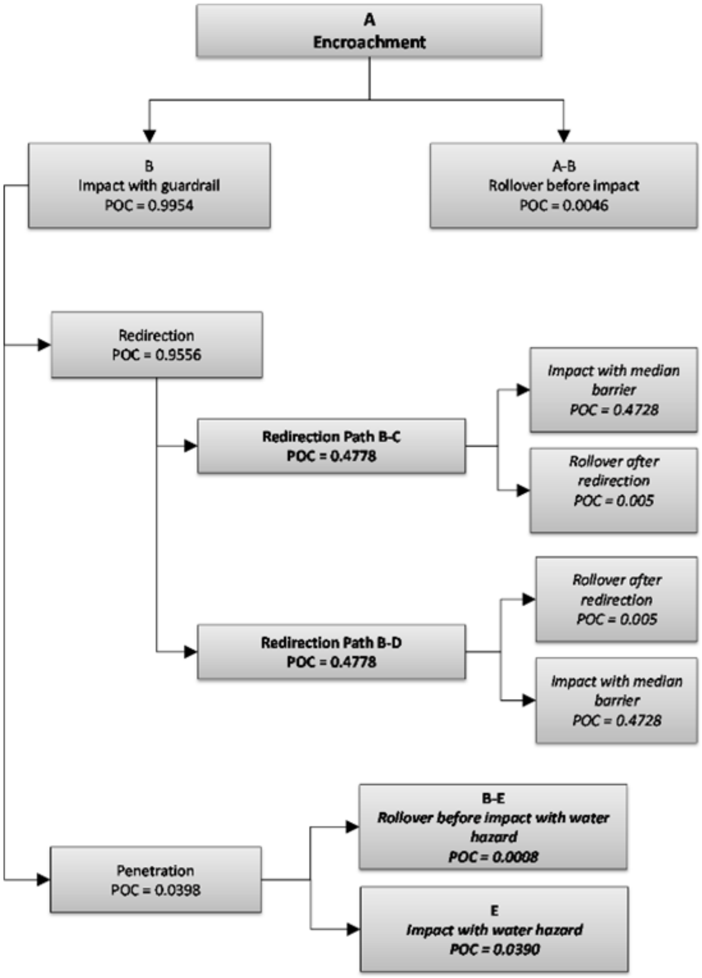


Figure 5.3. RSAPv3 crash probabilities flow[1].

5.1.3. Crash Severity Models

The severity of a crash is converted into several categories based on the scale of the injuries caused by the crash. Police reports describe the severity in the KABCO severity scale, which divides the crashes based on the following criteria.

- Type K: Crashes that result in a fatal injury
- Type A: Crashes that result in an incapacitating injury
- Type B: Crashes that result in a non-incapacitating injury
- Type C: Crashes that result in a possible injury
- Type O: Crashes that result in no injury

Simpler methods use the Severity Index (SI) method, which generally classifies crashes based on crash speeds into several categories from 1 to 9.

The severity model within the RSAPv3 model is based on police data that are adjusted for unreported crashes and different speed limits to develop the value of the Equivalent Fatal Crash Cost Ratio (EFCCR). This non-dimensional parameter describes the crash severity of a specific hazard, and the model calculates the percentage of crashes with a penetration, rollover, or vault or with a redirection that creates a rollover. Table 5.13 describes the classification employed in the RSAPv3 model.

Table 5.13. RSAPv3 Default Hazard Severity Table [1].

HAZARD NAME	**BARRIER HGT**	**EFCCR65**	**PENETRATION ROLLOVER VAULT**	**REDIRECTION ROLLOVER**	**HAZARD NAME**	**EFCCR65**	**PENETRATION ROLLOVER VAULT**	**REDIRECTION ROLLOVER**
	in		%	%			%	%
Bridge Rails					***Poles, Trees, Signs and Other Fixed Objects***			
GenericBR	27	0.0050	0.30	5.00	BridgePierColumn	0.1784	2.00	0.00
TL3FShapeBR	27	0.0035	0.50	1.50	Delineator	0.0020	15.00	0.00
TL3NJShapeBR	27	0.0035	0.50	2.00	Generic Fixed Obj	0.0300	0.00	0.00
TL3VertWallBR	27	0.0085	0.50	0.50	Luminaire	0.0130	30.00	1.00
TL4FShapeBR	32	0.0035	0.20	1.50	Mailbox	0.0170	40.00	1.00
TL4NJShapeBR	32	0.0035	0.20	2.00	SignsBrkwy	0.0030	7.00	0.00
TL4VertWallBR	32	0.0085	0.20	0.50	SmallWoodSign	0.0030	7.00	0.00
TL5FShapeBR	42	0.0035	0.10	1.50	TrafficSignal	0.0367	4.00	0.00
TL5NJshapeBR	42	0.0035	0.10	2.00	Tree	0.0320	5.00	0.00
TL5VertWallBR	42	0.0085	0.10	0.50	UtilityPole	0.0310	11.00	0.00
Crash Cushions					***Special Edges***			
GenericAttenuator		0.0120	7.00	0.00	ClearZoneFence	0.0060	15.00	0.00
Flexible Guardrails					EdgeOfMedian	0.0425	100.00	0.00
TL3HTCableGR	30	0.0018	7.00	0.50	GenericRigidWall	0.0035	0.10	1.00
TL3LTCableGR	30	0.0009	11.00	0.50	Rock Ledge	0.0300	0.00	0.00
Rigid Guardrails					TreeLine	0.0300	0.00	0.00
TL3FShapeGR	27	0.0035	0.50	1.50	Water	0.0300	0.00	0.00
TL3NJShapeGR	27	0.0035	0.50	2.00	***Terminal Ends***			
TL4FshapeGR	32	0.0035	0.20	1.50	GenericEnd	0.0168	0.00	0.00
TL4NJshapeGR	32	0.0035	0.20	2.00	***Rollover***			
TL5FshapeGR	42	0.0035	0.10	1.50	Rollover	0.0220		
TL5NJshapeGR	42	0.0035	0.10	2.00				
Semi-Reigid Guardrail								
TL3-WbeamGR	27	0.0047	2.00	0.10				
Flexible Median Barriers								
TL3HTCableMB	30	0.0018	4.00	0.50				
TL3LTCableMB	30	0.0009	6.00	0.50				
Rigid Median Barriers								
TL3FShapeMB	27	0.0035	0.50	1.50				
TL3NJShapeMB	27	0.0035	0.50	2.00				
TL4FShapeMB	32	0.0035	0.20	1.50				
TL4NJShapeMB	32	0.0035	0.20	2.00				
TL5FShapeMB	42	0.0035	0.10	1.50				
TL5NJshapeMB	42	0.0035	0.10	2.00				
Semi-Rigid Median Barriers								
TL3WbeamMB	27	0.0047	2.00	0.10				

5.1.4. Crash Cost

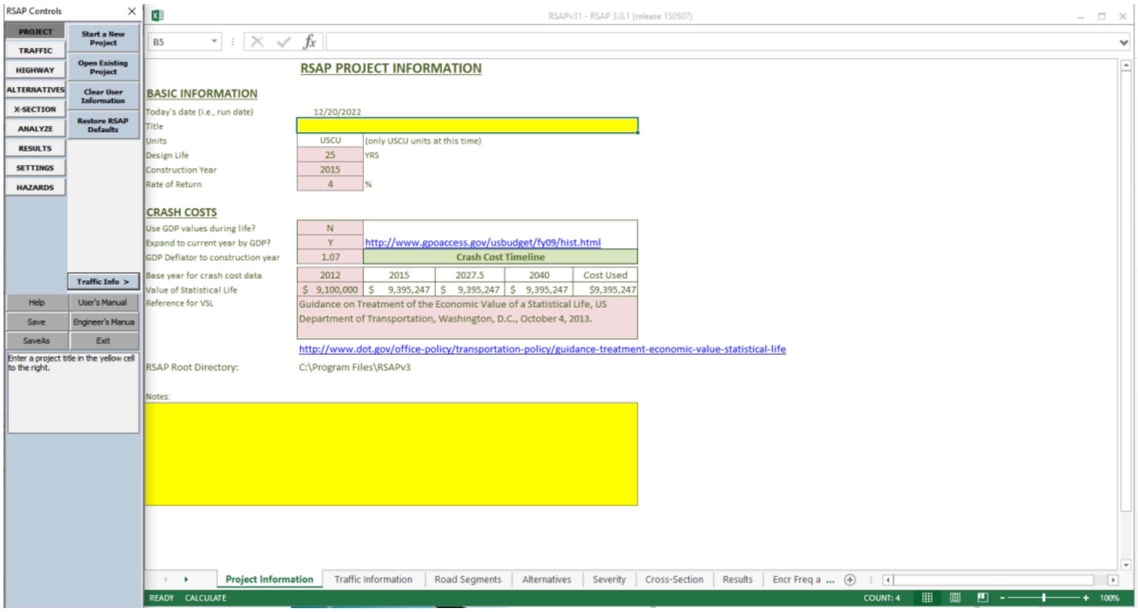
The RSAPv3 model bases crash costs on crash severity and includes adjustments for trucks and motorcycles (Mtc). The predicted costs and adjustments from 2009 are detailed in Table 5.14.

Table 5.14. Crash costs by severity [1].

Severity	All	Truck ADJ	Mtc ADJ
K	$6,000,000	1.24	0.98
A	$415,385	2.61	1.15
B	$83,077	4.49	0.79
C	$43,846	3.69	0.79
O	$4,615	6.77	0.76

5.1.5. RSAPv3 User Interface

In this section, a brief overview of the RSAPv3 model's different sections is presented. A view of the data entry area and the RSAP Controls Dialog Box is shown in Figure 5.4. Basic information about the project is entered on this worksheet. The rose-colored cells contain RSAPv3 default values, which may be edited. The yellow cells represent project-specific data that must be added. All other cells are protected and cannot be edited.



Enter a project title in the yellow cell to the right.

RSAP PROJECT INFORMATION

BASIC INFORMATION

Today's date (i.e., run date)	12/20/2022	
Title		
Units	USCU	(only USCU units at this time)
Design Life	25	YRS
Construction Year	2015	
Rate of Return	4	%

CRASH COSTS

Use GDP values during life?	N				
Expand to current year by GDP?	Y	http://www.gpoaccess.gov/usbudget/fy09/hist.html			
GDP Deflator to construction year	1.07	Crash Cost Timeline			
Base year for crash cost data	2012	2015	2027.5	2040	Cost Used
Value of Statistical Life	$ 9,100,000	$ 9,395,247	$ 9,395,247	$ 9,395,247	$9,395,247
Reference for VSL	Guidance on Treatment of the Economic Value of a Statistical Life, US Department of Transportation, Washington, D.C., October 4, 2013.				

http://www.dot.gov/office-policy/transportation-policy/guidance-treatment-economic-value-statistical-life

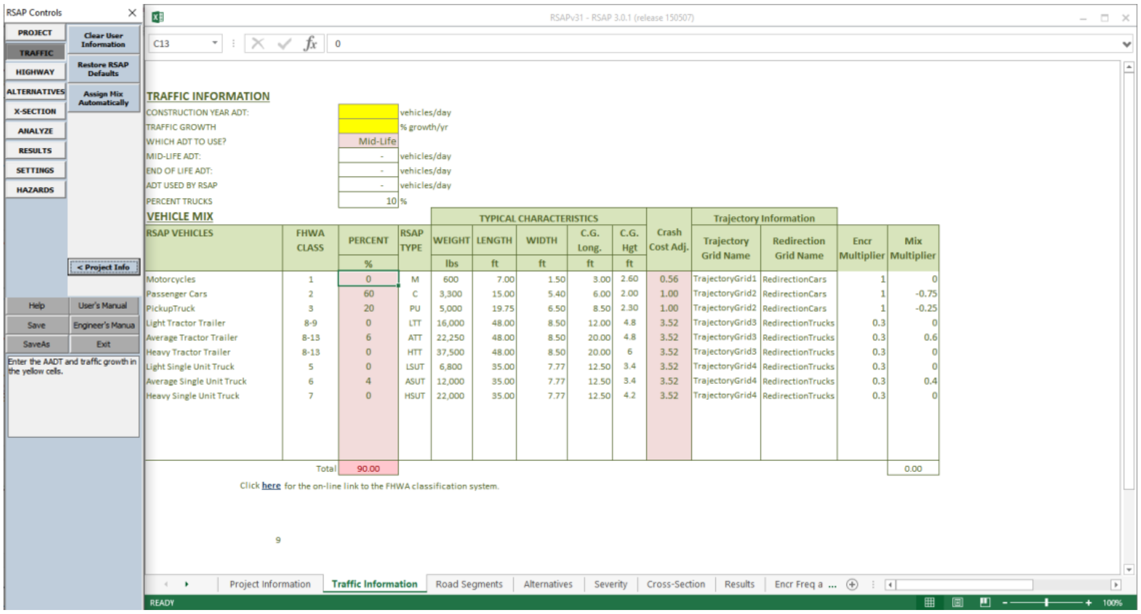
RSAP Root Directory: C:\Program Files\RSAPv3

Notes:

Figure 5.4. Project information entry page of RSAPv3.

In addition to the project title, Figure 5.4 also shows data entry such as expected life of the barrier, the construction year, and the rate of return.

Default values for these rose-colored cells are provided, but they may be edited by the user to conform to the specific project. The default is the 2009 Value of Statistical Life (VSL) of $6,000,000; nevertheless, this value can be changed by the user [1].



Enter the AADT and traffic growth in the yellow cells.

TRAFFIC INFORMATION

CONSTRUCTION YEAR ADT:		vehicles/day
TRAFFIC GROWTH		% growth/yr
WHICH ADT TO USE?	Mid-Life	
MID-LIFE ADT:	-	vehicles/day
END OF LIFE ADT:	-	vehicles/day
ADT USED BY RSAP	-	vehicles/day
PERCENT TRUCKS	10	%

VEHICLE MIX

RSAP VEHICLES	FHWA CLASS	PERCENT	RSAP TYPE	TYPICAL CHARACTERISTICS					Crash Cost Adj.	Trajectory Information		Encr Multiplier	Mix Multiplier
				WEIGHT	LENGTH	WIDTH	C.G. Long.	C.G. Hgt		Trajectory Grid Name	Redirection Grid Name		
		%		lbs	ft	ft	ft	ft					
Motorcycles	1	0	M	600	7.00	1.50	3.00	2.60	0.56	TrajectoryGrid1	RedirectionCars	1	0
Passenger Cars	2	60	C	3,300	15.00	5.40	6.00	2.00	1.00	TrajectoryGrid2	RedirectionCars	1	-0.75
PickupTruck	3	20	PU	5,000	19.75	6.50	8.50	2.30	1.00	TrajectoryGrid2	RedirectionCars	1	-0.25
Light Tractor Trailer	8-9	0	LTT	16,000	48.00	8.50	12.00	4.8	3.52	TrajectoryGrid3	RedirectionTrucks	0.3	0
Average Tractor Trailer	8-13	6	ATT	22,250	48.00	8.50	20.00	4.8	3.52	TrajectoryGrid3	RedirectionTrucks	0.3	0.6
Heavy Tractor Trailer	8-13	0	HTT	37,500	48.00	8.50	20.00	6	3.52	TrajectoryGrid3	RedirectionTrucks	0.3	0
Light Single Unit Truck	5	0	LSUT	6,800	35.00	7.77	12.50	3.4	3.52	TrajectoryGrid4	RedirectionTrucks	0.3	0
Average Single Unit Truck	6	4	ASUT	12,000	35.00	7.77	12.50	3.4	3.52	TrajectoryGrid4	RedirectionTrucks	0.3	0.4
Heavy Single Unit Truck	7	0	HSUT	22,000	35.00	7.77	12.50	4.2	3.52	TrajectoryGrid4	RedirectionTrucks	0.3	0
	Total	90.00											0.00

Click here for the on-line link to the FHWA classification system.

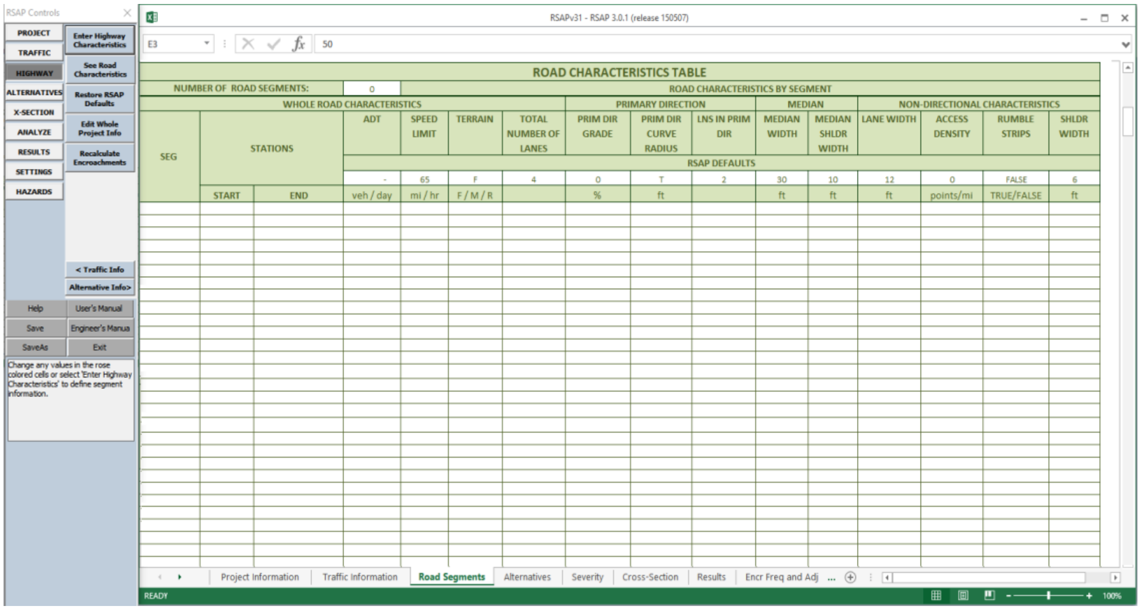
9

Figure 5.5. A view of the RSAPv3 Traffic Information Worksheet, which should be entered by the user.

Figure 5.5 shows a screenshot from the Traffic Information Worksheet, where project specific traffic information and the vehicle's information are entered. The rose-colored cells contain RSAPv3 default values, which may be edited or accepted. The yellow cells require project specific data, and all other cells are protected and may not be edited. In this worksheet, the following information is required, which should be entered by the user:

- Construction Year
- ADT
- Traffic Growth Rate
- Vehicle Type
- Vehicle Crash Cost Adj Factor

The Highway Worksheet is shown in Figure 5.6. This worksheet includes the horizontal and vertical alignment of the segment of the road, the lane width, number of lanes, and other related road characteristics. Highway characteristics entered on this worksheet are common to all types of roadside barriers that will be compared against each other. The RSAPv3 is designed to evaluate different roadside designs, not different roadway geometric designs [6].



Change any values in the rose colored cells or select 'Enter Highway Characteristics' to define segment information.

ROAD CHARACTERISTICS TABLE

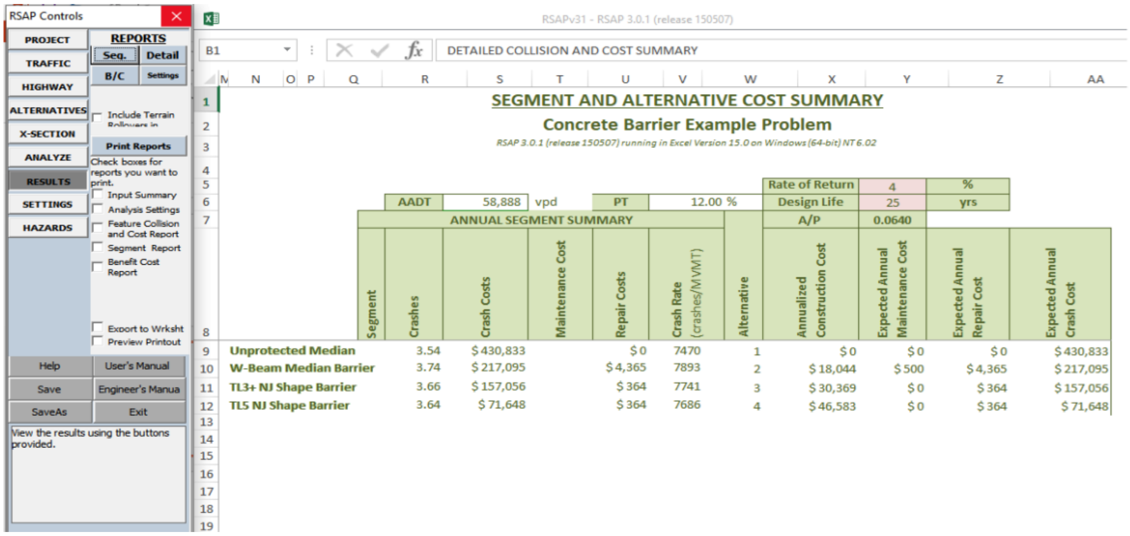
NUMBER OF ROAD SEGMENTS: 0

ROAD CHARACTERISTICS BY SEGMENT

SEG	STATIONS		WHOLE ROAD CHARACTERISTICS				PRIMARY DIRECTION			MEDIAN		NON-DIRECTIONAL CHARACTERISTICS			
			ADT	SPEED LIMIT	TERRAIN	TOTAL NUMBER OF LANES	PRIM DIR GRADE	PRIM DIR CURVE RADIUS	LNS IN PRIM DIR	MEDIAN WIDTH	MEDIAN SHLDR WIDTH	LANE WIDTH	ACCESS DENSITY	RUMBLE STRIPS	SHLDR WIDTH
			RSAP DEFAULTS												
			-	65	F	4	0	T	2	30	10	12	0	FALSE	6
	START	END	veh / day	mi / hr	F / M / R		%	ft		ft	ft	ft	points/mi	TRUE/FALSE	ft

Figure 5.6. Highway characteristics should be entered by user to the RSAPv3 software.

Figure 5.7 demonstrates the results calculated by the RSAPv3 software. Crash rate, crash cost, and expected annual crash cost are among the most important variables computed by the RSAPv3.



Check boxes for reports you want to print.

View the results using the buttons provided.

SEGMENT AND ALTERNATIVE COST SUMMARY

Concrete Barrier Example Problem

RSAP 3.0.1 (release 150507) running in Excel Version 15.0 on Windows (64-bit) NT 6.02

AADT 58,888 vpd

PT 12.00 %

Rate of Return 4 %

Design Life 25 yrs

A/P 0.0640

ANNUAL SEGMENT SUMMARY

Segment	Crashes	Crash Costs	Maintenance Cost	Repair Costs	Crash Rate (crashes/MVMT)	Alternative	Annualized Construction Cost	Expected Annual Maintenance Cost	Expected Annual Repair Cost	Expected Annual Crash Cost
Unprotected Median	3.54	$ 430,833		$ 0	7470	1	$ 0	$ 0	$ 0	$ 430,833
W-Beam Median Barrier	3.74	$ 217,095		$ 4,365	7893	2	$ 18,044	$ 500	$ 4,365	$ 217,095
TL3+ NJ Shape Barrier	3.66	$ 157,056		$ 364	7741	3	$ 30,369	$ 0	$ 364	$ 157,056
TL5 NJ Shape Barrier	3.64	$ 71,648		$ 364	7686	4	$ 46,583	$ 0	$ 364	$ 71,648

Figure 5.7. Results worksheet of the RSAPv3.

5.2. Traffic Delay Cost

In some cases, a temporary lane closure is necessary to conduct maintenance on roadside barriers. A lane closure, along with the lower posted speed limit in a work zone, slows and delays traffic. In a previous study conducted by AHMCT [7], a method was introduced to estimate the average cost of a lane closure. In the proposed method, the cost of lane closure is computed from the reduced traffic speed, AADT, and Value of Travel Time Savings (VTTS). The researchers considered that, on average, a lane closure reduces traffic speed by approximately five mph for a total length of two miles. An example of computing the travel delay cost using this approach is presented in Table 5.15.

Table 5.15. An example of calculating the lane closure cost. [7]

Assumed Cost of Congestion (per person-hour)	$16.79	[USD]
Assumed Nominal Traffic Speed	65	[MPH]
Assumed Speed Reduction	5	[MPH]
Calculated Average Time Added Per Vehicle	9.23	[Seconds]
Calculated Cost Per Vehicle	$0.043	[USD]
Assumed Daily Traffic Volume (per day)	64,075	[Cars]
Calculated Hourly Traffic Volume (per hour)	2,670	[Cars]
Calculated Traffic Impact Cost (per hour)	***$115***	***[USD]***

To further refine this method, the average length of lane closure required for the maintenance of each barrier type was calculated using data from the IMMS databases. By analyzing these data, we determined the typical duration of lane closures needed for maintenance activities specific to each barrier type. The frequency of lane closures for barrier maintenance was computed and documented in a previously published report by AHMCT [8]. This report provides valuable insights into the frequency at which lane closures are required for barrier maintenance.

VTTS is estimated and published by the U.S. Department of Transportation. We used the value published in the most recent report to compute the cost of travel delay [9]. It is reported the value of passenger vehicle motorist's time in 2020 is equal to $20.17 per hour per vehicle on average. We employed VTTS, the length of lane closure, time of lane closure, and AADT to compute cost of travel delay as the result of lane closure due to maintenance activities. The cost of traffic delay was adjusted based on the geometry of the road. Table 5.16 lists the cost of traffic delay resulting from maintenance of barriers per foot per year per AADT.

Table 5.16. Cost of traffic delay associated with each barrier type.

Barrier Type	**Unit**	**Cost**
Concrete Barrier	per foot per year per AADT	$\$0.1101{\times}10^{-6}$
Thrie-Beam Barrier	per foot per year per AADT	$\$0.7234{\times}10^{-6}$
W-Beam Barrier	per foot per year per AADT	$\$4.298{\times}10^{-6}$

6. Chapter 6:
Construction and Operational Cost of Barriers

6.1. Traffic Exposure Risks

The computation of the costs associated with the maintenance of barriers while workers are exposed to traffic involves the following factors:

- Worker fatality due to car crashes in the work zone.
- Worker injury due to car crashes in the work zone.
- Equipment damage due to car crashes during maintenance of barriers.
- Work injuries while performing the maintenance activity.

6.1.1. Workers' Fatality

A previous study conducted by AHMCT reported that the average fatal accident rate in California during maintenance activities from 1972 to 2013 was 2.18×10^{-7} deaths per person-hour of work on the road [7]. To compute the cost of worker fatality as a result of a car collision into the work zone, we also used the most recent Valuation of a Statistical Life (VSL) published by the U.S. DOT, which reports the VSL using the base year of 2022 is equal to $12.5 million [10] . Based on these data, we computed the cost of workers' fatality as a result of car collision into the work zone is equal to $2.57 per person-hour.

Using the IMMS database, we extracted the yearly person-hour of work spent to maintain concrete barriers and steel guardrails. Caltrans has spent an average of 203,560 person-hours per year to maintain the barriers over the last five years. Employing these data, we estimated that the annual cost of workers' fatality due to the exposure to high-speed traffic during maintenance of barriers is $523,149 per year.

6.1.2. Workers' Injury Due to Car Collisions

Data from 2009 to 2022 provided by Caltrans indicated that there were 1,425 collisions in work zones that ended with injuries to Caltrans employees. The data refer to all Caltrans maintenance activities. We computed the average cost of each injury to be $28,459.

A previous study conducted by AHMCT reported that work zone car collisions during the maintenance of barriers account for less than 3% of all Caltrans work zone collisions that are related to maintenance activities [8]. Using this information, we computed that the cost of workers' exposure resulting from car collision injuries during the maintenance of the barriers is $0.43 per person-hour.

6.1.3. Equipment Damage Due to Car Collision

According to data received from Caltrans, the total cost of accidents involving the Caltrans fleet amounted to $484,830 per year from 2016 to 2022. This amount included all accidents that occurred while performing maintenance work on California's highways and roads.

Despite the high number of accidents, work zone car collisions during the maintenance of barriers accounted for less than 3% of all Caltrans work zone collisions [8]. We estimated that the cost of equipment damage due to exposure to high-speed traffic during the maintenance of barriers is $0.072 per person-hour, which means that for every hour a Caltrans worker spends working on barriers, the cost of equipment exposure is $0.072.

6.1.4. Work Injuries

We also computed the cost of workers' injuries while performing maintenance on concrete barriers and steel guardrails that are not the result of a car collision. Caltrans reported 313 incidents in the 2009 to 2022 time period. A previous study conducted by AHMCT reported that the average cost of work injuries was $8,006 in 2006 [11]. We computed the 2022 equivalent, considering the change in VSL from 2006 to 2022 [10] and discovered the average cost of work injuries in 2022 was $15,745 per incident. Employing this information, we computed the cost of work injuries equal to $1.73 per person-hour.

The exposure cost for maintenance of barriers is a combination of different costs associated with worker fatalities and injuries, equipment damage, and work injuries. As presented in Table 6.1, the total exposure cost is estimated to be $4.80 per person-hour of activity, which is equal to $977,495 per year.

Table 6.1. The cost of workers exposure during maintenance of barriers.

Description	**Per person-hour**	**Per year**
Fatality cost	$2.57	$523,149
Injury due to car collision	$0.43	$87,531
Equipment damage	$0.072	$14,656
Work injuries	$1.73	$352,159
Total	**$4.80**	**$977,495**

By considering the maintenance requirements of each barrier type, we computed the exposure cost for each type of barrier per unit of length per year. The results are presented in Table 6.2.

Table 6.2. Cost of exposure associated with each barrier type.

Barrier Type	**Unit**	**Cost**
Concrete Barrier	per foot per year	$\$0.334\times10^{-2}$
Thrie-Beam Barrier	per foot per year	$\$2.828\times10^{-2}$
W-Beam Barrier	per foot per year	$\$3.857\times10^{-2}$

The reported numbers in Table 6.2 include the sum of four categories of exposure cost. To account for the impact of road geometry, the exposure cost of the barrier is adjusted accordingly.

6.2. Initial Cost

6.2.1. Construction Cost

Using the data obtained from the Caltrans Contract Cost database [12], we determined the initial construction cost for each type of barrier. The results are summarized in Table 6.3.

Table 6.3. Construction cost of various types of barriers.

Barrier Type	**Unit**	**Cost**
Concrete Barrier	Linear ft	$105.14
Thrie-Beam Barrier	Linear ft	$44.36
W-Beam Barrier	Linear ft	$30.94

The results presented in Table 6.3 represent the weighted average costs of concrete barriers constructed in California over the past three years. Tables 6.4 and 6.5 provide detailed information on the construction costs per unit of length for various types of concrete and steel barriers.

Table 6.4. Construction cost of various types of concrete barrier.

Barrier Type	Unit	Cost
Type 60M	Linear ft	$84.31
Type 60MC	Linear ft	$115.60
Type 60MD	Linear ft	$96.17
Type 60MF	Linear ft	$304.94
Type 60MG	Linear ft	$97.15
Type 60MGF	Linear ft	$288.38
Type 60MS	Linear ft	$94.09

Table 6.5. Construction cost of various types of w-beam steel barrier.

Barrier Type	Unit	Cost
With 6’ Steel Post	Linear ft	$33.82
With 6’ Wooden Post	Linear ft	$31.76
With 7’ Steel Post	Linear ft	$36.62
With 7’ Wooden Post	Linear ft	$35.92
With 8’ Steel Post	Linear ft	$43.17
With 8’ Wooden Post	Linear ft	$39.30

6.2.2. Vegetation Management Cost

In the case of concrete barriers, vegetation management is not a significant issue, because concrete is poured up to the pavement and the growth of undesirable vegetation is unlikely.

It is estimated that approximately 50 to 60% of California roads requires some type of vegetation management around the guardrails. Other areas do not need vegetation growth prevention, due to the weather conditions. To control the vegetation around the guardrails, if needed, two methods are commonly used: covering the ground with concrete or rubber (fiber) mats.

According to the Caltrans Contract Cost Database, the average cost of *VEGETATION CONTROL MAT (RUBBER OR FIBER)* with order code 832073 during the last five years was $57.96/SQYD, and on average Caltrans ordered 46,987 SQYR per year [12].

On the other hand, the average cost of concrete covering with official title of “*VEGETATION CONTROL (MINOR CONCRETE)*” and order code 832070 is around $60.94/SQYD, which is slightly higher than rubber mats. Nevertheless, on average Caltrans ordered around 822,925 SQYR per year during the last five years [12].

Rubber (or fiber) mats are less expensive and are simpler to install than covering the surface with concrete. However, rubber and plastic mats are vulnerable to fire, and they are not usually used in fire-prone areas. The data from the Caltrans database showed that despite the slightly cheaper cost, rubber mats have been far less used compared to concrete covering during the last five years.

In situations where it is deemed necessary to manage vegetation growth around the barriers, the cost of vegetation management will be included in the overall construction cost. This additional cost, specific to each type of barrier, is detailed in Table 6.6. The cost associated with covering the ground to prevent vegetation growth is considered to be the same for both types of guardrails.

Table 6.6. Cost of vegetation control measures during construction of various type of barriers.

Barrier Type	Unit	Cost
Concrete Barrier	Linear ft	$0.00
Thrie-Beam Barrier	Linear ft	$20.31
W-Beam Barrier	Linear ft	$20.31

6.3. Operational and Maintenance Costs

6.3.1. Snow Control and Removal

Snow control and removal are other key factors to consider when evaluating the costs associated with guardrails and concrete barriers. While snow removal around guardrails may be slightly more difficult than around concrete barriers, the cost of snow removal is nearly the same for both types of barriers. However, one major concern with snow removal around guardrails is that some snowplow operators use the barriers as guides, which can result in damage to the guardrails. On the other hand, concrete barriers are less likely to be damaged by snowplow machines. Despite this advantage, wear marks are visible on concrete barriers after just a few years of installation.

In District 3, many guardrails in the Tahoe Basin have already been replaced with concrete barriers, due to the aforementioned reasons. As part of this project, the impact of snow removal on concrete barriers was carefully considered by taking into account the expected lifetime of the guardrails in regions where snow removal performed regularly.

The weather conditions in different regions of California also affect the need for snow control and removal. In some areas, the need for snow removal may be minimal or non-existent. However, in areas where snowfall is a regular occurrence, the cost of snow removal and its impact on barriers must be considered when evaluating the total costs of guardrails and concrete barriers.

6.3.2. Water Management

There is not a significant cost difference between the two options when considering water management. Small water passages can be included in the construction of concrete barriers without significantly affecting their construction cost. In fact, small water passages are typically included in the bids for the construction of concrete barriers. If a large drainage system is needed, it may add to the construction cost. However, this cost is also typically included in the bids for concrete barriers. The cost difference between the maintenance of concrete barriers and guardrails, with regard to water management, is negligible.

6.3.3. Litter Pick-up

The litter pick-up procedure is different around guardrails and concrete barriers. Sweeping machines are employed to clean roads with concrete barriers, because of the risk of workers' exposure to high-speed traffic. However, litter pick-up around the guardrails can be done manually.

Caltrans uses different labor sources to clean the roadsides (litter pick-up). It is difficult to quantify the cost difference between litter pick-up of the roads with guardrails and concrete barriers, due to the multiple factors that affect this procedure.

6.3.4. Animal Crossing

Large animals do not have a problem jumping over concrete barriers and steel guardrails. For small animals, some openings are included in concrete barriers. The inclusion of the opening does not noticeably affect the construction costs. It is estimated that the cost difference is around $1 to $2 per foot. However, this cost is included in the bid price of concrete barriers.

On some occasions, large culverts are built to facilitate the crossing of animals and reduce accident risk. The procedure of building culverts is the same for steel guardrails and concrete barriers. It does not create an additional cost difference between these two barrier types.

6.3.5. Repair Costs

The average cost of maintenance and repair of barriers from 2020 to 2022 have been compiled and is presented in Table 6.7. These values were computed using the available information in IMMS database. The maintenance costs provide an insight into the expenditures required to maintain the barriers. The results demonstrate that the maintenance cost of concrete barriers is considerably lower compared to their steel counterparts.

Table 6.7. Cost of maintenance and repair of different types of barriers.

Barrier Type	Unit	Cost
Concrete Barrier	per foot per year	$0.075
Thrie-Beam Barrier	per foot per year	$1.01
W-Beam Barrier	per foot per year	$1.77

The characteristics of a road exert a significant influence on the frequency of crashes, thereby impacting the repair costs of barriers.

7. Chapter 7:
Cost-Benefit Analysis

7.1. Cost-Benefit Analysis of Wooden vs. Steel Guardrail posts and Signposts

The size of wooden guardrail posts directly impacts their price, with an average cost of $28.57 observed in California over the 2020-2022 period. In comparison, steel posts had an average cost of $63.87 during the same period. Although these data suggest a significant cost difference between wooden and steel posts, it is essential to consider the overall construction costs of each type.

The initial cost of barriers with steel and wooden posts was computed employing the construction cost provided in the Caltrans Contract Cost Database [12]. On average, the construction cost of guardrails using wooden posts, with a spacing of 6' 3", amounts to $31.80 per foot, while the construction of guardrails with metal posts costs $33.80 per foot.

Additionally, it is important to consider the disposal costs associated with treated wood and the recycling value of steel posts. The estimated disposal cost for treated wood ranges from $0.50 to $0.80 per pound. Consequently, the disposal cost of a small wooden post (6" x 8" x 6') would range between $33.60 and $53.70. Considering post spacing, the disposal cost of treated wood is approximately $5.38 to $8.59 per linear foot of barrier. In contrast, the scrap value of a metal post, such as a 6" x 9" x 6' post is around $6.10 (as of March 2023), translating to $0.98 per foot of installed barrier. Considering only construction and disposal costs, steel posts prove to be more cost-efficient by at least $2.40 per foot, which roughly accounts for 7% of the construction cost.

Furthermore, maintenance of metal guardrail posts appears to be more cost-effective. On average, work orders for a wooden post cost $3,737, while those with metal posts cost $3,470. Moreover, work orders involving wooden posts tend to require more time, resulting in the increased exposure of workers to traffic. On average, work orders with wooden posts entail 42.6 person-hours, whereas those with metal posts require 38.9 person-hours. The results are summarized in Table 7.1.

Table 7.1. Comparison of various costs associated with wood and steel guardrail posts.

Description	**Wood**	**Steel**
Average price of posts	$28.57	$63.87
Construction cost	$31.5/ft	$33.5/ft
Size	6"x6"x6', 8"x8"x7', 10"x10"x8'	W6x9
Post spacing	6'-3"	6'-3"
Disposal cost	50-80 cents/lb	-250$/ton
Disposal cost	$32.08	-$6.3 Scrap value (W6x9)
Average cost of work orders (that include a post repair)	$3,737	$3,470
Average number of changed post	5.44	4.79
Average required labor	42.61 person-hour	38.98 person-hour
Number of people per work orders	7.7	7.9

Table 7.2. Initial price and maintenance cost of wooden signposts.

Material ID	Material Description	Item Used Per Year (Pcs)	Price (USD)	Cost Of Performing Maintenance Per Post (USD)	Labor-Hour Per Post (Hr)	Estimated Disposal Cost (USD)
5510-02102	WOODEN SIGN S4S 4"X4"X10' TREATED DF,OR HEMLOCK	805	16.4	565.7	5.7	14.3-22.9
5510-02203	WOODEN SIGN S4S 4"X4"X12' TREATED DF, OR HEMLOCK	1296	19.4	600.8	6.6	17.2-27.5
5510-02304	WOODEN SIGN S4S 4"X4"X14' TREATED DF, OR HEMLOCK	2154	23.1	810.3	8.8	20.1-32.1
5510-02405	WOODEN SIGN S4S 4"X6"X12' TREATED DF OR HEMLOCK	203	23.6	880.5	10.0	27.0-43.2
5510-02607	WOODEN SIGN S4S 4"X6"X14' TREATED DF OR HEMLOCK	929	35.2	853.9	9.3	31.5-50.4
5510-04106	WOODEN SIGN S4S 6"X6"X20' TREATED DF OR HEMLOCK	261	106.9	1445.1	15.2	70.8-113.2
5510-32509	WOODEN SIGN S4S 6"X8"X24' TREATED DF OR HEMLOCK	315	177.6	1917.7	17.9	115.8-185.3
5510-04005	WOODEN SIGN S4S 6"X6"X18' TREATED DF OR HEMLOCK	139	96.6	1923.5	19.9	63.7-101.9
5510-04308	WOODEN SIGN S4S 6"X8"X18' TREATED DF OR HEMLOCK	15	96.7	3811.0	36.6	86.8-139.0
5510-02215	WOOD SIGN 4"X4"X12' REDWOOD	1	22.7	1328.1	14.0	17.2-27.5
5510-04207	WOODEN SIGN S4S 6"X6"X22' TREATED DF OR HEMLOCK	200	121.6	1630.4	16.2	77.8-124.5
5510-02809	WOODEN SIGN S4S 4"X6"X18' TREATED DF OR HEMLOCK	624	45.8	1138.1	11.9	40.5-64.8
5510-32651	WOODEN SIGN S4S 6"X8"X28' TREATED DF OR HEMLOCK	34	247.4	2085.9	18.2	135.1-21.2
5510-02708	WOODEN SIGN S4S 4"X6"X16' TREATED DF OR HEMLOCK	3114	43.2	874.8	9.6	36.0-57.6
5510-03003	WOODEN SIGN S4S 4"X6"X22' TREATED DF OR HEMLOCK	5	22.9	472.5	6.0	49.5-79.3
5510-02900	WOODEN SIGN S4S 4"X6"X20' TREATED DF OR HEMLOCK	134	42.6	844.8	9.8	45.0-72.1

Table 7.3. Initial price and maintenance cost of steel signposts.

Material ID	Material Description	Item Used Per Year (Pcs)	Price (USD)	Cost Of Performing Maintenance Per Post (USD)	Labor-Hour Per Post (Hr)	Scrap Value (USD)
5660-02705	METAL GUIDE POST 4' LONG. GALV. 6 SLOT HOLES FOR PLATES	6	7.2	234.6	2.5	N.A.
5660-02907	METAL GUIDE POST 6' LONG. GALV. 6 SLOT HOLES FOR PLATES	408	13.6	539.2	6.7	N.A.
5660-03303	METAL SIGN POST 8' LONG. GALV. PUNCHED FOR P MKR.	24	11.1	550.5	4.8	N.A.
5660-03404	METAL POST 10' LONG. GALV. X	184	25.2	908.7	10.4	N.A.
5660-02806	METAL GUIDE POST 5' LONG. GALV. 6 SLOT HOLES FOR PLATES	109	11.5	654.5	7.8	N.A.
5660-03354	METAL SIGN POST 2X2X10 10 GA UNISTRU #24H12.10GP . POWDERCOAT	2	48.3	859.6	7.0	4.1
5660-04608	POST METAL SIGN 2.1/4"X2.1/4"X3' 12 GA. UNSTRT #22F12.A3PG	111	14.2	833.2	8.8	1.1
5660-05106	METAL SIGN 2-1/2"X 2-1/2"X10' 10 GA. UNISTRUT #24H12-10PG	6	50.6	589.1	4.8	5.2
5660-05207	METAL SIGN 2-1/2"X 2-1/2"X12' 10 GA. UNISTRUT #24H12-12PG	24	41.8	1466.6	15.4	6.2
5660-04901	METAL SIGN 2"X2"X10' 12 GA. UNISTRUT #20F12-10PG	1098	33.9	536.9	5.9	3.2
5660-05005	METAL SIGN 2"X2"X12' 12 GA. UNISTRUT #20F12-12PG	652	46.0	829.4	8.1	3.8

Table 7.2 and Table 7.3 present the intial price of the various wooden and steel signposts, as well as the cost of repairing or replacing a post if maintenace is required. The average labor-hour required to perform the maintenace per post is also listed in Table 7.2 and Table 7.3.

It should be mentioned that the data available in the Caltrans Contract Cost database are sufficient to differentiate the construction costs associated with different types of signposts in recent years. We extracted the necessary information required to calculate the average costs of wooden and steel signposts from 2020 to 2022.

An overview of the lifetime cost of signposts including the weighted average price, maintenance, and disposal cost is presented in Table 7.4. The number of items used by Caltrans per year was included for the calculation of average values.

Table 7.4. Comparison of wooden and steel signposts.

Description	**Wooden**	**Steel**
Size of posts	4”x4”x10’, 4”x4”x12’ 4”x4”x14’, 4”x6”x12’,	2"X2"X10' 12 GA, 2"X2"X12' 12 GA, $2\frac{1}{2}$" X $2\frac{1}{2}$" X10' 10 GA, $2\frac{1}{2}$" X $2\frac{1}{2}$" X12' 10 GA
Average price	\$20.82	\$38.46
Number of used signposts per year	4457 Pcs	593 Pcs
Disposal cost	50-80 cents/lb	-250\$/ton
Estimated Disposal cost	\$18.51-\$29.61	-\$3.47 Scrap value
Average cost of work orders per post (that include a signpost repair)	\$708.44	\$657
Average required labor	7.68 person-hour	6.8 person-hour

It should be noted that many manufacturers produce various forms of signposts, which often incorporate proprietary designs that can significantly impact the lifetime cost of these signposts. A previous study, funded by the Kansas DOT in 2005, revealed that certain types of steel signposts exhibit lower life-cycle costs when compared to the standard 4” x 4”x 14’ wooden signpost, while some steel posts have higher life-cycle cost [13]. Notably, this study did not factor in the disposal cost of treated wood in its cost-benefit analysis. Therefore, it is anticipated that including the disposal cost of wooden signposts and considering the scrap value of steel signposts will further enhance the lifetime benefits associated with steel signposts.

As presented in Table 7.4, the material cost of an average wooden signpost is lower than that of an average steel post. However, if a wooden signpost requires repair or replacement, the associated work order tends to be slightly more costly, time-consuming, and typically requires a larger workforce to execute. Wooden signposts are susceptible to issues like twisting and warping due to improper treatment, which can significantly reduce their expected lifetime when compared to steel signposts. Moreover, the process of removing the remnants of a wooden signpost from the ground, after a crash, can pose additional challenges compared to steel signposts.

In addition to the factors already discussed, there are several other considerations that make wooden signposts and guardrail posts less favorable, although they are difficult to quantify with specific numbers per unit. These factors include:

Storage Space: Wooden guardrail posts require more storage space, and it is often recommended to store them in covered or undercover storage areas. This requirement adds logistical challenges and additional costs for storing the wooden posts.

Mountainous Areas and Rock Formations: In mountainous regions or areas with rocky formations, the installation of wooden posts may be challenging. The presence of rock formations can limit the ability to properly space and anchor wooden guardrail posts, making them less feasible for certain locations.

Fire-Prone Regions: Wooden posts are not considered a desirable choice in fire-prone regions. The combustible nature of wood increases the risk of fire damage to the posts, which can compromise the integrity and effectiveness of the guardrail system in areas prone to wildfires.

7.2. Cost-Benefit Analysis of Concrete vs. Steel Barriers

The lifecycle cost of the barriers was calculated across four categories: construction, maintenance, exposure, and public cost.

$$Lifetime\ Cost = Construction + Maintenace + Exposure + public$$

All the costs associated with the barrier during its lifetime in future years, including maintenance, exposure, and public costs, will be adjusted according to the inflation rate. The computed cost is also converted to its current value by considering the interest rate. To calculate the equivalent current value of the future costs, we utilized a method called computing "*present value of a future cost*" [14]. The present value of a future cost in a cost-benefit analysis refers to the process of determining the current worth of a monetary expense or cost that is expected to occur at some point in the future. This concept is crucial when evaluating the economic feasibility of projects or making decisions by accounting for the time value of money, which acknowledges that a dollar today is worth more than a dollar in the future, due to factors like inflation and the opportunity to invest and earn returns. The formula to calculate the present value of a future cost is typically expressed as:

$$PV = \frac{FV}{(1+r)^n} \tag{12}$$

where *PV* represents the present value of the future cost. *FV* is the future value or the amount of the cost in the future. *r* is the discount rate, representing the rate at which money is discounted over time. *n* is the number of time periods until the future cost is incurred.

Future maintenance, exposure, and public costs are adjusted based on the inflation rate, as described in the following equation:

$$FV = CV(1+i)^n \tag{13}$$

where *i* is the inflation rate, and *CV* is the cost computed in 2023.

7.2.1. Construction Cost

The construction cost per unit of length for various barriers is detailed in Table 6.3 to Table 6.5. In cases where vegetation control is required, the associated cost will be added to the construction cost of steel barriers, as outlined in Table 6.6.

$$C_C = BCP_C.L.\frac{(1+i)^{(Y-2023)}}{(1+r)^{(Y-2023)}} \tag{14}$$

$$C_s = (BCP_s + V).L.\frac{(1+i)^{(Y-2023)}}{(1+r)^{(Y-2023)}} \tag{15}$$

where BCP_C is the base construction cost of concrete barrier listed in Table 6.4, BCP_S is the base construction cost of steel barrier listed in Table 6.5, *V* is the base vegetation control cost listed in Table 6.6, *L* is the road length, *I* is the inflation rate, *r* is the interest rate (nominal discount rate), and *Y* is the start year of the project.

7.2.2. Maintenance Cost

The maintenance cost of a barrier is computed employing Equations (16) to (19).

$$M_C = \sum_{a}^{a+l} \frac{(1+i)^{(Y-2023)}}{(1+r)^{(Y-2023)}} \, (BMP_C.L.A_{AADT}.A_{VM}.A_{enc}) \tag{16}$$

$$A_{AADT} = \frac{AADT}{Average\ AADT} \tag{17}$$

$$A_{VM} = \frac{Vehicle\ Mix}{Average\ Vehicle\ Mix} \tag{18}$$

$$A_{enc} = \frac{Modified\ Encroachment\ Rate}{Base\ Encroachment\ Rate} \tag{19}$$

BMP_C is the base maintenance cost of concrete barriers as listed in Table 6.7, and *a* and *l* are the start year and expected life of the barrier, respectively. A_{AADT} is the modification factor based on the AADT, A_{VM} is the modification factor based on the vehicle mix, and A_{enc} is the modification factor based on the encroachment rate. The maintenance cost of steel barrier is computed in the same manner as a concrete barrier.

7.2.3. Exposure Cost

The costs, as a result of the exposure of workers and equipment to traffic, are computed using Equation (20).

$$EX_C = \sum_{a}^{a+l} \frac{(1+i)^{(Y-2023)}}{(1+r)^{(Y-2023)}} \left(BEP_C . L . AADT . A_{VM} . A_{enc}\right) \tag{20}$$

BEP_C is the base exposure cost of the concrete barriers as listed in Table 6.2, and $AADT$ is annual average daily traffic of the road segment. The exposure cost of steel barrier is computed in the same manner as concrete barrier.

7.2.4. Public Cost

Due to the statistical and iterative approach used by RSAPv3, executing the software takes a relatively long time. It may take up to 30 minutes on a powerful PC to calculate the crash cost for a 1-mile-long segment. Therefore, it was not practical for us to use the RSAPv3 directly in our tool. We executed the RSAPv3 model several times for various geometries of the road, then employed a data-driven approach to regenerate the outcomes of the RSAPv3 with adequate accuracy and low computational resources. Additionally, although RSAPv3 is relatively reliable in the calculation of crash cost, it is not accurate in the estimation of maintenance and construction costs. Therefore, we only used RSAPv3 to calculate crash cost.

The equation developed in this study to estimate the crash cost based on the computed modified encroachment cost is represented in Equation (21).

$$\begin{gathered} C_s = C_1 + C_2 Gr + C_3 Gr^2 + C_4 Hz + C_5 Hz^2 + C_6 S + C_7 S^2 + C_8 Enc + C_9 Enc^2 \\ + C_{10} Gr Hz + C_{11} Gr^2 Hz + C_{12} Gr Hz^2 \end{gathered} \tag{21}$$

In the above equation, C_S is the cost of each encroachment, *Gr* is vertical grade, *Hz* is road curvature, *S* is the posted speed limit, and *Enc* is the modified encroachment rate. The parameters C_1 to C_{12} are listed in Table 7.5.

Table 7.5. Constant parameter of the equation developed to estimate the crash cost of steel barriers.

Parameter	**Value**
C_1	2.95×10^5
C_2	8.6010
C_3	118.478
C_4	-42.366
C_5	0.01084
C_6	8867.96
C_7	-51.917
C_8	-297.811
C_9	0.141962
C_{10}	0.8951
C_{11}	0.093611
C_{12}	0.000322

Concrete barriers and steel guardrails exhibit different performance during car collisions, with passengers potentially sustaining more injuries when crashing into steel guardrails. The outcomes of the RSAPv3 model showed that, on average, crashing into steel barriers results in a 23% higher crash cost than a concrete barrier to the vehicle.

To calculate the cost of fatality, we utilized the VSL published by the U.S. Department of Transportation. The VSL in 2022 was $12.5 million.

$$P_s = \sum_{a}^{a+l} \frac{(1+i)^{(Y-2023)}}{(1+r)^{(Y-2023)}} \left(C_s.Enc.\frac{L}{5280}.\frac{VSL}{12.5} + BTD_s.AADT.L\right) \qquad (22)$$

In Equation (22), P_s is the public cost of the steel barrier, *Enc* is the modified encroachment rate, *VSL* is value of statistical life in million USD at the start of the project, *BTD_S* is the base traffic delay cost presented in Table 5.16.

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7. Duane Bennett and Steven A Velinsky, *Deployment Support and Caltrans' Implementation of the Sealzall Machine*. 2014

8. Patricia Fyhrie, Bahram Ravani, and Ankyd Ji, *Performance measures for roadside features*. 2018, California. Department of Transportation

9. *Revised Departmental Guidance on Valuation of Travel Time in Economic Analysis*. Available from: https://www.transportation.gov/office-policy/transportation-policy/revised-departmental-guidance-valuation-travel-time-economic.

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11. Andrew Hargadon, Eric Olson, and Brian Woodall, *Transfer tank longitudinal crack sealer business development case*. 2006, UC Davis

12. *Caltrans Contract Cost Database*. 2022; Available from: https://sv08data.dot.ca.gov/contractcost/.

13. Sankara Raman, Margaret J Rys, and Eugene R Russell, *Life-cycle economic comparison of common signpost materials and types.* Transportation research record, 2005. **1911**(1): p. 13-21.

14. *Time value of Money*. Available from: https://en.wikipedia.org/wiki/Time_value_of_money.

Appendix A:
Survey Questionnaire for Other State DOTs

This survey is being undertaken by the Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center at the University of California, Davis as part of a research project sponsored by the California Department of Transportation (DOT) (Caltrans). The purpose of the survey is to obtain information related to the decision-making process when choosing between different material for signposts and guardrails (wooden vs. metal) and when choosing between guardrail and concrete barriers. This project develops a life cycle analysis tool that reduces the cost in certain high-cost maintenance operations associated with barriers, and signposts in addition to improved safety for maintenance/construction workers and the traveling public.

Please provide your contact information, as we may wish to follow up with you for additional clarification or information.

Name:
Title:
Office type (district/region or central office/HQ):
Email:
Phone number:

Draft DOT Survey Questions
Wooden vs. metal signpost

1. Does your agency use wooden signposts in construction of signs?

No	Rarely (Less than 10%)	Occasionally (10-40 %)	Often (40-80 %)	Mostly (More than 80%)

2. Does your agency replace the damaged wooden signposts with metal post?

No	Rarely (Less than 10%)	Occasionally (10-40 %)	Often (40-80 %)	Mostly (More than 80%)

3. Does your agency have a guideline on choosing between wooden versus metal signposts?

No	No It is under development	No We plan to develop a guideline in future	Yes (Please provide information)

4. Has your agency conducted any study on life-cycle costs of wooden vs. metal signposts?

No	It is under development	We plan to develop a software (tool) in future	Yes (Please provide information)

5. Does your agency consider life-cycle cost of a signpost in the selection of signpost materials?

No (Only Technical Considerations)	No (Only Initial costs)	Rarely	Often	Mostly

6. Has your agency developed a software (tool) or method for selection of signpost materials? (If yes, please provide the software name, or title of the research)

No We select signpost material in each case independently based on available national and state guidelines	It is under development	We plan to develop a software(tool) in future	Yes

7. If your agency already developed a software, do you use the developed software for selection of signpost material?

No	Not yet But we plan to use it in future	Occasionally (10-40 %)	Often (40-80 %)	Mostly (More than 80%)

8. What factors are taken into consideration by your agency when selecting between wooden vs. metal signposts? Please explain all that apply.

a. Performance: ____________________

b. Initial cost: ____________________

c. Maintenance: ____________________

d. Signpost type: ____________________

e. Signpost size: ____________________

f. Crash safety: ____________________

g. Inventory (availability): ____________________

h. Location (environment): ____________________

i. Other: ____________________

Wooden versus metal guardrail posts

9. Does your agency use wooden posts in construction of guardrails?

No	Rarely (Less than 10%)	Occasionally (10-40 %)	Often (40-80 %)	Mostly (More than 80%)

10. Does your agency replace the damaged wooden guardrail posts with metal posts?

No	Rarely (Less than 10%)	Occasionally (10-40 %)	Often (40-80 %)	Mostly (More than 80%)

11. Does your agency have a guideline on replacing a wooden guardrail post with a metal post and vice versa?

No	No It is under development	No We plan to develop a guideline in future	Yes (Please provide information)

12. Has your agency conducted any study on life-cycle costs of wooden or metal guardrail posts?

No	No It is under development	No We plan to develop a software(tool) in future	Yes (Please provide information)

13. What factors are taken into consideration by your agency when selecting between wooden vs. metal posts for guardrails? Please explain all that apply.

a. Performance ______________________________

b. Initial cost: ______________________________

c. Maintenance: ______________________________

d. Post size/type: ______________________________

e. Inventory (availability): ______________________________

f. Public costs (traffic delay, crash probability/outcome, etc.): __________

g. Safety of construction/maintenance workers/equipment: __________

h. Location (environment): ______________________________

i. Other: ______________________________

Guardrail vs. concrete barriers

14. Does your agency replace guardrails (guidrails) with concrete barriers?

No	Rarely (Less than 10%)	Occasionally (10-40 %)	Often (40-80 %)	Mostly (More than 80%)

15. Does your agency have a guideline on replacing a guardrail with a concrete barrier?

No	No It is under development	No We plan to develop a guideline in future	Yes (Please provide information)

16. Has your agency conducted a life cycle analysis on selection of guardrails vs. concrete barrier?

No	No It is under development	No We plan to develop a guideline in future	Yes (Please provide information)

17. Has your agency developed a software (tool) or method for selection of barrier type?

No We select barrier type in each case independently based on available national and state guidelines	No It is under development	No We plan to develop a software (tool) in future	Yes (Please provide information)

18. If your agency has already developed a software, do you use the developed software for selection of barrier type?

No	Not yet But we plan to use it in future	Occasionally (10-40 %)	Often (40-80 %)	Mostly (More than 80%)

19. What factors are taken into consideration by your agency when selecting between guardrails and concrete barriers? Please explain all that apply.

a. Performance ______________________________

b. Initial cost: ______________________________

c. Maintenance: ______________________________

d. Inventory (availability): ______________________________

e. Public costs (traffic delay, crash probability/outcome, etc.): __________

f. Safety of construction/maintenance workers/equipment: ___________

g. Location (environment): ______________________________

h. Other: ______________________________

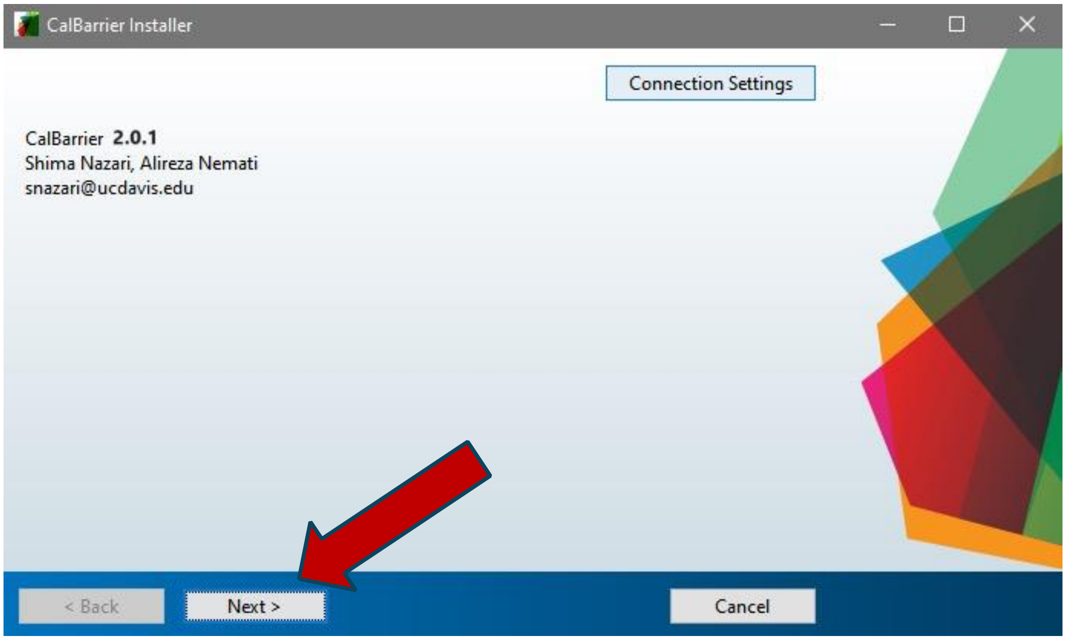
20. Please provide any other information or feedback that you believe may be of value for this research.

Appendix B:
CalBarrier Installation Guide

B.1 Installation guide: for user with administrator access

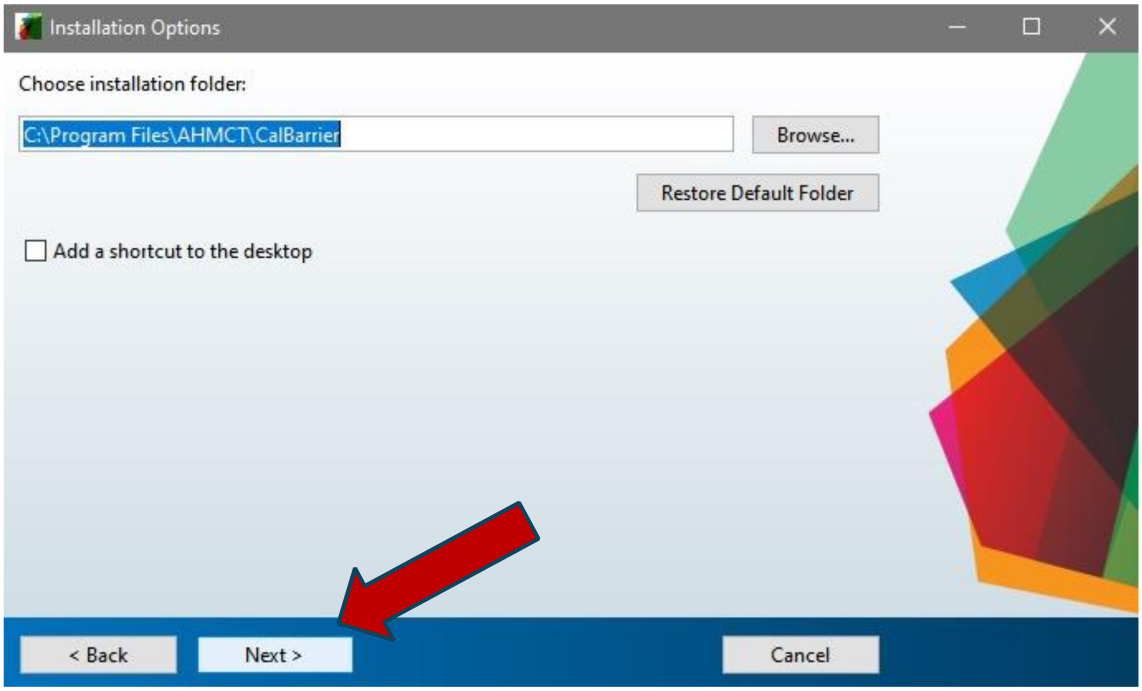
If the users have administrator access in their computers, they can install and use CalBarrier following this step-by-step guide.

1. Download the ***CalBarrier, Admin Access*** folder and its content from the link provided by the AHMCT team.
2. Execute the ***MyAppInstaller_mcr.exe*** by double-clicking on it.
3. Follow the installation steps and install the software as presented in the following images.
4. Now you can run CalBarrier. Go to the ***CalBarrier, Admin Access*** folder that you downloaded and run ***CalBarrier_V201.exe*** to run the software. Hereafter you can run CalBarrier by simply double-clicking on it. The future versions of CalBarrier can be also used by simply double-clicking on them without the need for any other changes.



CalBarrier 2.0.1
Shima Nazari, Alireza Nemati
snazari@ucdavis.edu

Figure B.1. Screenshot of first page of installation process.

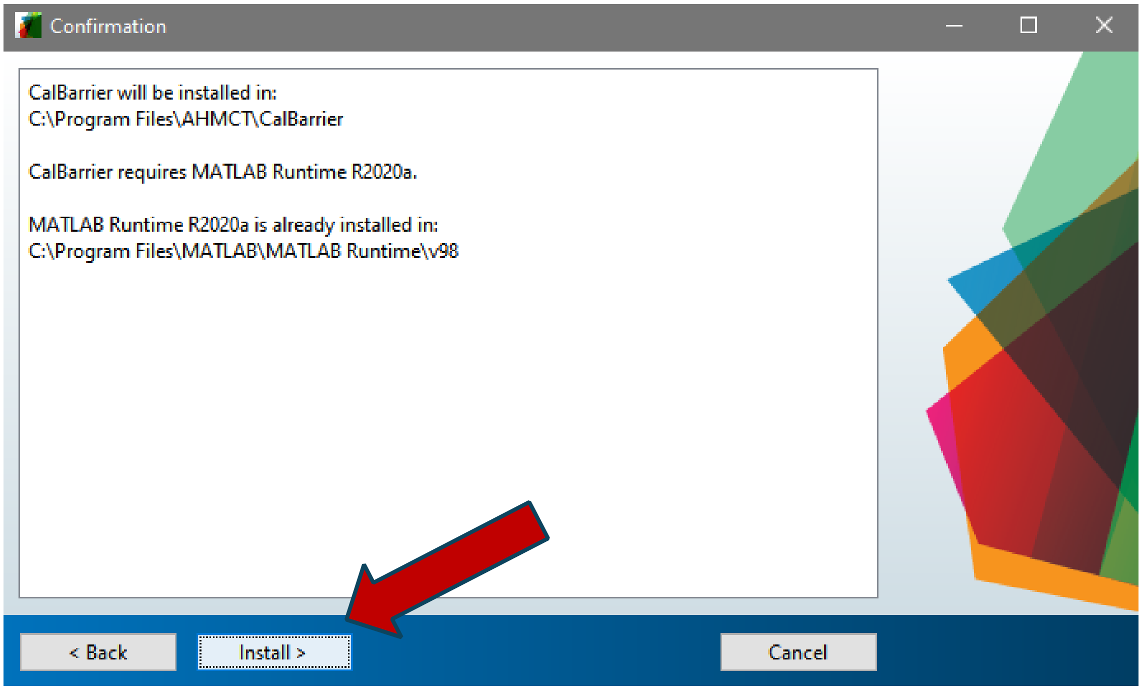


Choose installation folder:

C:\Program Files\AHMCT\CalBarrier

☐ Add a shortcut to the desktop

Figure B.2. Screenshot of second page of installation process.



CalBarrier will be installed in:
C:\Program Files\AHMCT\CalBarrier

CalBarrier requires MATLAB Runtime R2020a.

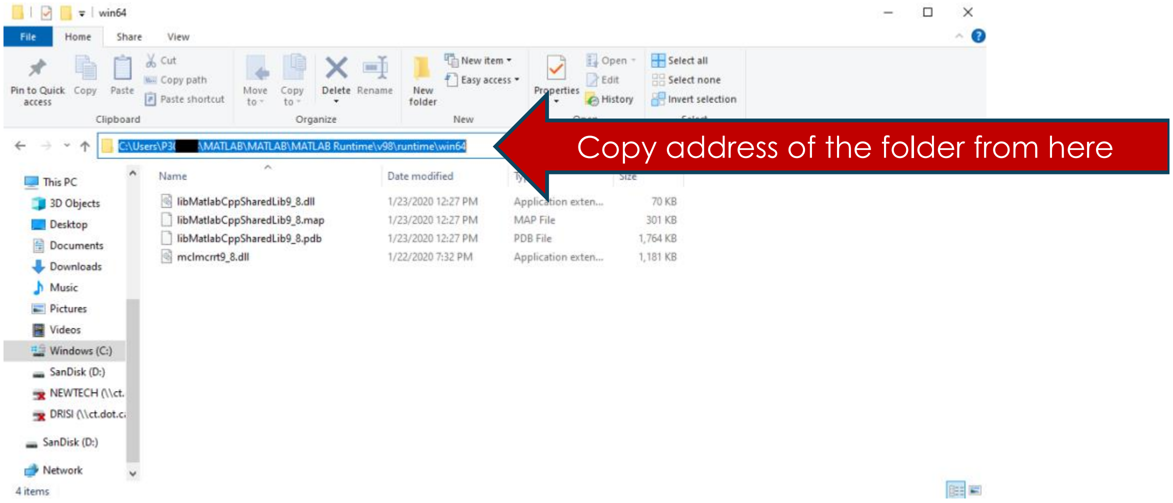
MATLAB Runtime R2020a is already installed in:
C:\Program Files\MATLAB\MATLAB Runtime\v98

Figure B.3. Screenshot of third page of installation process.

B.2 Installation Guide: For Users without Administrator Access

If users do not have administrator access on their computers, they can install and use CalBarrier following this step-by-step guide. This guideline has been tested on Windows 10.

1. Download the ***CalBarrier, Without Admin Access*** folder and its content from the link provided by the AHMCT team.
2. Copy ***MATLAB.ZIP*** file to the ***C:\Users\<your username>***. <your username> is the name you chose for your computer; it could be your name, your employee ID, or anything you or the computer admin chose for you. FOr example, if the username is ***P4125366***, copy the ***MATLAB.ZIP*** file to folder in ***C:\users\P4125366***.
3. Extract the ***MATLAB.ZIP*** file. Based on your computer's specifications, it could take up to 20 minutes to extract the file.
4. Go to the extracted file and go to ***…\MATLAB\MATLAB Runtime\V98\runtime\win64***.
5. Copy the folder address from the address bar.



C:\Users\P3[redacted]\MATLAB\MATLAB\MATLAB Runtime\v98\runtime\win64

Name	Date modified	Type	Size
libMatlabCppSharedLib9_8.dll	1/23/2020 12:27 PM	Application exten...	70 KB
libMatlabCppSharedLib9_8.map	1/23/2020 12:27 PM	MAP File	301 KB
libMatlabCppSharedLib9_8.pdb	1/23/2020 12:27 PM	PDB File	1,764 KB
mclmcrrt9_8.dll	1/22/2020 7:32 PM	Application exten...	1,181 KB

Copy address of the folder from here

Figure B.4. Address of the Win64 folder in the copied MATLAB folder

6. Right-click on the ***This PC*** icon on your desktop and go to the ***Properties*** menu.

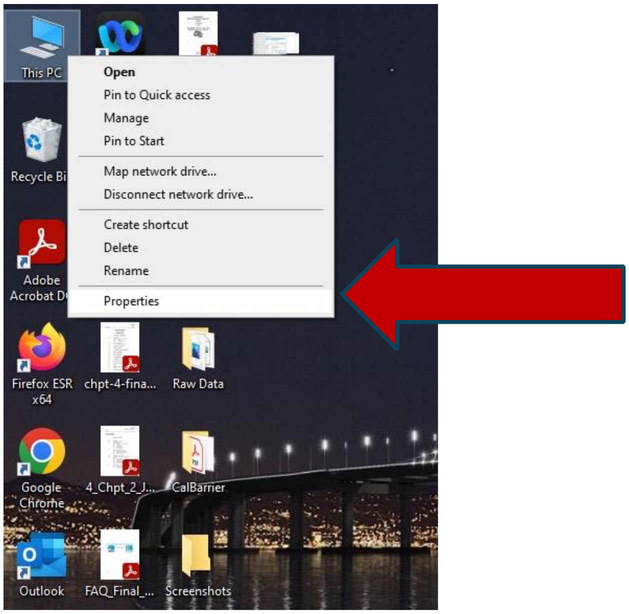
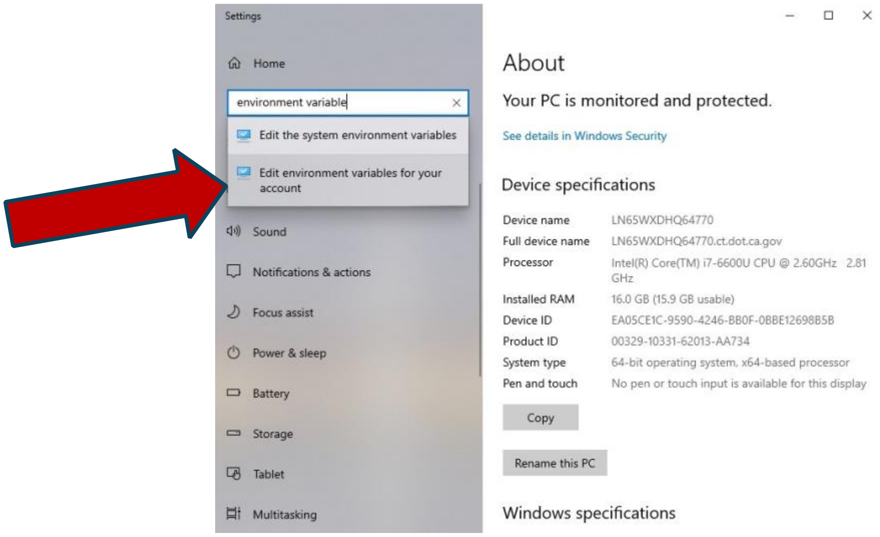


Figure B.5. Properties menu of "*This PC*" icon

7. Search ***Environment variables*** and select ***Edit environment variable for your account.***



environment variable

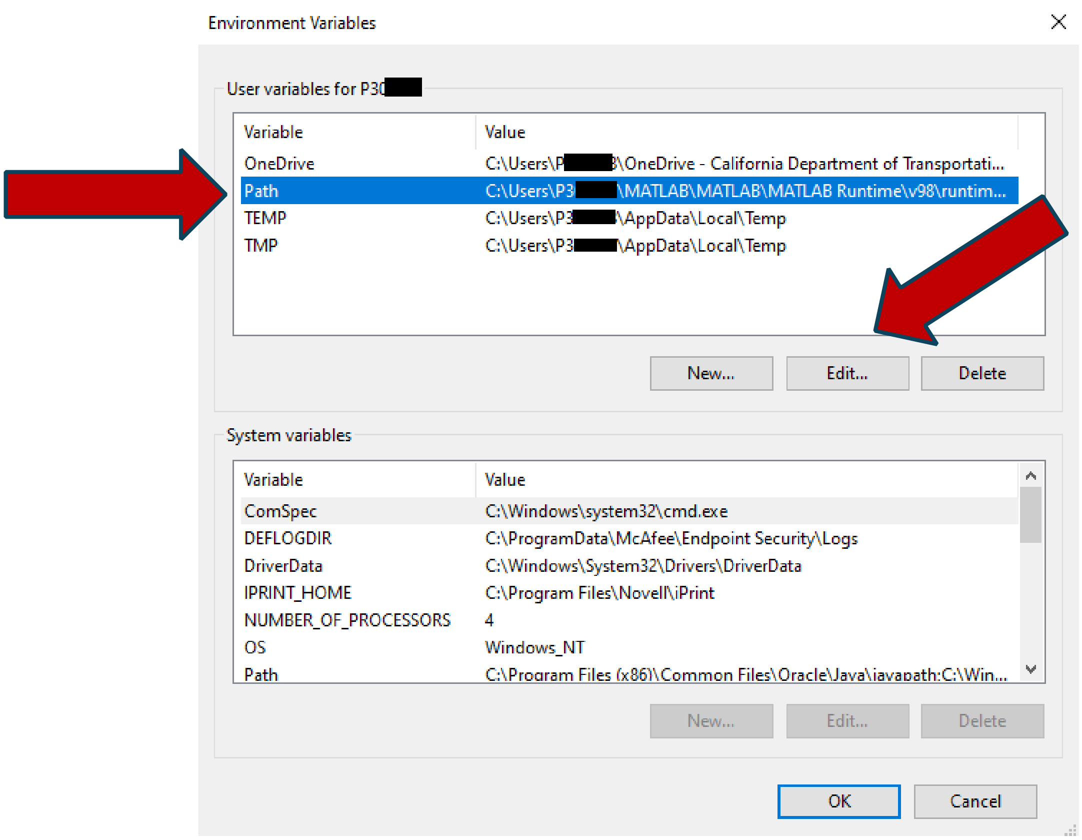
Your PC is monitored and protected.

Device specifications

Device name	LN65WXDHQ64770
Full device name	LN65WXDHQ64770.ct.dot.ca.gov
Processor	Intel(R) Core(TM) i7-6600U CPU @ 2.60GHz 2.81 GHz
Installed RAM	16.0 GB (15.9 GB usable)
Device ID	EA05CE1C-9590-4246-BB0F-0BBE12698B5B
Product ID	00329-10331-62013-AA734
System type	64-bit operating system, x64-based processor
Pen and touch	No pen or touch input is available for this display

Figure B.6. Searching *Edit Environmental Variables for Your Account*

8. Click on ***Path***, and then click the ***Edit*** button.



User variables for P3[redacted]

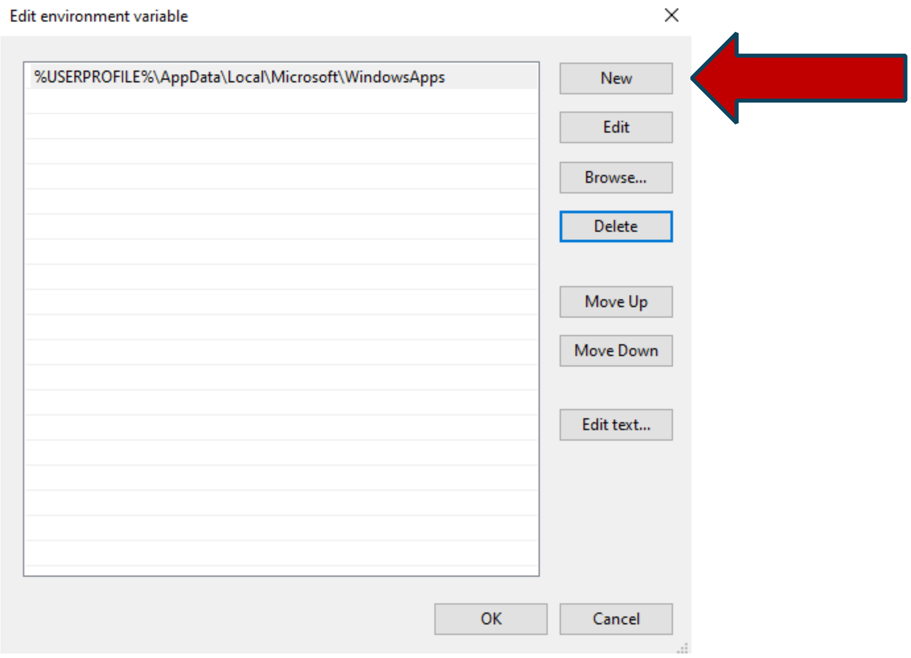
Variable	Value
OneDrive	C:\Users\P[redacted]\OneDrive - California Department of Transportati...
Path	C:\Users\P3[redacted]\MATLAB\MATLAB\MATLAB Runtime\v98\runtim...
TEMP	C:\Users\P3[redacted]\AppData\Local\Temp
TMP	C:\Users\P3[redacted]\AppData\Local\Temp

System variables

Variable	Value
ComSpec	C:\Windows\system32\cmd.exe
DEFLOGDIR	C:\ProgramData\McAfee\Endpoint Security\Logs
DriverData	C:\Windows\System32\Drivers\DriverData
IPRINT_HOME	C:\Program Files\Novell\iPrint
NUMBER_OF_PROCESSORS	4
OS	Windows_NT
Path	C:\Program Files (x86)\Common Files\Oracle\Java\javapath;C:\Win...

Figure B.7. Edit the path of Environmental Parameters

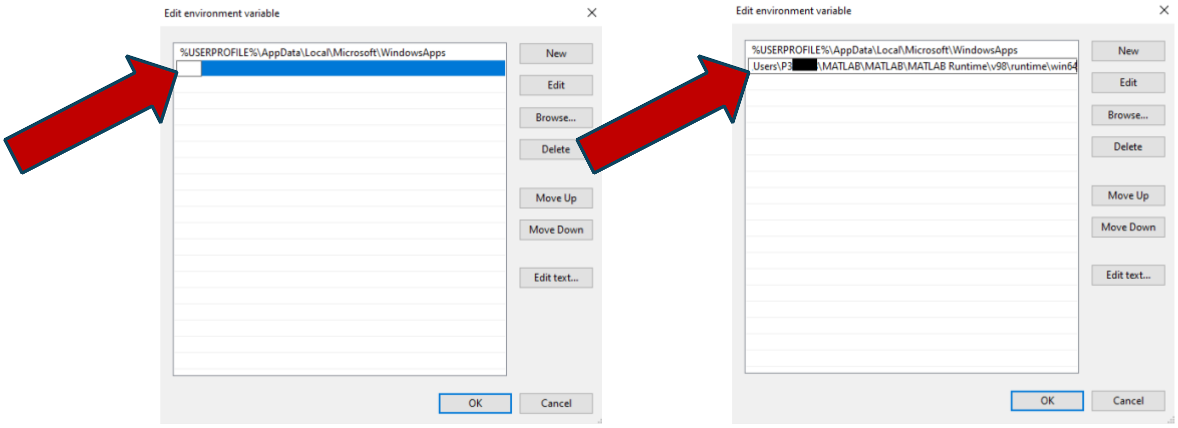
9. Click on ***New*** to add a new path.



%USERPROFILE%\AppData\Local\Microsoft\WindowsApps

Figure B.8. Editing the path of Environmental Parameters

10. In this box, copy the previously copied address. Click **OK** to confirm all changes.



%USERPROFILE%\AppData\Local\Microsoft\WindowsApps

%USERPROFILE%\AppData\Local\Microsoft\WindowsApps
Users\P3[redacted]\MATLAB\MATLAB\MATLAB Runtime\v98\runtime\win64

Figure B.9. adding a new path to the Environmental Parameters

11. Now you can run CalBarrier. Go to the ***CalBarrier, Without Admin Access*** folder that you downloaded and run ***CalBarrier_V201.exe***. Hereafter you can run CalBarrier by simply double-clicking on it. Future of versions of ***CalBarrier*** can be also used by simply double-clicking on them without the need for any other changes.

Appendix C:
CalBarrier User Manual

User Manual

CalBarrier

Version 2.0

Roadside Barriers Lifetime Cost Analysis Software

Advanced Highway Maintenance and Construction Technology (AHMCT)
University of California, Davis

455 Crocker Ln, Office 1001
Davis, California, 95616

August 2023

Introduction

Welcome to the CalBarrier User Manual. CalBarrier is a software developed as part of Task 3848 under Caltrans Contract 65A0749 with the Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center at University of California, Davis. This project centered on conducting a lifetime cost-benefit analysis of concrete and steel barriers utilizing data sourced from Caltrans databases, including the Integrated Maintenance Management System (IMMS) and Caltrans Contract Cost Data. Designed with user-friendliness in mind, CalBarrier aims to provide decision-makers with an accessible and efficient tool for selecting the most cost-effective roadside barrier solution.

General instructions

CalBarrier was developed using MATLAB App Designer software (R2020a) and is structured as a single executable software. This design ensures straightforward usage and streamlines functionality. CalBarrier is optimized for operation on computers equipped with Windows operating systems, specifically Windows 7, 8, 10, and 11.

In order to initiate the software, it is essential that the supporting library of fundamental functions is installed on your system. For the initial installation of any CalBarrier version, please proceed to install the accompanying *MyAppInstaller_mcr.exe* file that is provided with the CalBarrier software package. Following the installation of this file, you can proceed to launch CalBarrier. The installation process for *MyAppInstaller_mcr.exe* may takes a few minutes based on the specifications of your computer.

Getting Started

CalBarrier was designed with an emphasis on ongoing updates to the supporting data and research methodologies. This focus on adaptability empowers users to integrate the latest findings into their analyses. For projects centered around the analysis of roadside barriers using CalBarrier, version documentation is suggested. It is recommended that projects explicitly mention the version of CalBarrier employed in their project reports. This detail serves to enhance the transparency and credibility of the analysis.

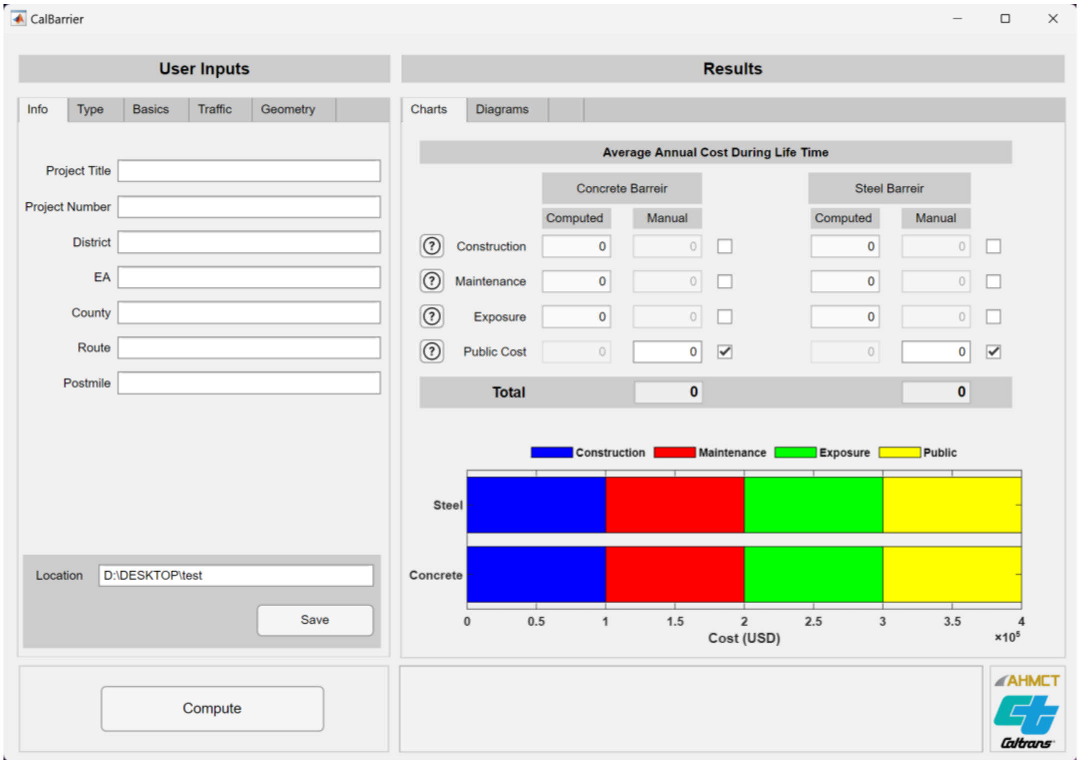
When running CalBarrier, the splash screen fades away after a few seconds, transitioning users to the main software interface. This transition marks the start of CalBarrier.

Figure C.1. CalBarrier startup splash screen.

User inputs

Info Tab

The primary interface of CalBarrier is shown in Figure C.2.



Location: D:\DESKTOP\test

	Concrete Barreir			Steel Barreir		
	Computed	Manual		Computed	Manual	
Construction	0	0	☐	0	0	☐
Maintenance	0	0	☐	0	0	☐
Exposure	0	0	☐	0	0	☐
Public Cost	0	0	☑	0	0	☑
Total		0			0	

Figure C.2. The primary interface of the CalBarrier software.

The software encompasses two distinct sections: "*User Inputs*" and "*Results*". On the left-hand side is the "*User Inputs*" section, which is comprised of five data entry tabs, each serving as a conduit for essential user-provided information. Conversely, the "*Results*" section, situated on the right side, is constituted of two tabs that present computed outcomes through charts and diagrams.

The "*User Inputs*" segment is divided into five tabs: "*Info*", "*Type*", "*Basics*", "*Traffic*", and "*Geometry*". As shown in Figure C.2, the "*Info*" tab has been activated.

In the "*Info*" tab, users can input project information into the software. This information includes the project title, project number, district, county, route, postmile, and more. All the information entered by the user about the project will be included in the output file generated by the software.

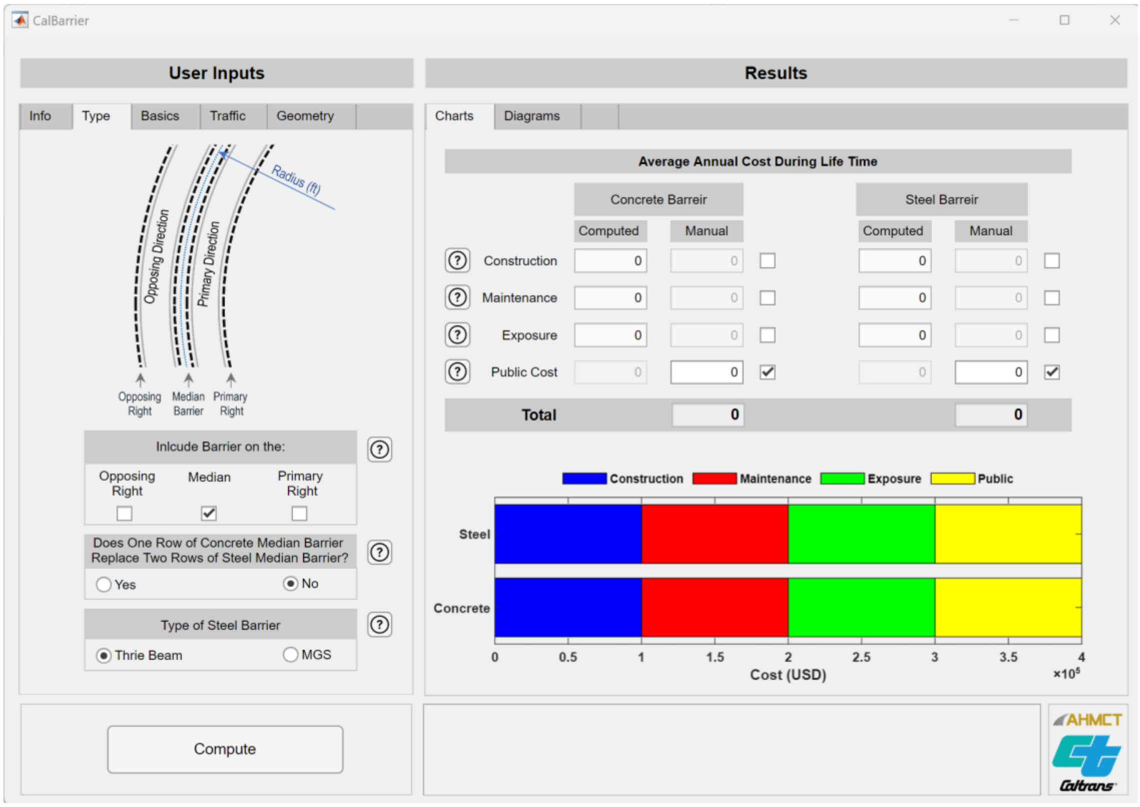
At the bottom of the "*Info*" tab, the user can write or paste (using the **Ctrl+V** shortcut) the folder address in which they want the software outputs to be saved.

After performing the cost comparison between concrete and steel barriers, the user can save the results by clicking the "*Save*" button at the bottom of the "*Info*" tab. All user-entered information and computed results will be saved in a text file named "*Output*" in the folder specified by the user. Additionally, all diagrams, including bar charts, pie charts, and line graphs, will be saved in the same folder. These saved files are labeled with the date and time of saving, making it convenient to identify that the diagrams and text file belong to the same set of software outputs.

Users can modify the input information, run the software, and save the results. The results will be saved in the provided folder with a different file name indicating the time of saving, without overwriting any existing files in that folder. This practical feature allows users to compare outcomes from multiple sets of data entries and include all relevant diagrams in their reports.

Type **Tab**

As shown in Figure C.3, within "*Type*" tab, users can designate the location of the barrier along the road. Options include to the right side of the primary direction, on the median barrier, and on the right side of the opposing direction. Both sides of the road can be designated as either the primary or opposing direction; it is imperative to adhere to this assumption throughout the information entry process.



Inlcude Barrier on the:

Opposing Right ☐
Median ☑
Primary Right ☐

Does One Row of Concrete Median Barrier Replace Two Rows of Steel Median Barrier?

○ Yes ● No

Type of Steel Barrier

● Thrie Beam ○ MGS

Average Annual Cost During Life Time

	Concrete Barreir			Steel Barreir		
	Computed	Manual		Computed	Manual	
Construction	0	0	☐	0	0	☐
Maintenance	0	0	☐	0	0	☐
Exposure	0	0	☐	0	0	☐
Public Cost	0	0	☑	0	0	☑
Total		0			0	

Figure C.3. Snapshot of "*Type*" data entry tab in User Inputs section.

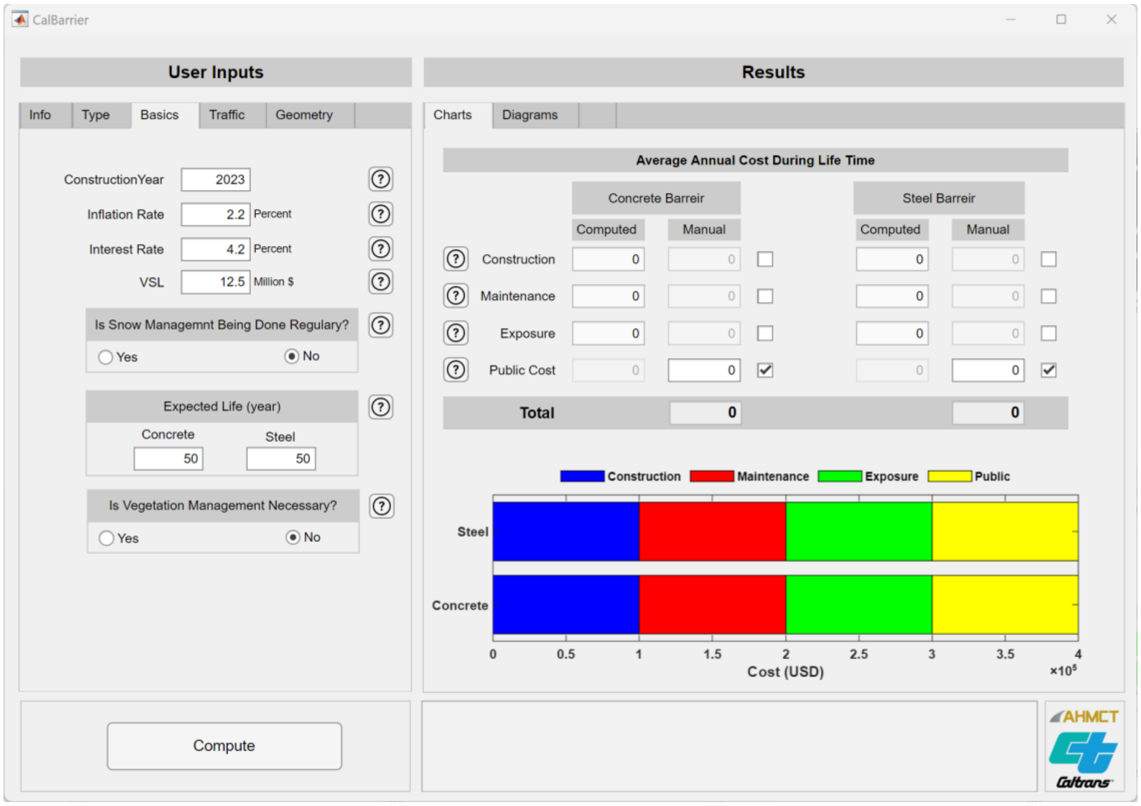
In scenarios where the road's median is relatively narrow, it is common practice to install a single row of concrete barrier. Should this be the case, users must indicate this preference within the *General* tab. Such a selection ensures accurate calculations.

CalBarrier can compute lifetime costs and compare two barrier options: concrete and steel. The steel barrier can be selected as W-beam and Thrie-beam barrier. Users can specify their preferred steel barrier variant within the designated field of the *General* tab.

To facilitate user understanding, each data entry field is accompanied by a small question mark icon. Clicking on this icon triggers a concise explanation about the respective field's purpose. Additional details are conveniently displayed at the bottom of the page.

Basics Tab

In the "*Basics*" tab, users can enter various details, including fundamental economic factors. Figure C.4 provides a representation of the "*Basics*" tab within the CalBarrier software.



ConstructionYear 2023

Inflation Rate 2.2 Percent

Interest Rate 4.2 Percent

VSL 12.5 Million $

Is Snow Managemnt Being Done Regulary?
○ Yes ● No

Expected Life (year)
Concrete 50
Steel 50

Is Vegetation Management Necessary?
○ Yes ● No

Average Annual Cost During Life Time

	Concrete Barreir			Steel Barreir		
	Computed	Manual		Computed	Manual	
Construction	0	0	☐	0	0	☐
Maintenance	0	0	☐	0	0	☐
Exposure	0	0	☐	0	0	☐
Public Cost	0	0	☑	0	0	☑
Total		**0**			**0**	

Figure C.4. Snapshot of *Basics* data entry tab in User Inputs section.

Within this tab, users are prompted to specify the construction year. The software calculates costs related to barrier construction, maintenance, and other associated expenses utilizing data from Caltrans databases spanning the 2020 to 2022 period. If the start of the project is after 2023, the software adjusts future costs in accordance with the inflation rate.

The inflation rate constitutes another vital input from the user. Users are required to provide the anticipated average inflation rate for the lifespan of the barrier. This input is essential, as the software modifies maintenance and other future costs based on the inflation rate. Notably, a report by the Executive Office of President [2] suggests considering an average inflation rate of 2.2% for cost-benefit analyses spanning 20 years or longer.

Likewise, users are prompted to input the interest rate. For federally-funded projects exceeding 20 years in duration, a recommended interest rate of 4.2% is advocated for cost-benefit analyses.

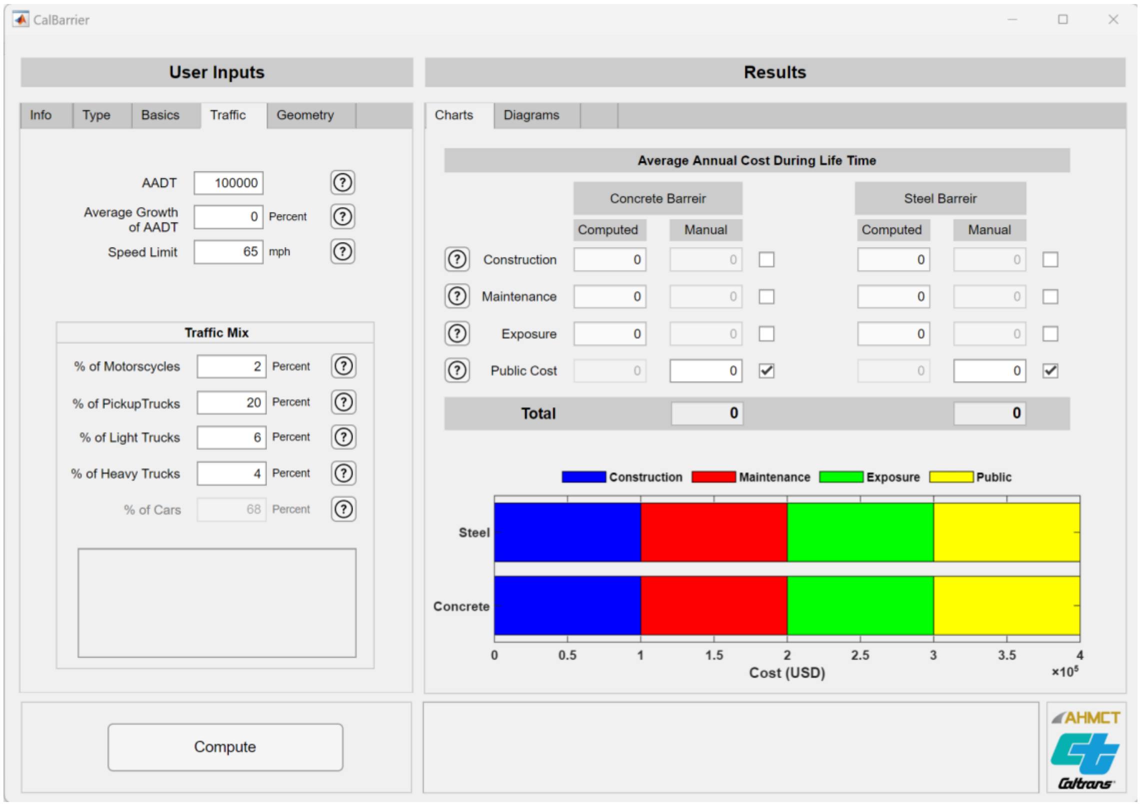
The concept of Value of Statistical Life (VSL) embodies the comprehensive cost of a fatal crash on average. FHWA's periodic release of VSL data now supersedes the usage of GDP for inflating crash costs. The most recent FHWA VSL, valid at the time of this publication, stands at 12.5 million USD in 2022 [1]. Users can adjust this value based on the latest published VSL.

Noteworthy insights from Caltrans personnel underscored that regular snow removal operations significantly impact the anticipated lifespan of steel barriers. In scenarios involving consistent snow removal, users must select the appropriate choice and manually adapt the expected lifespan of the barrier based on historical records of that specific road segment. The default expected lifespans for both concrete and steel barriers are pre-set at 25 years.

Instances that necessitate vegetation growth management around barriers require the inclusion of these costs into the overall construction cost. According to feedback from Caltrans personnel, concrete barriers typically require minimal vegetation growth prevention. Furthermore, costs linked to ground covering for vegetation control remain uniform for both W-beam and Thrie-beam steel barriers. Should vegetation control measures be indispensable, users can specify their requirements in the *Basics* tab. Subsequently, if needed, vegetation management costs will be integrated into the construction expenses for steel barriers.

***Traffic* Tab**

The “*Traffic*” tab is designated for user-input data regarding the traffic conditions of the specific road segment under study. Figure C.5 provides a comprehensive overview of the “*Traffic*” tab, including essential components, such as annual average daily traffic (AADT), projected traffic growth, and traffic mix.



AADT: 100000
Average Growth of AADT: 0 Percent
Speed Limit: 65 mph

Traffic Mix

% of Motorscycles	2	Percent
% of PickupTrucks	20	Percent
% of Light Trucks	6	Percent
% of Heavy Trucks	4	Percent
% of Cars	68	Percent

Average Annual Cost During Life Time

	Concrete Barreir Computed	Concrete Barreir Manual		Steel Barreir Computed	Steel Barreir Manual	
Construction	0	0	☐	0	0	☐
Maintenance	0	0	☐	0	0	☐
Exposure	0	0	☐	0	0	☐
Public Cost	0	0	☑	0	0	☑
Total		0			0	

Figure C.5. Snapshot of Traffic data entry tab in User Inputs section.

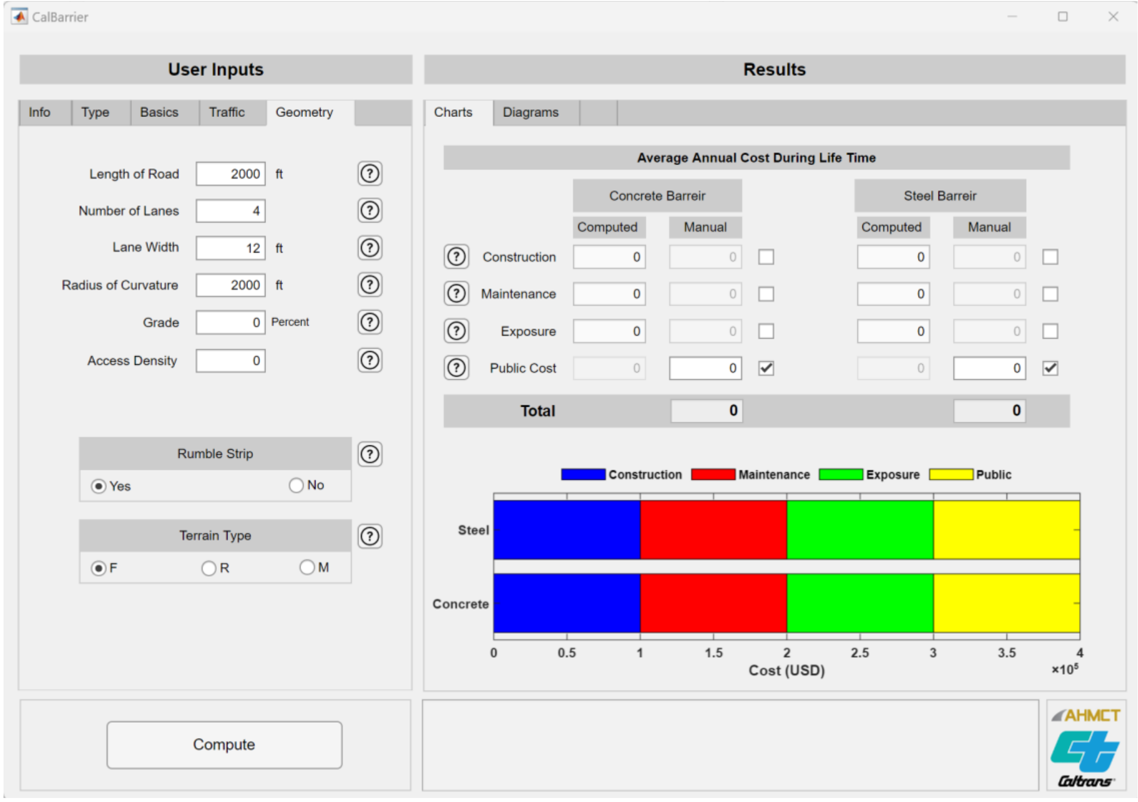
Within this tab, users are prompted to input both the AADT and the anticipated average growth rate of AADT. The selected growth rate should effectively encapsulate the entire lifespan of the barrier. By default, the software sets the average growth rate of AADT to zero.

Additionally, users are requested to provide the posted speed limit for the road segment in question. The software uses a default value of 65 mph for this parameter.

The composition of the vehicle mix on the studied road segment represents another crucial input field within the "*Traffic*" tab. Users are required to specify the percentages of motorcycles, pickup trucks, light trucks, and heavy trucks seen on the road. It is important to note that trailers should be categorized as light trucks. The CalBarrier software calculates the percentage of cars on the road based on the user-input data for the other vehicle types. Should the cumulative vehicle mix exceed 100%, an error message will be displayed in the text area below the traffic mix, prompting users to rectify the values. If the user-input traffic mix exceeds 100%, the crash cost computed by the software would be rendered invalid. Default traffic mix values are derived from data published by FHWA [3].

Geometry Tab

The "Geometry" data entry tab holds substantial influence over crash rates, consequently impacting crash costs and maintenance expenses. Figure C.6 offers a glimpse of this Geometry tab within the Barrier software. In this tab, users provide crucial road geometry information.



Length of Road 2000 ft

Number of Lanes 4

Lane Width 12 ft

Radius of Curvature 2000 ft

Grade 0 Percent

Access Density 0

Rumble Strip: ● Yes ○ No

Terrain Type: ● F ○ R ○ M

Average Annual Cost During Life Time

	Concrete Barreir			Steel Barreir		
	Computed	Manual		Computed	Manual	
Construction	0	0	☐	0	0	☐
Maintenance	0	0	☐	0	0	☐
Exposure	0	0	☐	0	0	☐
Public Cost	0	0	☑	0	0	☑
Total		0			0	

Figure C.6. Snapshot of Geometry data entry tab in User Inputs section.

The "*Geometry*" tab prompts users to input vital details pertaining to road geometry, including:

- **Length of Road**: The length of the road segment in linear feet.
- **Number of Lanes**: The cumulative count of lanes in both primary and opposing directions.
- **Lane Width:** The average width of traffic lanes in linear feet, ideally ranging between 8 ft to 20 ft. The software defaults to a 12-ft width.
- **Radius of Curvature:** This value denotes the radius of road curvature, particularly at the median. Valid values range from 600 ft to 10,000 ft. Straight segments warrant an entry of 10,000 ft.

- **Grade:** The vertical grade of the road, which can be positive (uphill in the primary direction) or negative (downhill in the primary direction).
- **Access Density:** The count of access points per mile, showcasing its impact on encroachment rates. This value is an integer between 0 and 10, with 0 being the default.
- **Rumble Strip**: Users select the suitable option to indicate the presence of rumble strips on the road.
- **Terrain Type:** Users define the terrain type, with "F" representing flat terrains, "R" indicating rolling terrains, and "M" signifying mountainous terrains. The default selection is flat terrain.

Result

By clicking on the "Compute" button situated at the bottom left corner of the software main interface, users initiate the computation of the lifetime cost of the barrier. The results are subsequently displayed in charts and diagrams within the *Results* section.

Charts

Within the "*Results*" section, users are presented with two tabs: "*Charts*" and "*Diagrams*". In the "*Chart*" tab, the average annual cost of concrete and steel barriers is detailed. This average annual cost shows the total expenses associated with the barrier's expenses over their entire lifespan divided by their expected lifespan. For instance, if a barrier incurs a total lifetime cost of one million USD and is projected to endure for 25 years, its annual average cost will amount to $40,000.

In the "*Charts*" tab, a breakdown of construction, maintenance, exposure, and public costs for both concrete and steel barriers is illustrated (see Figure C.6). Each cost category is accompanied by a checkbox. Upon activation, these checkboxes enable users to manually input cost values for comparison within the lifetime cost assessment. This feature is particularly valuable when users have accurate construction or other cost data specific to their region. Enabling a checkbox and manually inputting such values ensures that the software integrates the user-provided costs into the lifetime cost comparison. This flexibility extends to maintenance, exposure, and public costs as well.

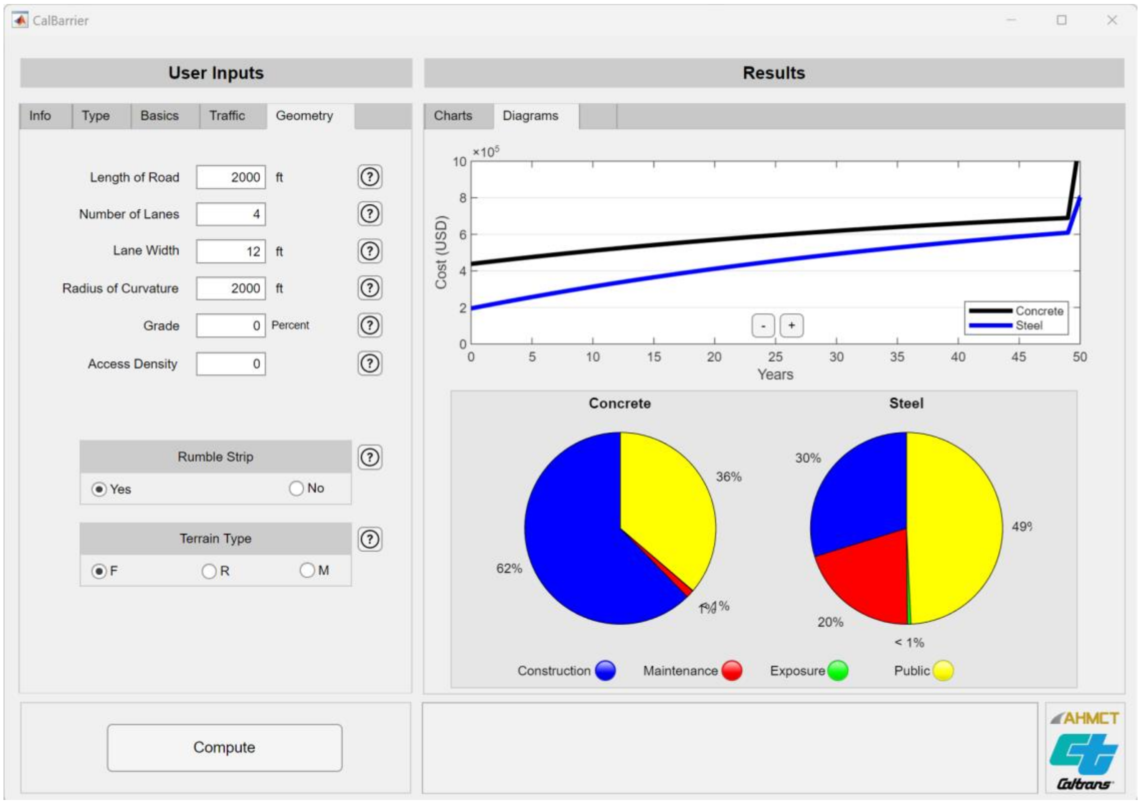
While the software computes the public cost for each barrier type, the public costs are excluded from the barrier lifetime cost comparison by default. By deselecting the checkbox adjacent to the public cost, users can choose to include these costs in the barrier cost comparison.

User-initiated adjustments, such as selecting or deselecting checkboxes, necessitate clicking the "*Compute*" button to reflect the changes in the presented charts and diagrams.

Towards the bottom of the *Chart* tab, a bar diagram visually demonstrates and contrasts the annual average costs of each barrier throughout their respective lifetimes. To enhance clarity, distinct components of lifetime costs are color-coded, facilitating user-friendly comparison between concrete and steel barriers.

Diagrams

As illustrated in Figure C.7, the "*Diagrams*" tab within the results section showcases a pair of diagrams, offering comprehensive insights into the lifetime cost of the concrete and steel barriers.



Length of Road 2000 ft

Number of Lanes 4

Lane Width 12 ft

Radius of Curvature 2000 ft

Grade 0 Percent

Access Density 0

Rumble Strip: ● Yes ○ No

Terrain Type: ● F ○ R ○ M

Figure C.7. Snapshot of the Diagrams tab in Results section of the software.

The upper portion features a line diagram that visually represents all costs associated with each barrier type throughout their respective lifetimes. The horizontal axis corresponds to time in years and can be adjusted by users. Small buttons labeled with "**+**" and "**–**" are positioned within the line diagram. A click on these buttons expands or retracts the horizontal axis by five years, offering a tailored view.

At the lower section of the "*Diagrams*" tab, two pie diagrams provide a breakdown of the lifetime cost for concrete and steel barriers. These pie chart diagrams detail the proportion of construction, maintenance, exposure, and public costs over the course of the barriers' existence. This visualization empowers users to distinguish the most significant contributors to the lifetime cost of each barrier option, enhancing decision-making capabilities.

Through the "*Diagrams*" tab, users can readily grasp the temporal distribution of costs, as well as the relative impact of various cost factors on the lifetime cost of each barrier.

References

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