Variable Speed Limits Guidelines

October 2023

Colorado Department of Transportation

2829 Howard Place

Denver, CO 80204

Table of Contents

List of Figures

List of Tables

Revision History

Revision	Date	Description

Acknowledgements

This plan was prepared by:

Ulteig
5575 DTC Parkway, Suite 200
Greenwood Village, CO 80111

DiExSys
8608 West Mountain View Lane
Littleton, CO 80125

Colorado Department of Transportation
2829 Howard Place
Denver, CO 80204

IronStride Solutions
2000 South Colorado Boulevard, Tower 2, Suite 975
Denver, CO 80222

Acronyms and Abbreviations

AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
ADAP	Advanced Data Analytics Platform
ADT	Average Daily Traffic
API	Application Programming Interface
B/C	Benefit/Cost (B/C)
CDOT	Colorado Department of Transportation
CDOT HQ Traffic	CDOT Traffic Safety & Engineering
CDOT ITS	CDOT ITS & Network Services
CISP	Colorado Information Security Policy
ConOps	Concept of Operations
CORA	Colorado Open Records Act
CSP	Colorado State Patrol
CTMC	Colorado Traffic Management Center
EFR	Equipment Failure Report
FHWA	Federal Highway Administration
FWB	Flashing Warning Beacon
GVWR	Gross Vehicle Weight Rating
HCM	Highway Capacity Manual
ITS	Intelligent Transportation Systems
LED	Light-Emitting Diode
LOS	Level of Service
LOSS	Level of Service of Safety
MP	Mile Point
mph	Miles per Hour
MUTCD	Manual on Uniform Traffic Control Devices
MVMT	Million Vehicle-Miles of Travel
MVRD	Microwave Vehicle Radar Detector
ODM	Office of Data Management
PDO	Property Damage Only
PIO	Public Information Office
PM	Project Manager
PS&E	Plans, Specifications, and Estimates
PTZ	Pan-Tilt-Zoom
PSA	Public Service Announcement
QMP	Qualified Manufacturers and Products
ROW	Right-of-Way
RTM	Regression-to-the-Mean
RTO	Real-Time Operations
RWIS	Roadway Weather Information System
RTDH	Real-Time Data Hub
SEA	Systems Engineering Analysis
SPF	Safety Performance Function
TAMP	Transportation Asset Management Plan
UPS	Uninterruptible Power Supply
VMS	Variable Message Sign
vmtphpl	Vehicle-miles of Travel per Hour per Lane
vphpl	Vehicles per Hour per Lane
VSL	Variable Speed Limit

1. Introduction to VSL Design

Posted static speed limits provide guidance to the traveling public on reasonable and prudent speed, regardless of roadway conditions. As congestion builds or weather and road conditions deteriorate, drivers make decisions to lower their speed and maintain requisite headways based on their individual experiences, perception of risk, and comfort level; however, it is not always clear what speed is safe for these conditions. When using their own discretion, many drivers lower their speeds too little and too late to effectively preserve safe operations, especially when the posted static speed limit is significantly higher than the safe speed limit under prevailing conditions. A variable speed limit (VSL) sign is an electronic version of a static speed limit sign with a light-emitting diode (LED) display of the regulatory speed limit which can be changed to best suit current traffic conditions. A VSL algorithm is designed to compute what the appropriate safe speed limit should be based on real-time data about weather and traffic conditions, and the speed calculated by the algorithm is posted to the VSL signs in the VSL corridor.

The Colorado Department of Transportation (CDOT) provides the maximum speed limit that can be posted for all vehicles, as well as the maximum speed limit for vehicles over 26,000 pounds gross vehicle weight rating (GVWR), such as trucks, if applicable. The maximum speed limits are equal to what the posted speed limits would be in the absence of VSL. CDOT also provides the minimum speed limits that can be posted for cars and overweight vehicles/trucks, which vary depending on whether the road conditions are dry or adverse.

1.1. Project Development Timeline

This guidelines document covers conceptual planning, design, construction, and operations for VSL projects. It includes guidance for evaluating the feasibility of VSL deployment on the basis of a benefit/cost (B/C) analysis, identifying safety concerns that may be improved through VSL, configuring the algorithm for a specific corridor, designing a VSL corridor and completing the systems engineering analysis (SEA) documentation, planning for testing and calibration, operating and maintaining the system long-term, and planning for public involvement. This section provides a summary of the project development timeline as outlined in these guidelines.

1.1.1. Scoping (Chapter 2–3)

Chapters 2 and 3 cover the initial scoping phase of a VSL project. These chapters focus on evaluating whether a VSL system will be feasible and cost-effective and whether VSL deployment is expected to provide significant improvements to safety within the corridor.

> **Chapter 2** **(VSL Feasibility Study)** provides flowcharts for evaluating the feasibility and cost effectiveness of VSL deployment in a freeway or highway environment.
>
> **Chapter 3** **(VSL Safety Assessment)** outlines the details and requirements of the VSL Safety Assessment, which informs whether and how VSL deployment could reduce the frequency and severity of crashes.

1.1.2. Design (Chapters 4–5)

Chapters 4 and 5 provide guidance for the design of a VSL project. They describe the inputs the Project Team must provide for the algorithm used in a VSL corridor, as well as the design requirements the Project Team must follow for VSL devices and systems.

> **Chapter 4** **(Algorithm Development)** provides detail on how the algorithm was developed and how data collected in the corridor is used to determine the appropriate speed limit. It discusses how the VSL algorithm considers weather and road conditions, traffic flow, queuing, speed limit transitions, and overweight vehicle/truck speed limits in its calculations.
>
> **Chapter 5** **(VSL System Design)** outlines the requirements for deployed devices in a VSL corridor, VSL signs, system communications, and other project design elements required for the project plans and specifications.

1.1.3. Construction (Chapter 6)

Chapter 6 provides an overview of planning for the period of construction and time leading up to the system Go-Live.

Chapter 6 **(VSL System Configuration and Testing)** outlines the testing requirements between the Intelligent Transportation Systems (ITS) devices and CDOT ITS & Network Services (CDOT ITS) once the physical construction is complete and prior to posting speed limits on the VSLs (Go-Live).

1.1.4. Operations & Maintenance (Chapter 7)

Chapters 7 covers the time after construction and Go-Live are complete.

Chapter 7 **(VSL System Long-Term Operations and Maintenance)** outlines how the VSL corridor will operate and describes the people and ITS systems that must be involved throughout the life of the VSL system.

1.1.5. Ongoing Coordination (Chapter 8)

Chapter 8 spans the design, construction, and post-construction phases.

Chapter 8 **(Public Information and Enforcement)** outlines key elements of public information outreach to educate drivers on why speed limits are changing and identifies the responsibilities of Colorado State Patrol (CSP) or local law enforcement to enforce real-time posted speed limits.

1.2. Purpose of the Guidelines

This VSL Guidelines document is intended to summarize what is presently known about planning, design, construction, testing, operation, and maintenance of VSL systems. The purpose of these guidelines is to:

- Inform a CDOT Project Manager (PM) of the project development process and how it advances in parallel with the SEA process.
- Outline the responsibilities of CDOT ITS, CDOT Office of Data Management (ODM), CDOT Region Traffic, and CDOT Traffic Safety & Engineering (HQ Traffic) in a VSL implementation project.
- Help CDOT HQ Traffic, CDOT Public Information Office (PIO), CSP, and various CDOT disciplines and Region staff work as a multidisciplinary team to successfully deliver VSL projects.
- Guide Project Teams through the VSL project development process by providing an overview of each step of the process from scoping to VSL system design and planning for construction and long-term operations and maintenance.

1.3. Roles and Responsibilities

All VSL stakeholder roles and associated responsibilities have been compiled in Table 1. These high-level responsibilities can be viewed with more context in the reference chapter.

Table 1. Summary of Stakeholder Roles and Responsibilities

Stakeholder	Reference Chapter	Responsibilities
Project Team	Ch. 2	• Participate in a VSL Feasibility Workshop with CDOT HQ and Region Traffic. • Consider the estimated cost of VSL development, including all infrastructure and software configuration. • Coordinate with CDOT ITS to develop the project-specific cost of the algorithm development and integration for the VSL corridor. • Complete the Technology/SEA Assessment document.
	Ch. 3	• Coordinate with CDOT HQ Traffic to complete a VSL Safety Assessment for the proposed corridor. • Collect corridor crash data for the most recent five years. • Conduct a B/C analysis, reflecting the most current trends in the cost of labor and materials and the most recent bids received by CDOT. • Conduct a traffic investigation that is approved by CDOT HQ Traffic. • Hold an initial stakeholder meeting to gather wants and needs that will drive design assumptions. • Complete the Alternative Analysis and Concept of Operations SEA documents.

Stakeholder	Reference Chapter	Responsibilities
Project Team (continued)	Ch. 5	• Finalize the design of the VSL system, including all VSL zones, device locations, communications, electrical power, and required corridor-specific inputs for the selected VSL algorithm. • Submit a Network Design and Fiber Assignment request to CDOT ITS. • Discuss the maximum offset distance for double-posted VSL signs and supplemental signage needs with CDOT Region Traffic. • Discuss the operations of VSL for express lanes, if applicable. • Re-engage with project stakeholders after finalizing the design of the VSL system to plan for long-term operations. • Obtain the latest version of project specifications for all devices from CDOT ITS. • Complete all remaining SEA documents, including: 　○ System Functional Requirements 　○ High Level System Design 　○ Detailed Level System Design 　○ Testing and Integration 　○ Agreements with Partners 　○ Standard Operating Procedures 　○ Maintenance Plan 　○ Validation Plan • Complete the PS&E package.
	Ch. 7	• Identify primary system operations during the SEA and project planning process. • Discuss system operations with CDOT Region Traffic and CDOT RTO. • Identify the parties responsible for replacing VSL assets and document these responsibilities in the Maintenance Plan SEA document (e.g., CDOT ITS, CDOT Region Traffic, CDOT HQ Traffic, etc.).
CDOT PM	Ch. 2	• Complete a VSL Feasibility Workshop in coordination with CDOT HQ and Region Traffic. • Coordinate with CDOT ITS and CDOT HQ Traffic during the application process for any grants intended to fund the VSL corridor.
	Ch. 3	• Submit the VSL Corridor Justification Memorandum that justifies the need for VSL to the CDOT State Traffic Engineer, Region Traffic Engineer, and ITS Branch Manager.
	Ch. 5	• Coordinate with CDOT ITS to install new fiber, if applicable. • Provide CDOT ITS with all necessary utility account information. • Work with the CDOT Region Utility Account Coordinator to ensure all billing is set up properly prior to project closeout per PD 90.1.
	Ch. 6	• Conduct dim testing in coordination with CDOT Region Traffic, CDOT ITS (OpenTMS Team), and CDOT ODM (RTDH Team). • Determine Go-Live date in coordination with CDOT Region Traffic, with input from CDOT HQ Traffic, CDOT ITS, CDOT ODM, and CDOT PIO.
	Ch. 8	• Coordinate corridor-specific talking points with CDOT PIO and CDOT Region Customer Service Team and provide answers to technical questions that may arise during public information outreach. • Distribute pictures or videos demonstrating how the VSL system operates.
Contractor	Ch. 6	• Install all VSL-related devices and submit 1411s. • Respond to device issues that occur during testing and integration within 24 hours for troubleshooting and correction. • Maintain and replace ITS devices, as needed, during the system testing process and any specified warranty period after validation.
CDOT HQ Traffic	Ch. 2	• Support the CDOT PM in completing a VSL Feasibility Workshop.

Stakeholder	Reference Chapter	Responsibilities
CDOT HQ Traffic (continued)	Ch. 3	• Support the Project Team in completing a VSL Safety Assessment. • Approve the traffic investigation conducted by the Project Team. • Archive the VSL Corridor Justification Memorandum.
	Ch. 7	• Share the results of any post-deployment studies with each CDOT Region and CDOT ITS to learn from previous VSL corridors.
	Ch. 8	• Support Law Enforcement with requests for the date and time period that speed limit changes were posted in the VSL corridor.
CDOT Region Traffic	Ch. 2	• Support the CDOT PM in completing a VSL Feasibility Workshop.
	Ch. 3	• Review and sign the VSL Corridor Justification Memorandum.
	Ch. 5	• Determine the maximum offset distance for double-posted VSL signs in the same direction and the use of supplemental signs within the VSL corridor.
	Ch. 6	• Conduct dim testing in coordination with the CDOT PM, CDOT ITS (OpenTMS Team), and CDOT ODM (RTDH Team). • Determine Go-Live date in coordination once the system functionality is validated with the CDOT PM, with input from CDOT HQ Traffic, CDOT ITS, CDOT ODM, and CDOT PIO.
	Ch. 7	• Monitor the VSL system status on a regular basis (as determined by CDOT Region Traffic for each VSL corridor), validating all traffic data inputs and outputs, coordinating necessary repairs with CDOT ITS, and providing VSL system status reports to CDOT ITS. • Monitor conditions after the VSL system is implemented and conduct post-deployment studies to measure effectiveness (on an as-needed basis as determined by CDOT Region Traffic for each VSL corridor). This should be done in coordination with CDOT HQ Traffic. • Share the engineering speed study with Law Enforcement.
	Ch. 8	• Coordinate with law enforcement throughout the VSL design, construction, and operational phases, including notifying CSP of speed limit changes in operational VSL corridors.
State Traffic Engineer	Ch. 3	• Review and sign the VSL Corridor Justification Memorandum or have a designated representative provide the signature.
CDOT ITS	Ch. 2	• Support the CDOT PM in completing a VSL Feasibility Workshop.
	Ch. 5	• Support the Project Team with completion of all SEA documentation. • Review and approve all SEA documentation. • Perform an audit for the Network Design and Fiber Assignment request submitted by the Project Team. • Provide the latest version of the project specifications for ITS devices to the Project Team.
	Ch. 6	• Approve all submitted 1411s and initiate VSL corridor configuration. • Verify with CDOT ODM the device mapping and integration between OpenTMS and the Real-Time Data Hub (RTDH). • Run daily Equipment Failure Reports (EFRs) to identify roadway device hardware issues.

CDOT ITS (continued)	Ch. 7	• Perform final inspection, testing, and acceptance of ITS devices installed by construction projects along State highways. (Acceptance is only for the device and integration, not for the functionality of the algorithm.) • Monitor the health of individual CDOT ITS-owned devices, network switches, and communications, and track all identified or reported issues. • Provide initial remote troubleshooting for all ITS devices and auxiliary equipment, then escalate issues for repair as needed. • Provide corrective, scheduled, and preventive maintenance for structures used to mount ITS devices.
	Ch. 7	• Provide VSL system data storage and reporting that is accessed by the VSL algorithm and includes an archive of both automated and manual speed limit changes along with the date and time period they were posted. • Generate and monitor speed recommendations for VSL signs and share a report of these recommendations with Region Traffic Engineers.
CDOT RTO	Ch. 7	• Observe VSL corridors and check the visibility and correct display of the posted VSL speed limit (only applies to corridors where cameras for viewing VSL speed limit signs are included). • Submit tickets through OpenTMS when issues are identified.
CDOT Region Maintenance	Ch. 7	• Provide corrective, scheduled, and preventive maintenance of roadway, ROW area, static signs, and striping. • Provide support to CDOT ITS Field Operations as requested for major infrastructure needs such as lighting, signposts, and electrical power.
CDOT PIO	Ch. 8	• Lead coordination at both Region and Statewide levels for the safety strategic planning initiative. • Share all corridor-specific talking points with the CDOT Region Customer Service Team and push information to the public via news outlets or social media.
CDOT Region Customer Service Team	Ch. 8	• Respond to or redirect questions from the traveling public that come in via phone or email. • Coordinate with CDOT HQ Traffic or the CDOT PM as needed for questions requiring technical support.
Law Enforcement	Ch. 7, 8	• Review the engineering speed study provided by CDOT. • Access the VSL system, in coordination with the CDOT HQ Traffic, to request the date and time period that speed limit changes were posted in the VSL corridor. • Enforce static and variable speed limits.

1.4. VSL Systems Engineering Analysis

CDOT's SEA process is required for all projects statewide. The SEA is a federally mandated process per 23 CFR 940 and is intended to provide accountability for the use of transportation capital funding, ensure proper planning for long-term maintenance and operations, and improve consistency in the deployment of technology. The SEA is completed concurrently with the project development process and consists of 11 standard documents that are completed by the Project Team, in coordination with relevant stakeholders, and submitted to CDOT ITS for approval. The documents increase in level of detail as the project progresses from initial scoping through to final design. It is important to begin the SEA process as early as possible in the project scoping and design process, as all SEA documents must be complete and approved before a project can be advertised for construction.

All required documents and information regarding the SEA process can be accessed via the CDOT ITS website.[1] The SEA documents have been completed at a programmatic level for VSL systems to streamline the project-specific SEAs,

[1] https://www.codot.gov/programs/intelligent-transportation-systems/systems-engineering-analysis-sea/sea-documents

as well as to encourage uniformity on VSL system projects statewide. These documents are available on the internal CDOT SEA Document Library website (access available upon request)[2] and are to be used by every VSL Project Team, which can simply track changes for any deviations from the programmatic version. Table 2 provides the relevant chapter of this document for information on each SEA document.

Table 2. Summary of SEA Documents

SEA Document	Relevant Section
Technology/SEA Assessment	2.2.1
Alternative Analysis	3.6.1
Concept of Operations	3.6.2
System Functional Requirements	5.1.1
High Level System Design	5.1.2
Detailed Level System Design	5.2.6
Testing and Integration	5.2.7
Agreements with Partners	5.3.2
Standard Operating Procedures	5.3.2
Maintenance Plan	5.3.2
Validation Plan	5.4.3

1.5. Guidelines Revisions

Because development and implementation of VSL systems are still evolving at CDOT, these CDOT VSL Guidelines summarize current VSL design, operations, and maintenance standards and will be revised periodically. The VSL algorithm described in Chapter 4 has only recently been deployed in its present configuration. How drivers respond to a VSL system utilizing this algorithm and whether crash reduction is significant will be determined from observational before-and-after studies following the deployment of each corridor (see Chapter 7.2.3). This information will be incorporated into future guidelines revisions.

[2] https://sites.google.com/u/0/d/1uP3O1yTW4hqacKwX_D2BAe342LTiTsEe/p/1AHnQ-J97Gj1fhFwAvGvDKS1UbnP45d13/preview?authuser=0&pli=1

2. VSL Feasibility Study

Most drivers in the posted static speed limit environment adapt their speed to changing conditions (e.g., weather, traffic density, queueing) in real time based on their individual experiences, perception of risk, and comfort level. However, when left to their own devices, drivers' speed reductions tend to be insufficient to effectively preserve safe operations. Crash data analysis reveals that incidents increase with the onset of reduced friction due to rain, snow, ice, or reduced visibility. Similarly, both speed and crash rate remain relatively constant up to a certain threshold flow rate, typically around 900–1,200 vehicles per hour per lane (vphpl) on a freeway. When this threshold is exceeded, the crash rate rapidly rises as flow continues to increase before a notable reduction in speed. VSL systems can mitigate this by proactively posting lower speed limits based on real-time observations of weather, road, and traffic conditions before crash frequencies increase. CDOT's current Performance Plan[3] aims to reduce the percentage of fatal and serious injury crashes within the State by 15 percent, and according to the Federal Highway Administration's (FHWA) Proven Safety Countermeasures website,[4] deployment of VSLs on freeways can reduce up to 34 percent of total crashes.[5] These VSL Guidelines should be updated with Colorado-specific crash data for VSL corridors within the State once sufficient data is available.

This chapter outlines key considerations for implementing a VSL corridor and provides flowcharts for determining whether a VSL system would be beneficial and cost effective in the project corridor. Prior to project scoping, the Project Team must complete a VSL Feasibility Workshop, during which the feasibility flowchart assessments below are completed by the CDOT PM in coordination with CDOT HQ Traffic, CDOT Region Traffic, CDOT ITS, and CDOT RTO. These feasibility flowcharts will help the Project Team determine if a project is cost effective based on factors such as whether there is existing fiber and accessible power. If the corridor has insufficient fiber and/or power, the feasibility flowcharts guide the Project Team in assessing whether the project is still cost effective given the added cost of installing fiber and/or power in the corridor. In addition, the feasibility of operating and maintaining a VSL system should be considered by answering the following questions, as VSL systems rely on well-maintained roadside devices:

- Is the corridor located within two hours (including traffic delays) of one of the CDOT ITS Maintenance Patrol Yards, located in Golden and Grand Junction?
- Are the CDOT ITS maintenance hours resourced for the corridor sufficient to maintain the proposed VSL system?

If the answer to either of these questions is "no," the Project Team must coordinate with CDOT ITS to understand the practicability of operating and maintaining a VSL corridor in the project location.

When the results of the VSL Feasibility Study indicate that a VSL system is cost effective and feasible in the corridor, the project scope and design schedule should account for completing the SEA process as outlined in Chapter 1.4 and detailed throughout these Guidelines.

If CDOT is pursuing external funding to be used for a VSL corridor, the CDOT PM must coordinate with CDOT ITS and CDOT HQ Traffic during the grant application process.

2.1. VSL Development Costs

Based on VSL projects currently in progress, high-level planning estimates for construction costs should be $500,000 per mile for deployment of a weather-based VSL system and $1,000,000 per mile for deployment of a flow-based VSL system on a divided highway. These high-level cost estimates include the cost of installing fiber and hard-wired electrical power to VSL devices if they are accessible nearby (including boring, cabling, wiring, and conduit), traffic control and mobilization, construction engineering and indirect budget allocations, and contingency costs; however, they exclude the cost to extend fiber or power to cover any gaps. A planning-level cost estimate template is provided in Appendix A. When conducting a B/C analysis (see the case studies in Chapter 2.3 and 3.4), the Project Team should update these cost estimates to reflect the most current trends in cost of labor and materials and the most recent bids received by CDOT.

The Project Team should also be aware of the costs associated with configuration of a VSL corridor into the OpenTMS software and the RTDH. This configuration includes implementation, as well as initial testing and field calibration to verify that OpenTMS is posting the speeds recommended by the VSL algorithm. Any additional integration or ongoing

---

[3] https://www.codot.gov/performance/performance-plan

[4] https://highways.dot.gov/safety/proven-safety-countermeasures

[5] FHWA. *Proven Safety Countermeasures*. https://safety.fhwa.dot.gov/provencountermeasures/variable-speed-limits.cfm.

monitoring costs for the VSL algorithm must be discussed with CDOT ITS and documented in the Testing and Integration and Maintenance Plan SEA documents. If the VSL corridor leverages the existing algorithm described in Chapter 4, the Project Team must utilize a specialized consultant/VSL subject matter expert to configure and test the algorithm. The typical cost for one-time configuration and testing of $100,000 (as of 2023); however, Project Teams must coordinate with CDOT ITS to develop the project-specific cost, which depends on a variety of factors, such as number of devices and corridor length. If the project does not leverage the existing VSL algorithm, the Project Team must coordinate with CDOT ITS and CDOT ODM to determine the feasibility of the proposed VSL system and estimate the additional cost for developing a new or modified VSL algorithm. The Project Team's VSL subject matter expert must develop a new or modified VSL algorithm. The Project Team is also responsible for coordinating with CDOT ITS and CDOT ODM to identify any additional costs and responsibilities associated with data archival and reporting necessary for the VSL system.

2.2. Evaluating Weather-Based and Flow-Based VSL Systems

The two types of VSL systems are weather-based and flow-based. A weather-based VSL system, which utilizes Roadway Weather Information Systems (RWISs) to detect weather and road conditions, is intended for lower volume freeways and arterials that have a requisite number of severe crashes during adverse weather to justify the expenditure (for details on conducting a VSL Safety Assessment, which includes crash history analysis, see Chapter 3). A flow-based VSL system, which uses Microwave Vehicle Radar Detectors (MVRDs) to detect traffic flow, is intended to be implemented on high, uninterrupted flow facilities that have a requisite number of severe crashes to justify the expenditure.

A weather-based VSL system may be applicable to any highway, and since drivers seeing VSL signs will likely expect those signs to respond to adverse weather conditions, RWISs will always be included in any VSL deployment. A flow-based VSL system is intended to be used only in continuous flow environments (i.e., primarily freeways).

As part of the VSL Feasibility Workshop, the Project Team must complete both the Weather-Based and Flow-Based VSL System Feasibility flowcharts presented in Figure 1 and Figure 2, respectively, to determine which VSL system is appropriate for a corridor and whether implementing a VSL system makes sense from a high-level B/C basis. Note that, although all VSL systems include RWISs, the flow-based feasibility flowchart will still be completed even when a weather-based VSL system is not justified.

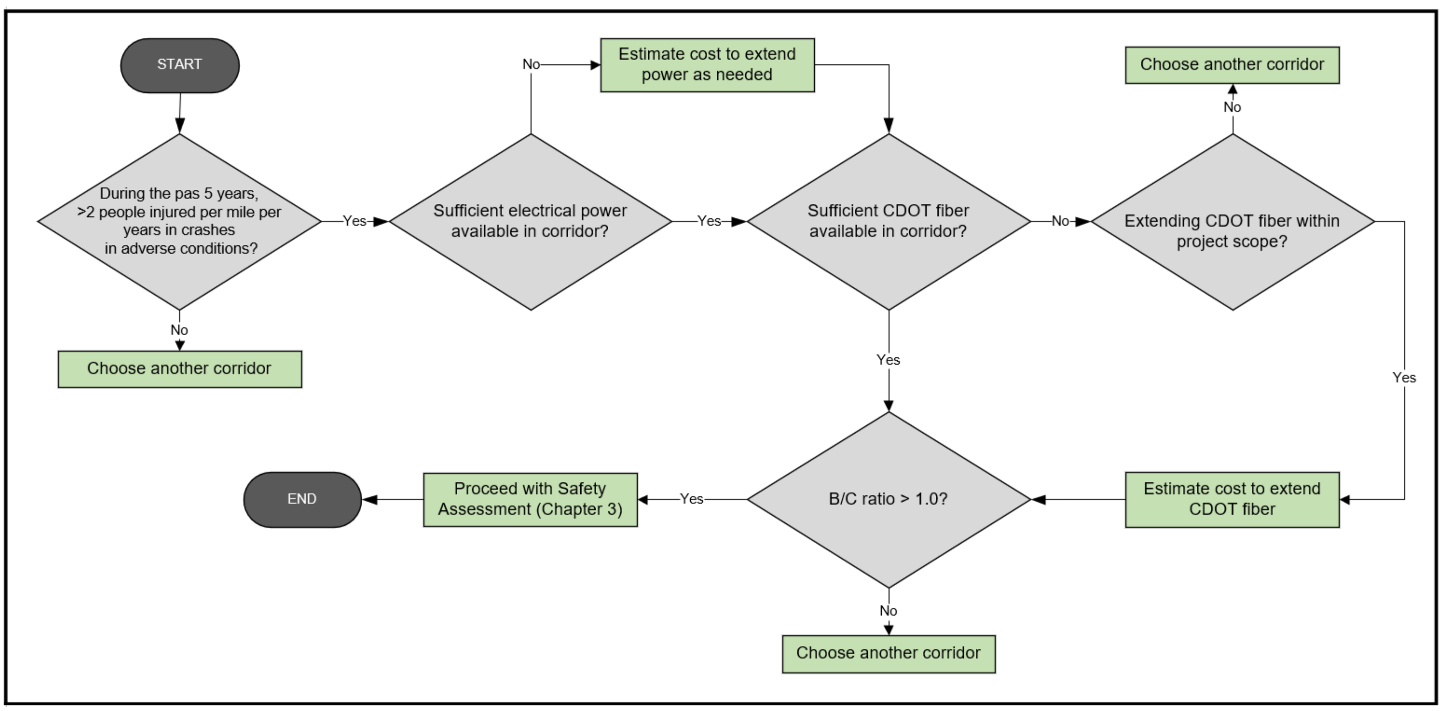


Figure 1. Weather-Based VSL System Flowchart
(Note: Weather-based VSL systems will always include the transition component described in Chapter 4.)

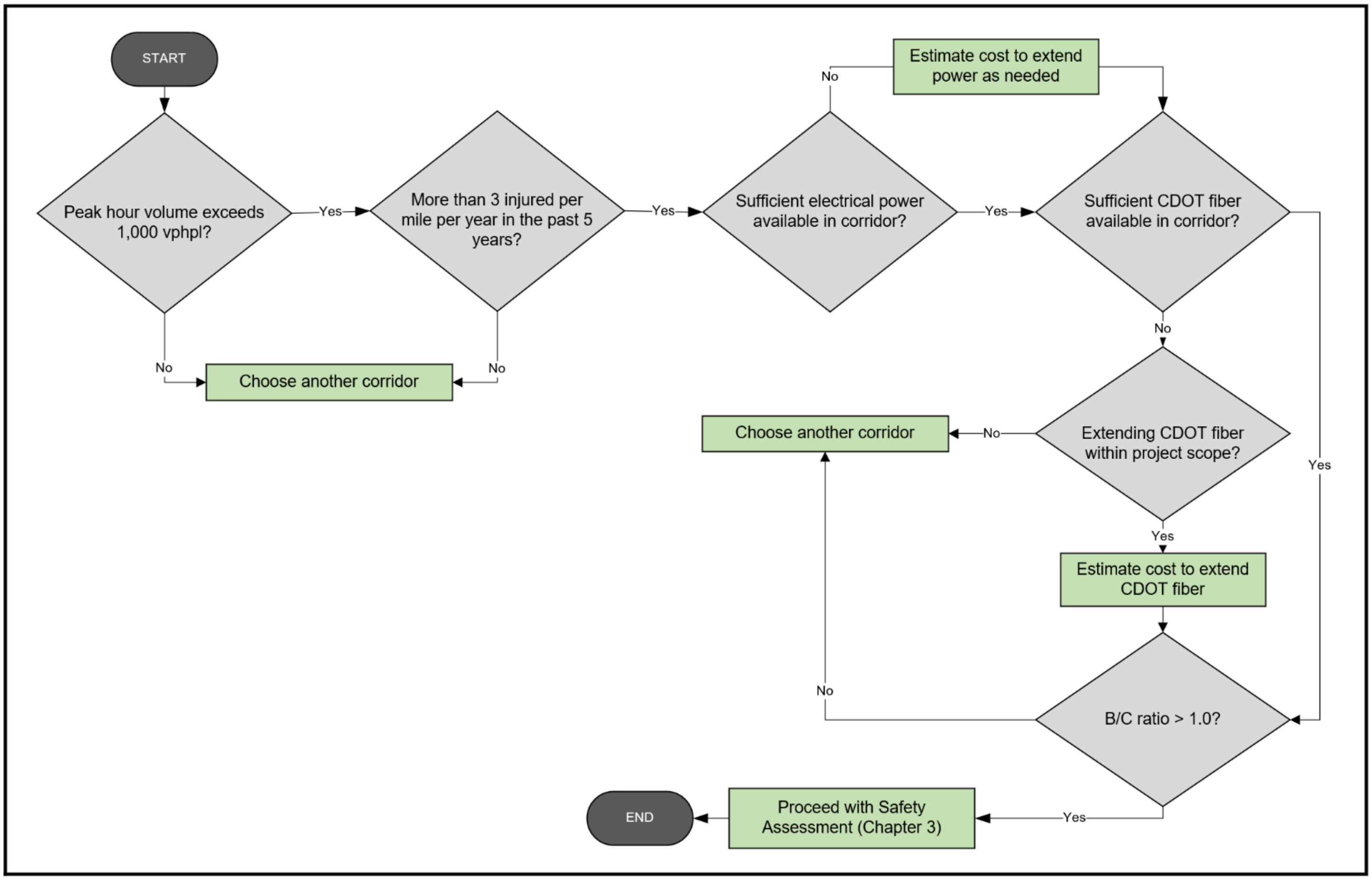


Figure 2. Flow-Based VSL System Flowchart

(Note: Flow-based VSL systems will always include RWISs, as well as the queue and transition components described in Chapter 4. Applicable to Continuous Flow Facilities Only.)

2.2.1. Technology/SEA Assessment

The **Technology/SEA Assessment** document is to be completed by the Project Team during project scoping, utilizing the Programmatic VSL document as a framework (see Chapter 1.4). The intent of this document is to assess whether or not a full SEA process is needed and what impact, if any, a proposed VSL system would have on existing ITS systems. The **Technology/SEA Assessment** should include a clear identification of the problem and how VSL technology may solve it, as well as the results of the VSL Feasibility Workshop. This includes initial consideration of whether maintaining a VSL system in the proposed corridor is feasible, especially if the corridor is located more than two hours (including traffic delays) from the CDOT ITS Maintenance Patrol Yards in Golden and Grand Junction, and whether there are sufficient CDOT ITS maintenance hours resourced for the proposed VSL system. If there are maintenance challenges for the proposed VSL corridor given its remote location or lack of CDOT ITS maintenance resources, the Project Team must coordinate with CDOT ITS and CDOT Region Traffic to form an agreement for shared maintenance responsibilities, and this agreement must be documented in the **Technology/SEA Assessment**. Many design details will not yet be known at the time of this document's submission; nonetheless, it is important to submit this document as soon as possible after project kickoff to initiate the SEA process and begin coordination with relevant CDOT stakeholders.

2.3. Example VSL Feasibility Studies

The following two case studies apply the decision flowcharts to specific corridors and demonstrate the corresponding B/C analysis.

2.3.1. Case Study 1: I-70 through Vail Pass

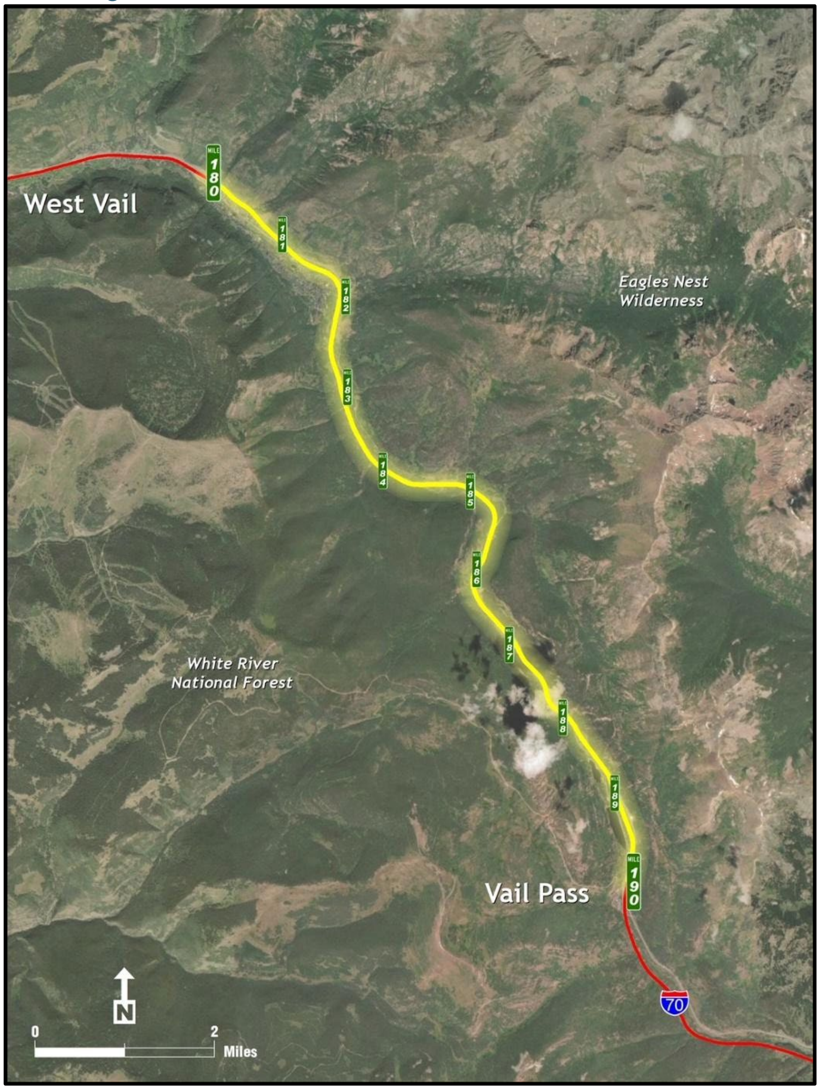


Figure 3. I-70 through Vail Pass (MP 180–190)

This case study demonstrates the evaluation of the feasibility and cost effectiveness of weather-based VSL deployment on I-70 between Vail and the Vail Pass summit.

I-70 is a rural, mountainous four-lane freeway from mile point (MP) 180 in Vail to MP 190 at the Vail Pass summit. It carries about 22,000 annual average daily traffic (AADT), suggesting a peak-hour volume of approximately 550 vphpl. Given this volume, a flow-based VSL system was not appropriate. The flowchart highlighted in Table 3 and Figure 4 was used to evaluate the feasibility of weather-based VSL deployment.

Table 3. Weather-Based VSL System Flowchart Evaluation

The I-70 through Vail Pass project evaluated the feasibility of deploying a weather-based VSL system, using the flowchart shown in Figure 1. This table summarizes the project's response to each question in the flowchart, with notes added for justification.

> than 2 injured per mile per year in past 5 years in adverse conditions?	Figure 5 shows: (168 injuries + 2 killed) / 10 miles / 5 years = 3.4 injuries per mile per year	Yes

Input	Notes	Response
Sufficient electrical power available in corridor?	There was electrical power in most of the corridor; however, there was a gap between roughly MP 183.0 and MP 186.2 that did not have electrical power at the time of this project.	No
Estimate cost to extend power	Given the mountainous terrain, the cost to extend electrical power to cover the gap was conservatively estimated as $500,000 per mile, or $1,600,000 total for the 3.2-mile gap.	$1,600,000
Sufficient CDOT fiber available in corridor?	CDOT's fiber plan[6] showed that fiber existed in this corridor of I-70. Capacity of existing fiber and expansion plans for proposed and in-progress fiber was confirmed with CDOT ITS.	Yes
B/C > 1.0?	Figure 6 shows the B/C analysis, which evaluates the cost effectiveness of a potential VSL project by computing the B/C ratio of crash reduction benefits in dollars over the cost of construction and maintenance. Because a B/C ratio of one (1.0) signifies a break-even scenario, the B/C should be greater than 1.0 for the benefits to outweigh the costs. As mentioned in Chapter 2.1, construction cost estimates should be $500,000 per mile for the deployment of a weather-based VSL system. For this stretch of I-70, the cost estimate was $500,000 x 10 miles = $5,000,000. The $1,600,000 previously estimated to bring power into the existing gap brought the project cost to $5,000,000 + $1,600,000 = $6,600,000. In addition, the B/C analysis assumed a conservative 20% crash reduction and a 20-year service life.	Figure 6 shows that the B/C ratio = 2.34.
Summary	Because the B/C ratio was 2.34, which is greater than 1.0, the implementation of a weather-based VSL system was feasible for I-70 through Vail Pass and was cost effective for reducing crashes in adverse weather/road conditions.	

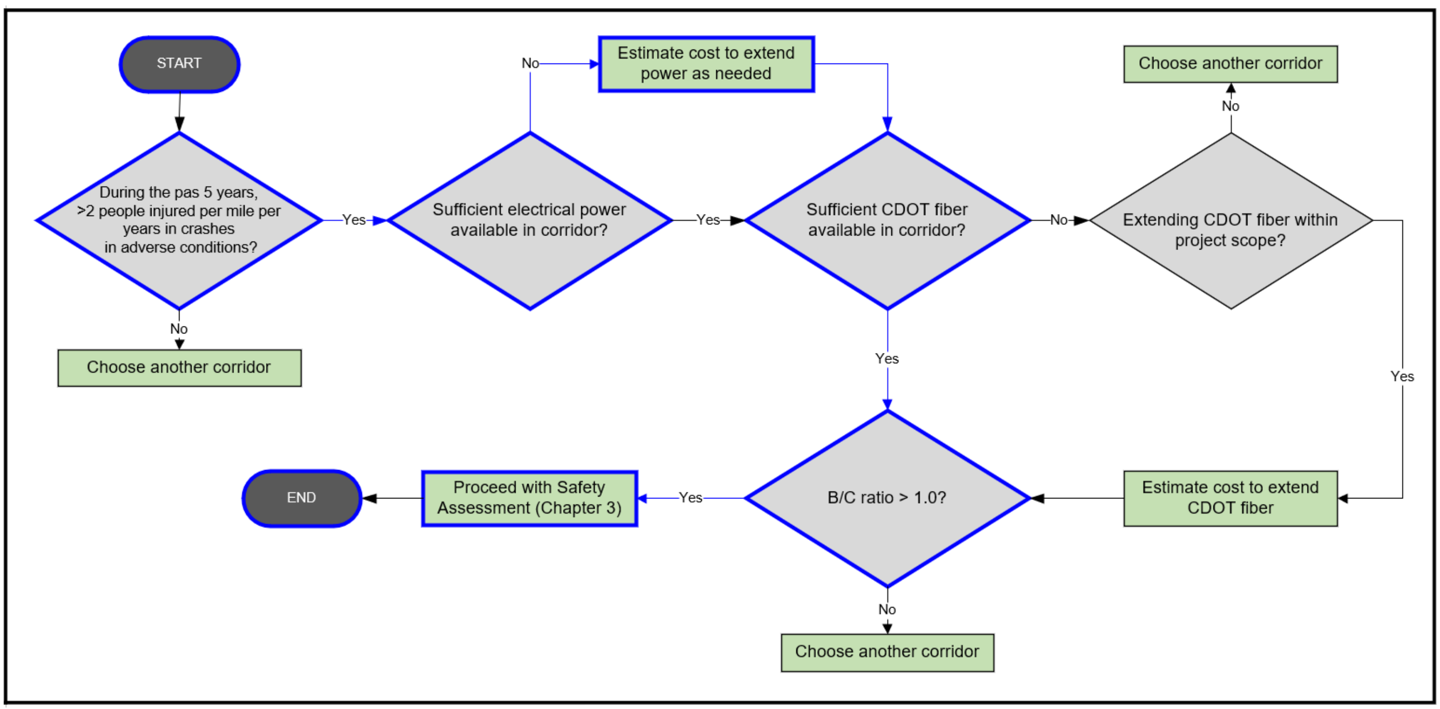


Figure 4. Weather-Based VSL System Flowchart (I-70 through Vail Pass)
(Note: Weather-based VSL systems will always include the transition component described in Chapter 4.)

[6] https://www.codot.gov/programs/intelligent-transportation-systems/fiber-leases-right-of-way-use

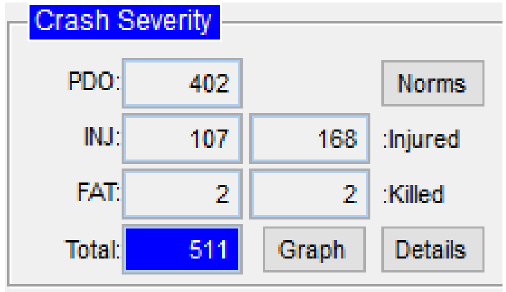
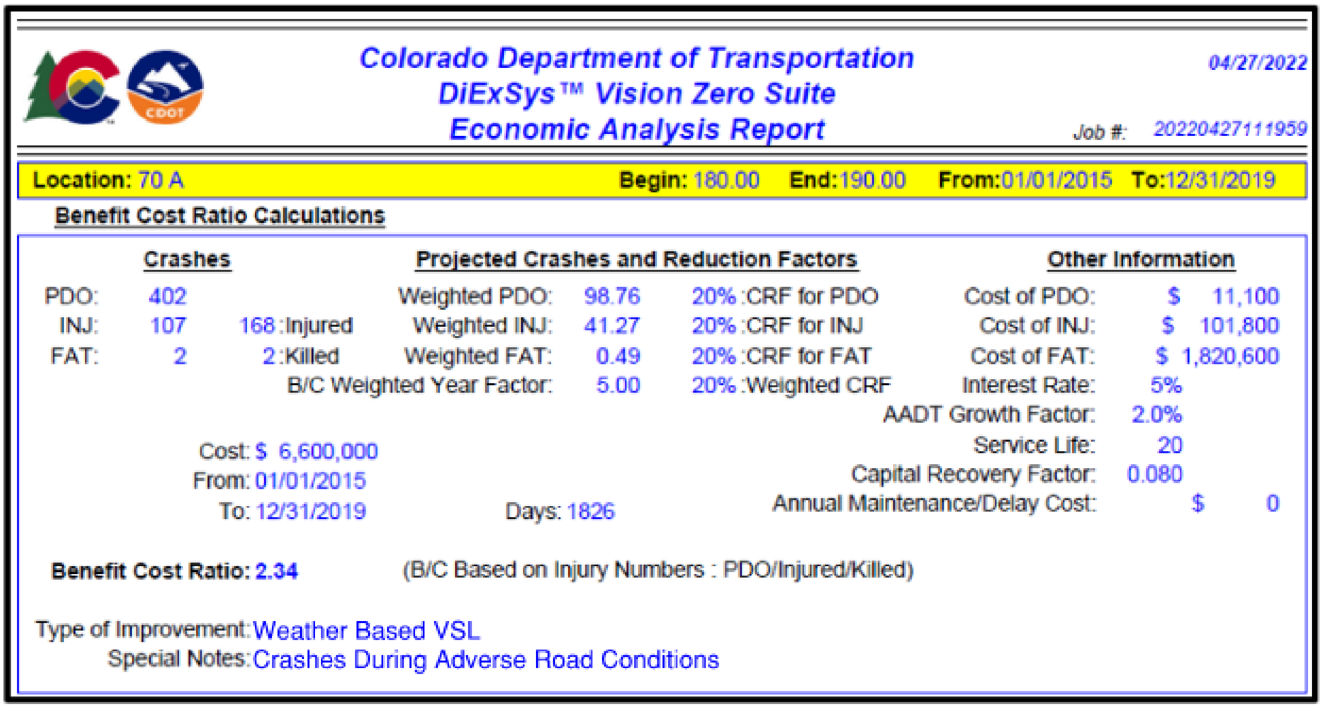


Figure 5. Crashes in Adverse Road Conditions, 2015–2019 (I-70 through Vail Pass)


Colorado Department of Transportation
DiExSys™ Vision Zero Suite
Economic Analysis Report

04/27/2022

Job #: 20220427111959

Location: 70 A Begin: 180.00 End: 190.00 From: 01/01/2015 To: 12/31/2019

Benefit Cost Ratio Calculations

Crashes			Projected Crashes and Reduction Factors			Other Information	
PDO:	402		Weighted PDO:	98.76	20% :CRF for PDO	Cost of PDO:	$ 11,100
INJ:	107	168 :Injured	Weighted INJ:	41.27	20% :CRF for INJ	Cost of INJ:	$ 101,800
FAT:	2	2 :Killed	Weighted FAT:	0.49	20% :CRF for FAT	Cost of FAT:	$ 1,820,600
			B/C Weighted Year Factor:	5.00	20% :Weighted CRF	Interest Rate:	5%
						AADT Growth Factor:	2.0%
		Cost: $ 6,600,000				Service Life:	20
		From: 01/01/2015				Capital Recovery Factor:	0.080
		To: 12/31/2019	Days: 1826			Annual Maintenance/Delay Cost:	$ 0

Benefit Cost Ratio: 2.34 (B/C Based on Injury Numbers : PDO/Injured/Killed)

Type of Improvement: Weather Based VSL

Special Notes: Crashes During Adverse Road Conditions

Figure 6. Benefit/Cost Analysis for a Weather-Based VSL System (I-70 through Vail Pass)
Economic Analysis Report exported from the DiExSys Vision Zero Suite. All crashes are weighted against reduction factors and assigned a cost. The cost of crashes is $11,100 for Property Damage Only [PDO], $101,800 for INJ, and $1,820,600 for FAT. Considering a 5% interest rate, 2% AADT growth factor, 20-year service life, and 0.08 capital recovery factor, a benefit-cost ratio is calculated to compare the anticipated crash reductions with the overall cost of a VSL system. The ratio for this weather-based VSL analysis equals 2.34, indicating the system would have significant benefit.

2.3.2. Case Study 2: I-25 through Colorado Springs

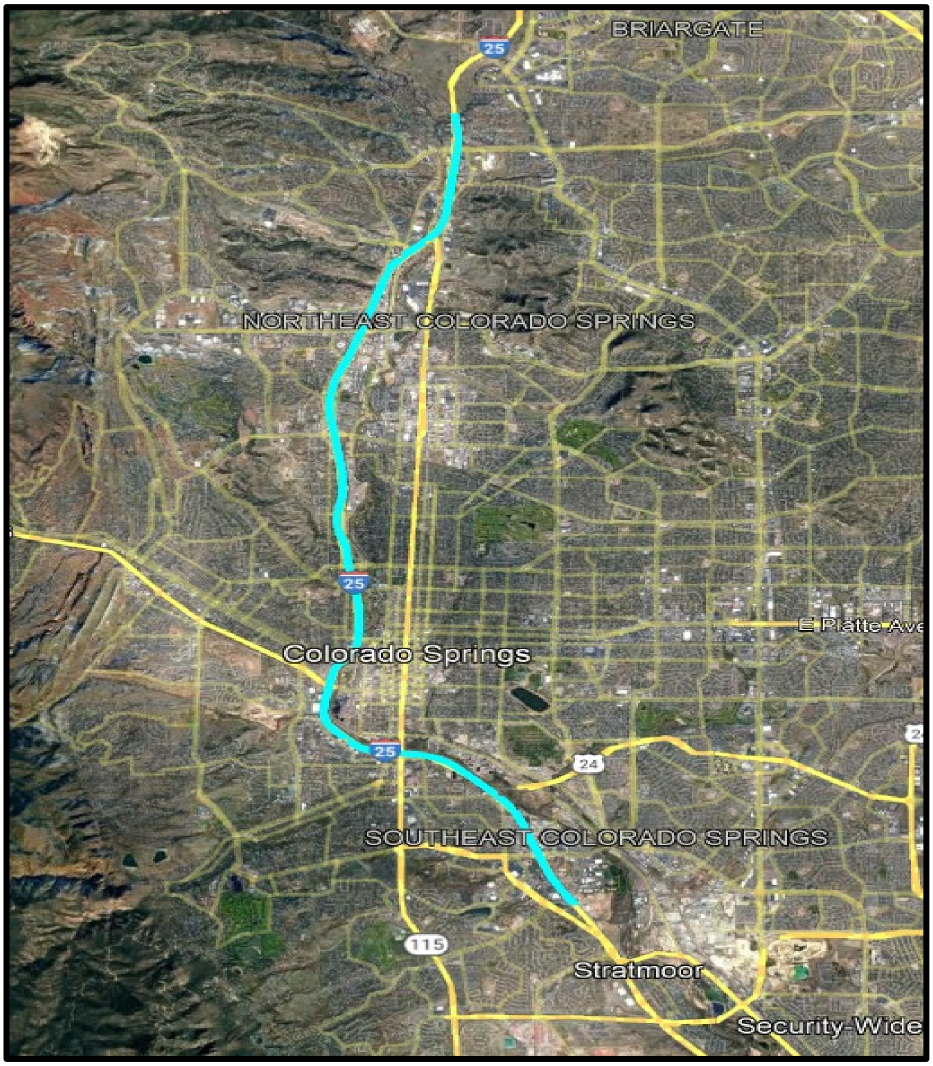


Figure 7. I-25 through Colorado Springs (MP 137.00–149.33)

This case study demonstrates the evaluation of the feasibility and cost effectiveness of flow-based VSL deployment (which includes RWISs, as well as the transition and queue components described in Chapter 4.1.1 and 4.2.1, respectively) on I-25 through Colorado Springs. The primary goal of deploying a VSL system in this corridor was improving safety by reducing frequency and severity of crashes, and improving travel time reliability was a secondary goal.

I-25 is an urban, six-lane freeway from MP 137.00 near the World Event Center to MP 149.33 north of Woodmen Road. It carries about 125,000 AADT within those limits, implying peak-hour flows as high as 2,000 vphpl. It performs predominately in Level of Service of Safety II (LOSS-II) and LOSS-III from the standpoint of frequency and LOSS-III and LOSS-IV in terms of severity, as shown in Figure 8.

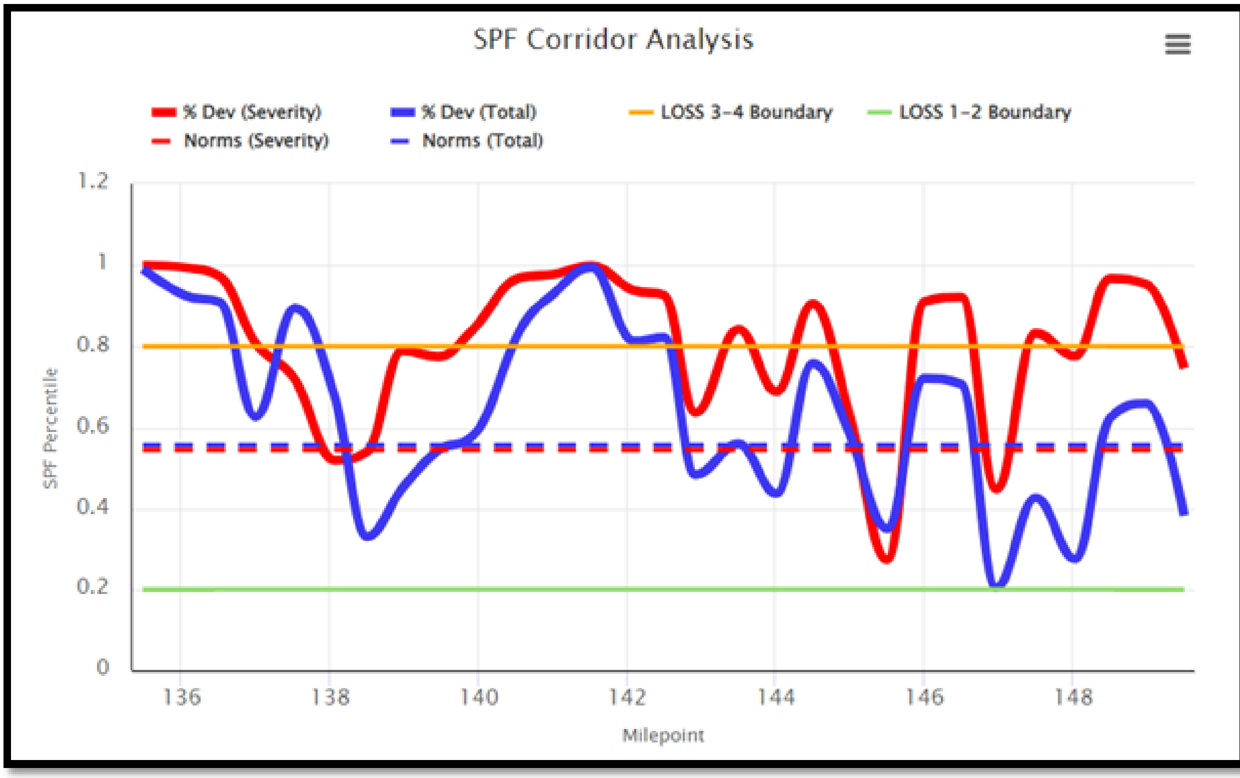


Figure 8. Corridor Safety Performance Function (SPF) Profile (I-25 through Colorado Springs)
This graph shows the SPF percentile for all crashes and severe crashes (i.e., those with INJ or FAT) by mile point. The total crashes generally operate within LOSS-III. However, severe crashes operate within LOSS-III and -IV. The norm baseline, which denotes what is typically expected for an urban freeway, is approximately SPF percentile 0.55 for all crashes and severe crashes. The I-25 through Colorado Springs corridor generally operates above this baseline, with notable exceptions at mile points 138 and 147.

To evaluate whether a flow-based VSL system was feasible and cost effective on I-25 through Colorado Springs, the Flow-Based VSL System Flowchart was used:

Table 4. Flow-Based VSL System Flowchart Evaluation
The I-25 through Colorado Springs project evaluated the feasibility of deploying a flow-based VSL system, using the flowchart shown in Figure 2. This table summarizes the project's response to each question in the flowchart, with notes added for justification.

Input	Notes	Response
Peak hour volume exceeds 1,000 vphpl?	Peak-hour volume approached 2,000 vphpl	Yes
More than 3 injured/mi/year in the past 5 years?	Figure 10 shows: (968 injuries + 12 killed) / 12.33 miles / 5 years = 15.90 injuries per mile per year	Yes
Sufficient electrical power available in the corridor?	Since the location was entirely within urban Colorado Springs, electrical power was available where needed.	Yes
Sufficient CDOT fiber available in corridor?	CDOT's fiber plan showed that fiber existed in this corridor at the time of the plan. Capacity of existing fiber and expansion plans for proposed and in-progress fiber was confirmed with CDOT ITS.	Yes

Input	Notes	Response
B/C > 1.0?	Figure 11 shows the B/C analysis, which evaluates the cost effectiveness of a potential VSL project by computing the B/C ratio of crash reduction benefits in dollars over the cost of construction and maintenance. Because a B/C ratio of one (1.0) signifies a break-even scenario, the B/C should be greater than 1.0 for the benefits to outweigh the costs. As mentioned in Chapter 2.1, construction cost estimates should be $1,000,000 per mile for the deployment of a flow-based VSL system. For I-25 through Colorado Springs, the cost estimate was $1,000,000 x 12.33 miles = $12,330,000. In addition, the B/C analysis assumed a conservative 20% crash reduction and a 20-year service life.	Figure 11 shows that the B/C ratio = 7.02.
Summary	Because the B/C ratio was 7.02, which is greater than 1.0, the implementation of a flow-based VSL system, including RWISs and a queue component, was very cost-effective despite better-than-expected safety performance for I-25 through Colorado Springs.	

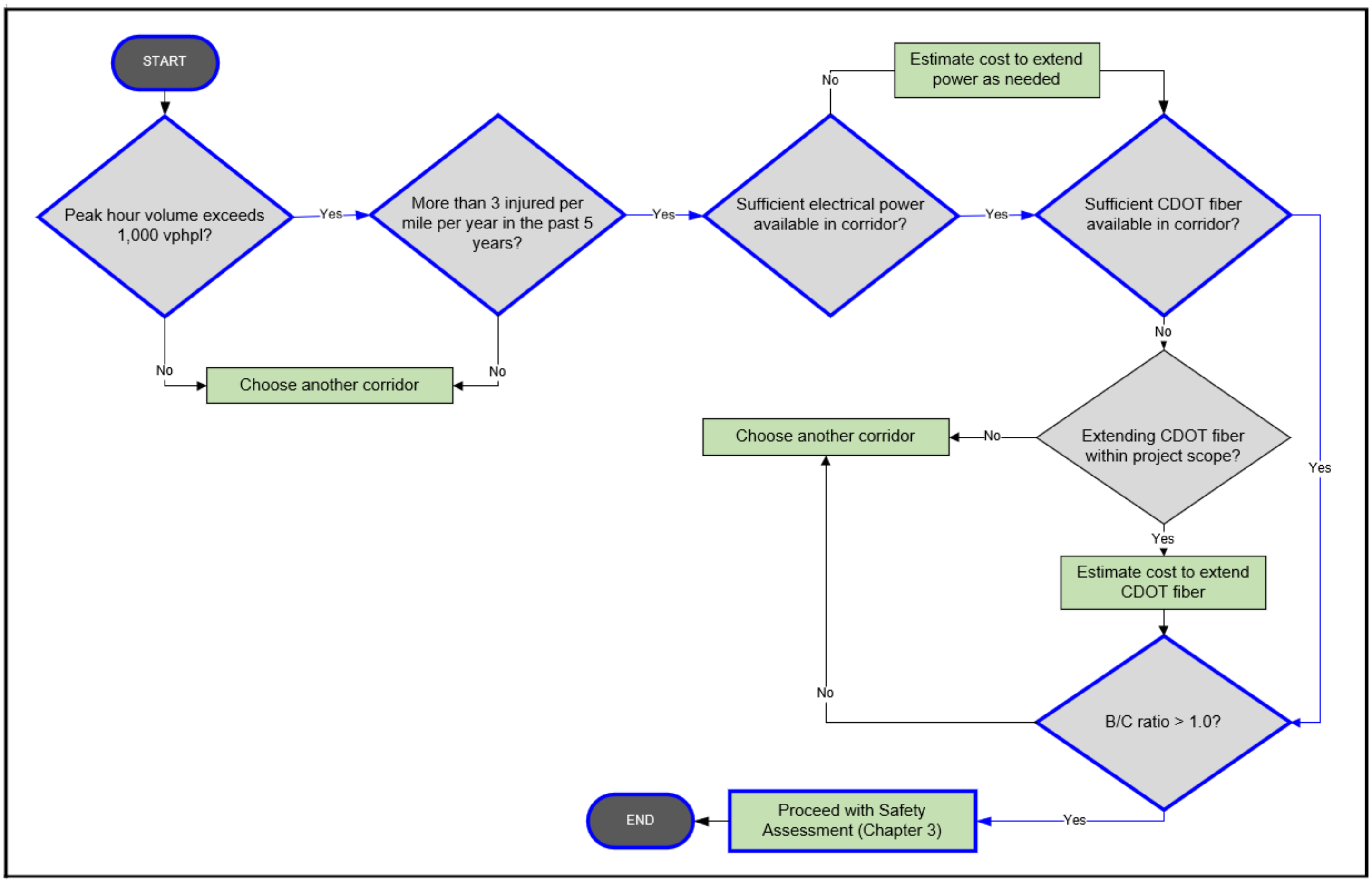


Figure 9. Flow-Based VSL System Flowchart (I-25 through Colorado Springs)
(Note: Flow-based VSL systems will always include RWISs, as well as the queue and transition components described in Chapter 4. Applicable to Continuous Flow Facilities Only.)

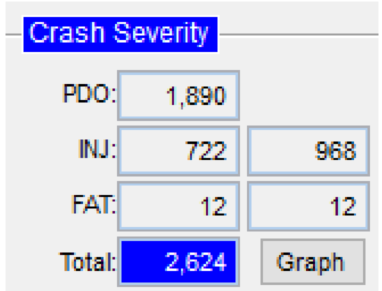
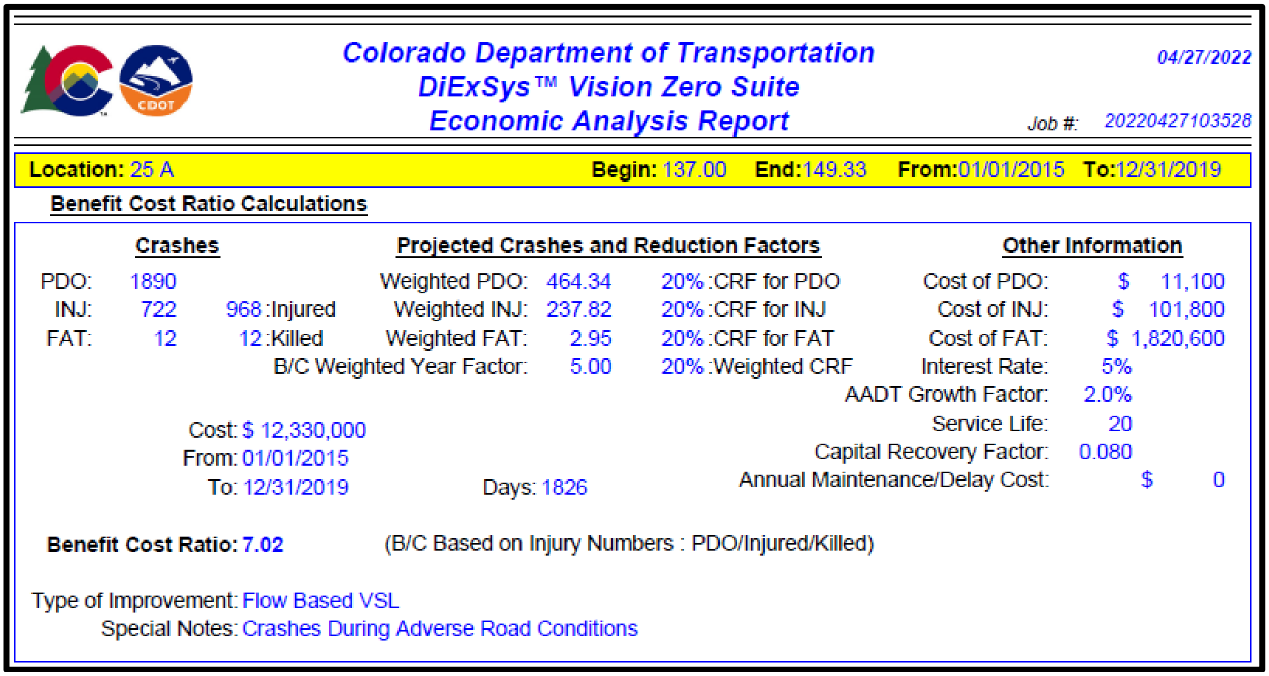


Figure 10. Crashes, 2015–2019 (I-25 through Colorado Springs)



Colorado Department of Transportation
DiExSys™ Vision Zero Suite
Economic Analysis Report

04/27/2022
Job #: 20220427103528

Location: 25 A **Begin:** 137.00 **End:** 149.33 **From:** 01/01/2015 **To:** 12/31/2019

Benefit Cost Ratio Calculations

Crashes			Projected Crashes and Reduction Factors			Other Information	
PDO:	1890		Weighted PDO:	464.34	20% :CRF for PDO	Cost of PDO:	$ 11,100
INJ:	722	968 :Injured	Weighted INJ:	237.82	20% :CRF for INJ	Cost of INJ:	$ 101,800
FAT:	12	12 :Killed	Weighted FAT:	2.95	20% :CRF for FAT	Cost of FAT:	$ 1,820,600
			B/C Weighted Year Factor:	5.00	20% :Weighted CRF	Interest Rate:	5%
						AADT Growth Factor:	2.0%
		Cost: $ 12,330,000				Service Life:	20
		From: 01/01/2015				Capital Recovery Factor:	0.080
		To: 12/31/2019	Days: 1826			Annual Maintenance/Delay Cost:	$ 0

Benefit Cost Ratio: 7.02 (B/C Based on Injury Numbers : PDO/Injured/Killed)

Type of Improvement: Flow Based VSL
Special Notes: Crashes During Adverse Road Conditions

Figure 11. Benefit/Cost Analysis for a Flow-Based VSL System (I-25 through Colorado Springs)
Economic Analysis Report exported from the DiExSys Vision Zero Suite. All crashes are weighted against reduction factors and assigned a cost, as defined previously in Figure 6. The ratio for this flow-based VSL analysis equals 7.02, indicating the system would have significant benefit.

3. VSL Safety Assessment

Because safety is the primary goal of a VSL system, the presence of crashes correlated with adverse weather/road conditions, high-speed/high-density operation, or overweight vehicle/truck -at-fault circumstances suggests that a corridor may potentially benefit from VSL deployment. A VSL Safety Assessment to evaluate whether and how the deployment of a VSL system may reduce the frequency and severity of crashes must be completed by the Project Team following the VSL Feasibility Workshop. The VSL Safety Assessment goes above and beyond the normal safety assessment performed for CDOT projects, and an example is provided in Appendix B.

To complete the VSL Safety Assessment, the Project Team should coordinate with CDOT HQ Traffic for any technical questions that arise, as well as for final review. The Project Team is responsible for the cost of the Safety Assessment.

3.1. Data Collection

The Project Team must collect crash data for the corridor for the most recent five years that crash data is available. A shorter timeframe may be considered if major, permanent changes have been made to the corridor that have impacted safety performance during that five-year timeframe. A minimum of three years of historical crash data should be used for this analysis. Using the Empirical Bayes method will correct for the regression-to-the-mean (RTM) bias[7] to assess the magnitude of the safety problem.

Data is compiled for all crashes and for the direction for which a VSL system is considered. Table 5 shows a typical format for summarizing crash and traffic data for the VSL corridor, and this includes AADT and number of crashes by severity (i.e., PDO, Injury, or Fatality). In this example, a VSL system is being developed in the eastbound direction only.

Table 5. Summary of Crash History, I-70 MP 253.00–269.00

The total number of crashes is listed for each classification (PDO, INJ, FAT). The total crashes that occurred in the eastbound direction are highlighted in parentheses next to the total. For this segment of I-70 between 2014 and 2019, there was a total of approximately 487 crashes, 257 of which occurred in the eastbound direction.

Year	AADT	PDO	INJ	FAT	Total
7/1/14–6/30/15	93,803	407(225)	126(73)	6(2)	539(300)
7/1/15–6/30/16	98,034	384(204)	118(68)	1(0)	503(272)
7/1/16–6/30/17	100,775	416(218)	102(61)	0(0)	518(279)
7/1/17–6/30/18	102,837	341(171)	101(56)	2(1)	444(228)
7/1/18–6/30/19	103,759	332(152)	89(49)	6(5)	427(206)
Average	**99,446**	**376.4(194.0)**	**107.2(61.4)**	**3.0(1.6)**	**486.6(257.0)**

In addition to collecting crash data, it is useful to obtain a roadway reference file that lists roadway features, number of lanes, interchange locations, average daily traffic (ADT), and percentage of overweight vehicles/trucks. Table 6 shows an extract of typical information contained in CDOT's roadway reference file for I-70 within the VSL project limits.

[7] Hauer et al. Estimating Safety by the Empirical Bayes Method. In *Transportation Research Record 1174,* TRB, National Research Council, Washington, D.C., 2002, pp 126–131.

Table 6. Extract from CDOT's Roadway Reference File

Route	Section	Mile point	Description	ADT	Terrain	Lanes
70	A	255.72		73000	Mountainous	6
70	A	255.77	RAMP PM – (FROM GRAPEVINE RD RAMP D) EXIT 256	73000	Mountainous	6
70	A	255.8	MINORSTR (070A255800BL) – RAMP OFF – (TO GRAPEVINE DR RAMP E) EXIT 256	73000	Mountainous	6
70	A	255.82		73000	Mountainous	6
70	A	255.93		73000	Mountainous	6
70	A	255.97	INTERCHANGE STR (F-15-AE) UNDERPASS – RD N AND S	80000	Mountainous	6
70	A	256	MILEPOST 256	80000	Mountainous	6
70	A	256.03		80000	Mountainous	6
70	A	256.13	MINORSTR (070A256120BL) DRAINAGE	80000	Mountainous	6
70	A	256.14	MINORSTR (070A256130BL) UNNAMED DRAINAGE	80000	Mountainous	6
70	A	256.16		80000	Mountainous	6
70	A	256.28	RAMPS ON AND OFF – (TO/FROM GRAPEVINE RED ACCESS TO US 040C) EXIT 256	80000	Mountainous	6
70	A	256.29		80000	Mountainous	6

A representative sample of hourly traffic volume counts over a 24-hour period for weekdays, weekends, and holidays is also vital. This information will be correlated with crash history when a flow-based algorithm is considered.

3.1.1. Crash Data Impact to VSL Classification

A weather-based VSL system determines what the speed limit should be during adverse weather and road conditions (such as low visibility and/or low friction), and a VSL Safety Assessment identifies crash attributes related to these conditions that may be correctable though VSL deployment. These attributes apply to all crash types, but more specifically, road conditions should include one or more of the following characteristics:

- Wet
- Muddy
- Snowy
- Icy
- Slushy
- Dry with Icy Road Treatment
- Wet with Icy Road Treatment
- Snowy with Icy Road Treatment
- Icy with Icy Road Treatment
- Slushy with Icy Road Treatment

Weather conditions should include one or more of the following:

- Rain
- Snow/Sleet/Hail
- Fog
- Dust

Even if adverse weather and road characteristics in the crash history are not over-represented, VSL deployment may still be justified by the feasibility flowcharts outlined in Chapter 2. For example, crashes under snowy and icy road conditions are not unusual in the mountains and will not constitute an abnormal pattern, yet these crashes can be reduced through VSL deployment.

A flow-based VSL system determines what the speed should be during high flow and high density conditions, and a VSL Safety Assessment identifies crash attributes related to these conditions that may be correctable though VSL deployment. Empirical examination of this relationship on State freeways suggests that the crash rate remains relatively stable until a certain threshold of volume and speed is reached. Once this threshold is exceeded, the crash rate rapidly rises. The rise in the crash rate occurs because compression of flow without a notable reduction in speed produces headways so small that it becomes very difficult or even impossible to compensate for driver error to avoid a crash.

Slowing traffic down in real time using a VSL system prior to when the crash rate begins to rise can effectively counteract the lack of available deceleration distance. The VSL Safety Assessment should examine high-speed, high-density operations and relate these conditions to overrepresentation in rear-end, side-swipe, same direction, and multi-vehicle crashes. For example, distribution of crashes by type on a VSL zone of I-70 eastbound between Genesee and Wadsworth shows that rear-end and sideswipe-same crashes account for 89.5 percent of all crashes, which is indicative of high-speed, high-density operations (Figure 12).

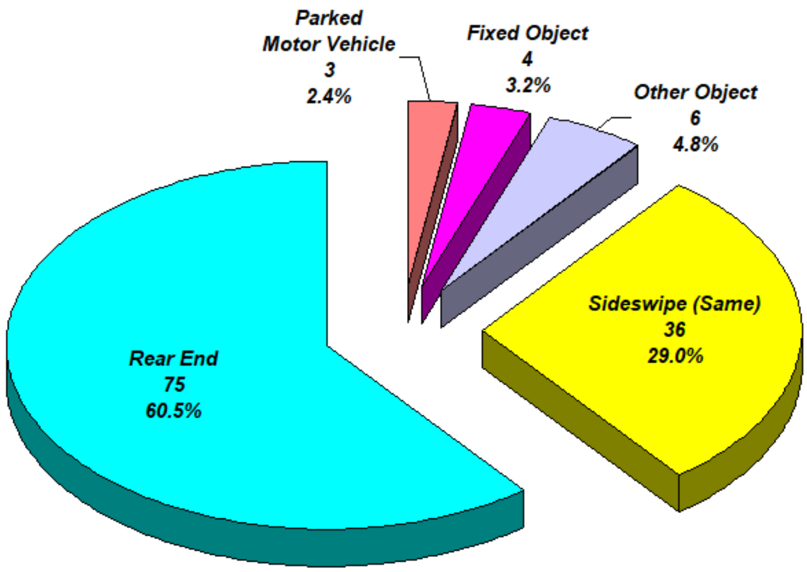


Figure 12. Distribution of Crashes by Type Indicative of High-Speed, High-Density Operations

In some cases, roadway departure crashes result from trying to avoid a rear-end crash due to high-speed, high-density operations. These should also be examined.

3.2. VSL Zone Identification

The Project Team must define the VSL zones for the project corridor. VSL zones are generally defined as the distances between interchanges established by direction, with potential adjustments based on distinguishing features such as visibility, grade, or traffic pattern changes. These zones are analyzed individually during the VSL Safety Assessment and are used to determine where the VSL algorithm operates (see Chapter 4). Figure 13 shows the VSL zone designations for the I-70 Mountain Express Lane project.

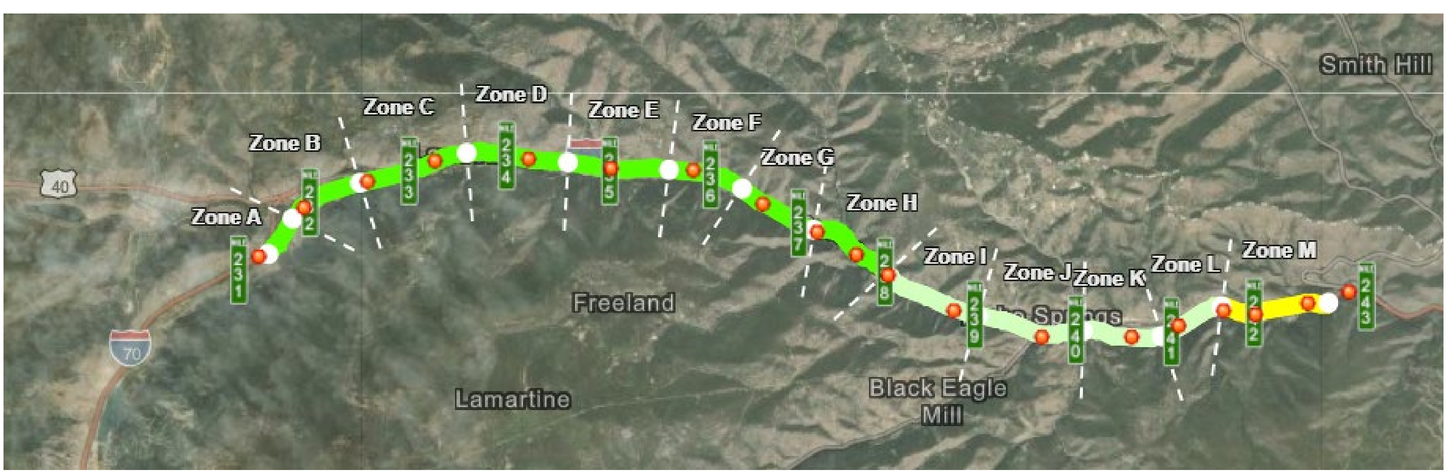


Figure 13. VSL Zones on the Eastbound I-70 Mountain Express Lane Project

3.3. Safety Performance Function (SPF) Analysis

Safety performance in each zone is evaluated in both directions and by direction using the appropriate Safety Performance Function (SPF) and LOSS concept. Figure 14 shows continuous SPF analysis of a section of I-70, MP 253.00–269.00 (Genesee Park to Wadsworth) for both directions, corrected for the RTM bias using the Empirical Bayes method. It shows changes in safety performance using a one-mile sliding interval.

Figure 15 represents Empirical Bayes-corrected zone safety performance of I-70 *eastbound only* because VSL deployment was considered only for the eastbound direction. This figure shows safety performance from the total crash frequency standpoint. Severity SPF is not shown.

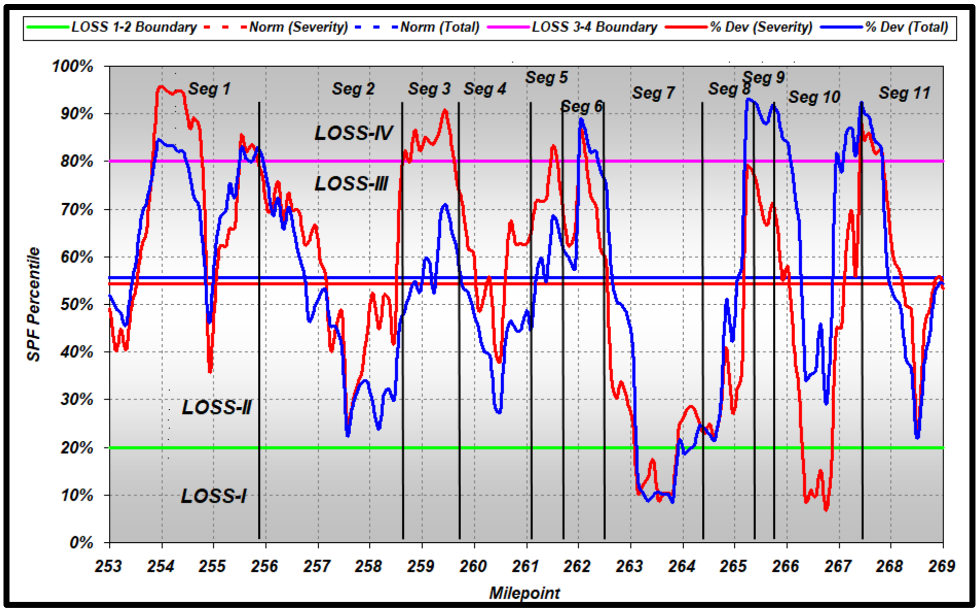


Figure 14. Continuous SPF Empirical-Bayes-Corrected for RTM Analysis, I-70 MP 253.00–269.00 (Both Directions)
This graph shows the corrected SPF percentile for all crashes and severe crashes (those with INJ or FAT) by mile point. All crashes generally operate within LOSS-II and -III, with some locations operating at LOSS-IV and others at LOSS-I. The norm baseline is approximately SPF percentile 0.55 for all crashes and severe crashes. The I-70 corridor segment generally operates above this baseline, with notable exceptions at mile points 263, 264, and 266.5.

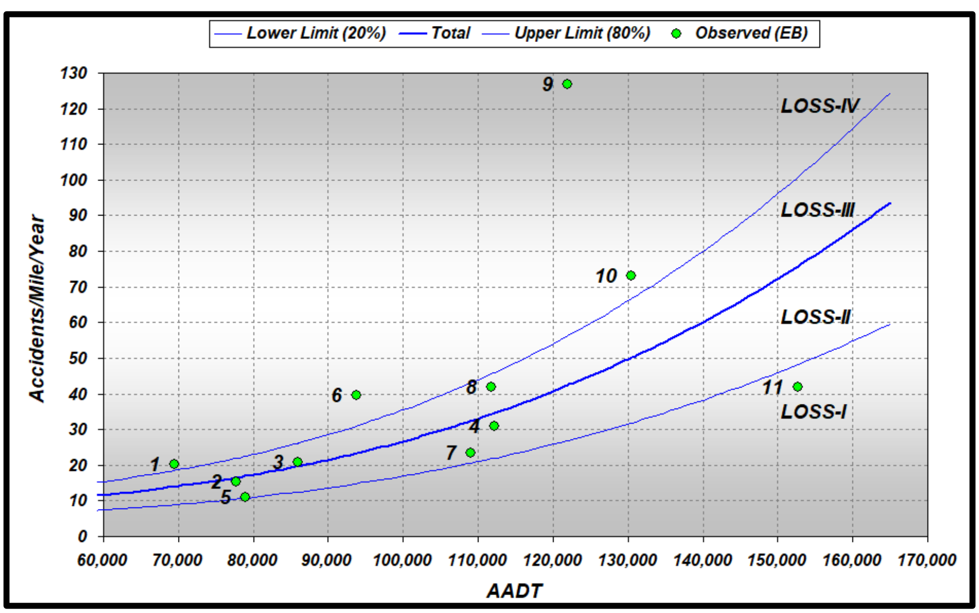


Figure 15. Empirical-Bayes-Corrected Zone Safety Performance, Total Crashes I-70 Mainline (Eastbound Only)

3.4. Benefit/Cost Analysis

During a VSL Safety Assessment, the B/C analysis evaluates the cost effectiveness of a potential VSL project by computing the ratio of crash reduction benefits in dollars over the cost of construction and maintenance. The Project Team should have more design details at this stage to allow for a more precise cost estimate than the high-level estimate completed in Chapter 2. Because a B/C ratio of one (1.0) signifies a break-even scenario, the B/C ratio must be greater than 1.0 for the benefits to outweigh the costs.

As discussed in Chapter 2.1, the B/C analysis should assume a conservative 20 percent crash reduction and a 20-year service life. Based on VSL projects currently in progress, construction cost estimates should be $500,000 per mile for a weather-based VSL system and $1,000,000 per mile for a flow-based VSL system. When conducting a B/C analysis, the Project Team should update these cost estimates to reflect the most current trends in cost of labor and materials and the most recent bids received by CDOT. As an example, Figure 16 shows the B/C analysis for flow-based VSL deployment on I-70 in both directions between MP 215.30–MP 221.50. For this corridor, the cost estimate is $1,000,000 x 6.2 miles = $6,200,000. An additional $2,000,000 is estimated for power supply, bringing the project cost to $8,200,000.

Colorado Department of Transportation
DiExSys™ Vision Zero Suite
Economic Analysis Report

09/06/2022

Job #: 20220906083049

Location: 70 A **Begin:** 215.30 **End:** 221.50 **From:** 01/01/2015 **To:** 12/31/2020

Benefit Cost Ratio Calculations

Crashes			Projected Crashes and Reduction Factors			Other Information	
PDO:	363		Weighted PDO:	74.32	20% :CRF for PDO	Cost of PDO:	$ 11,100
INJ:	128	211 :Injured	Weighted INJ:	43.20	20% :CRF for INJ	Cost of INJ:	$ 101,800
FAT:	1	1 :Killed	Weighted FAT:	0.20	20% :CRF for FAT	Cost of FAT:	$ 1,820,600
			B/C Weighted Year Factor:	6.00	20% :Weighted CRF	Interest Rate:	5%
						AADT Growth Factor:	2.0%
						Service Life:	20
						Capital Recovery Factor:	0.080
						Annual Maintenance/Delay Cost:	$ 0

Cost: $ 8,200,000
From: 01/01/2015
To: 12/31/2020 Days: 2192

Benefit Cost Ratio: 1.70 (B/C Based on Injury Numbers : PDO/Injured/Killed)

Type of Improvement: Flow Based VSL (inc. weather/road conditions, queue & transition components) East & Westbound.
Special Notes: All Crash Types

Figure 16. Benefit/Cost Analysis for Flow-Based VSL System

Economic Analysis Report exported from the DiExSys Vision Zero Suite. All crashes are weighted against reduction factors and assigned a cost, as defined previously in **Figure 6**. The ratio for this flow-based VSL analysis equals 1.70, indicating the system would have some benefit.

3.5. VSL Corridor Justification Memorandum

CDOT may change the speed limit for any road under their jurisdiction if they determine that the speed limit established by law is greater or less than what is reasonable or safe for road or traffic conditions. To establish or change posted speed limits, the Project Team must conduct a thorough traffic investigation that is approved by CDOT HQ Traffic. An example can be obtained from CDOT HQ Traffic by contacting the Traffic Operations Manager.[8] Each traffic investigation follows requirements within the Manual on Uniform Traffic Control Devices (MUTCD) and considers many factors. These include:

- 85^{th} percentile speed data
- Existing development
- Observed crash history
- Road characteristics

[8] https://www.codot.gov/safety/traffic-safety/operations/main

- Environmental factors
- Parking practices
- Pedestrian/bicycle activity and multimodal use of the corridor

When establishing a VSL corridor, the CDOT PM submits the information generated from the VSL Safety Assessment and traffic investigation alongside an official project memorandum (memo) justifying the need for VSL in the corridor. This memo is submitted to the CDOT State Traffic Engineer, Region Traffic Engineer, and CDOT ITS Branch Manager and must be signed by the parties or their designated representatives. This memo serves as the traffic investigation for altering speed limits required by Colorado Revised Statute 42-4-1102 to change the posted speed limit in the corridor, and it must be archived by CDOT HQ Traffic in the event of a Colorado Open Records Act (CORA) request regarding how the posted speed limit was established in the corridor (see Chapter 8.3.1). A template for this memo is included in Appendix C, and a signed copy should be submitted as an attachment to the **Detailed Level System Design** document as part of the SEA process (for more on this SEA document, see Chapter 5.2.6).

3.6. Stakeholder Engagement

At this early phase of the project, the Project Team should hold an initial stakeholder meeting to begin gathering the stakeholder wants and needs that will drive design assumptions. As part of this initial stakeholder meeting, the Project Team should highlight the results of the VSL Feasibility Workshop and the VSL Safety Assessment so that stakeholders are aware of any serious safety concerns in the existing corridor and are informed about whether adding VSL to the corridor will be cost effective.

3.6.1. SEA Alternative Analysis

After initial stakeholder engagement, the Project Team should complete the **Alternative Analysis** SEA document utilizing the Programmatic VSL document as a framework (see Chapter 1.4). This document cannot be submitted until the **Technology/SEA Assessment** is approved by CDOT ITS. The purpose of the **Alternative Analysis** is to determine any alternative options for the technology portion of the project. The VSL Feasibility Workshop and the VSL Safety Assessment completed as part of the project will provide information on what design alternative to select for the project (i.e., a weather-based VSL system or a flow-based VSL system, and whether an overweight vehicle/truck component should be included). The **Alternative Analysis** also documents maintenance impacts, which is especially important if the corridor is located more than two hours (including traffic delays) from the CDOT ITS Maintenance Patrol Yards in Golden and Grand Junction and/or if there are insufficient CDOT ITS maintenance hours currently resourced for the proposed VSL system. The **Alternative Analysis** also begins evaluating if there is any required software development for OpenTMS or the RTDH. The basic VSL software platform has already been developed, but each project must coordinate with CDOT ITS to determine the project-specific cost for configuring the VSL corridor in OpenTMS and the RTDH. Any projects not utilizing the existing algorithm must coordinate with CDOT ITS to establish an estimate for the additional cost of developing a new or modified VSL algorithm (see Chapter 2.1). Finally, the **Alternative Analysis** documents the names and roles of stakeholders—including those external to CDOT, such as local agencies or law enforcement—who will be impacted by the system and must be coordinated with throughout the design process.

3.6.2. SEA Concept of Operations

After the **Alternative Analysis** document is approved by CDOT ITS, the Project Team must complete the **Concept of Operations (ConOps)** SEA document utilizing the Programmatic VSL document as a framework (see Chapter 1.4). The **ConOps** provides a high-level description of the VSL system, identifies stakeholders and system users, documents their wants and needs for the system, prioritizes those wants and needs, and documents why any wants and needs were not selected. Some stakeholder and user needs are similar across VSL projects, so the Programmatic VSL **ConOps** document is filled in with many of the overarching and anticipated wants/needs. It is important to document the justification for either the inclusion of any optional features, such as cameras and flashing beacons, or the omission of any of the overarching wants/needs. The Project Team should also review and add any additional project-specific information. The Project Team is also encouraged to use visuals where possible to describe the project concept.

The stakeholder and user needs identified in the **ConOps** form the basis of the **Validation Plan**, described in detail in Chapter 5.4.3.

4. VSL Algorithm

Each VSL corridor has a unique set of characteristics (e.g., grade, number of lanes, and past safety performance) that influence how the VSL algorithm is designed and configured. The VSL algorithm is designed to calculate an appropriate speed limit based on real-time weather and traffic conditions. The recommended appropriate speed limit is then automatically posted to VSL signs in each zone. OpenTMS collects data from deployed ITS devices and passes it to the RTDH, where the algorithm resides.

This chapter explains the development of the existing VSL algorithm and serves as a reference for Project Teams showing how speed limits in VSL systems are calculated. The Project Team is responsible for dividing the VSL corridor into zones (Chapter 3.2), providing the required algorithm inputs during design (Chapter 5.2.2), and paying a one-time cost for configuration and testing of the algorithm in OpenTMS and the RTDH. If a project utilizes the existing algorithm, the estimated one-time configuration and testing cost is $100,000 (as of 2023), but the Project Team must coordinate with CDOT ITS (OpenTMS Team) and CDOT ODM (RTDH Team) to develop a project-specific cost, which may vary based on factors such as number of devices and corridor length. If the project does not leverage the existing VSL algorithm that is described in this chapter, the Project Team's VSL subject matter expert must coordinate with CDOT ITS and CDOT ODM to determine the feasibility of the proposed VSL system and to estimate the additional cost for developing a new or modified VSL algorithm (see also Chapter 2.1).

4.1. Weather-Based Algorithm

The weather-based algorithm uses roadway characteristics and sensor data from deployed RWISs to calculate an appropriate speed based on friction, grade, and visibility in the corridor. CDOT has extensive experience deploying non-invasive pavement friction sensors across the state of Colorado. The friction sensors are updated on a 10-minute cycle and are generally accurate and reliable, with the caveat that they reflect conditions at only one point on the road. The data collected from these sensors can inform CDOT Real-Time Operations (RTO) and the Colorado Traffic Management Center (CTMC) as they make decisions about:

- Road conditions to post on the https://cotrip.org/ website[9]
- Recommendations to implement chain law restrictions
- Messages to post on Variable Message Signs (VMSs) at problematic locations

To determine the appropriate posted speed limit for various friction conditions, the dry braking distance (D_{brake}) can be calculated as follows:

Equation 1

$$D_{brake} = \frac{{S_f}^2}{30 \times C_f}$$

Where:

- D = Braking distance to stop, in feet
- S_f = Dry speed, in miles per hour (mph)
- C_f = Coefficient of friction, from deployed RWIS
- 30 = Constant including unit conversion and gravity

The observed coefficient of friction (C_f) used to calculate braking distance assumes level ground. However, the VSL algorithm must also consider if a grade is present, as most corridors will not be entirely level.

Downgrade in a VSL corridor is expressed as a decimal (e.g., 6% downgrade is 0.06) and is the steepest average downhill grade measured at two locations along the road that are 500 feet apart. The list below shows the steepest average downgrade for an example freeway for zone 1 to 11 within a VSL corridor:

- 6.2%

[9] https://COtrip.org

- 6.0%
- 8.6%
- 4.0%
- 3.6%
- 3.6%
- 2.8%
- 1.6%
- 1.6%
- 2.6%
- 3.4%

Once the steepest average downhill grade for a corridor is known, the coefficient of friction and grade (C_{fg}) can be calculated by subtracting the grade from the coefficient of friction in the same zone:

Equation 2

$$C_{fg} = C_f - grade\ (\%)$$

A reasonable assumption can be made that travelers would like to maintain the same dry braking distance, regardless of downgrade or other road conditions. Using this assumption, the terms in the equation above can be rearranged algebraically to calculate the speed required to maintain the braking distance, known as the raw friction and grade-based speed ($\boldsymbol{S_{fg}}$):

Equation 3

$$S_{fg} = \sqrt{30 \times D_{brake} \times C_{fg}}$$

Where:

- S_{fg} = Raw friction and grade-based speed, in mph
- D_{brake} = Dry braking distance, in feet (calculated previously using C_f)
- C_{fg} = Coefficient of friction and grade
- 30 = Constant including unit conversion and gravity

Low visibility due to fog, smoke, dust, rain, or blowing snow may naturally reduce travelers speed and thus warrant a lower speed limit. This speed limit should be low enough that a driver can see, recognize, respond, and stop before striking an object in the road under the prevailing visibility. The distance to stop can be calculated by determining the distance required to perceive and react, known as the minimum acceptable visibility (D_{min}):

Equation 4

$$D_{min} = 2.5\left(1.47\ S_{fg}\right) + \frac{{S_{fg}}^2}{30 \times C_{fg}}$$

Where:

- D_{min} = Minimum acceptable visibility, in feet
- 2.5 = Perception + reaction time for an unexpected stimulus, in seconds (AASHTO Green Book)
- 1.47 = Constant converting mph to feet per second
- S_{fg} = Raw friction and grade-based speed, in mph
- C_{fg} = Coefficient of friction and grade

This equation then simplifies to:

Equation 5

$$D_{min} = 3.675\, S_{fg} + \frac{{S_{fg}}^2}{30 \times C_{fg}}$$

If the current observed visibility distance (determined from the deployed RWIS) is less than the minimum acceptable visibility (D_{min}), the input speed (S_{fg}) must be lowered 5 mph to solve for D_{min} again. This iterative process will yield a shorter distance that reflects the lower speed and will not stop until the current observed visibility distance equals or exceeds D_{min}. The value of S_{fg} that achieves this result becomes the weather-based speed for final speed limit consideration.

4.1.1. Transition-Based Component

Smooth speed transitions from zone to zone are required for a VSL system to be effective. The transition-based component addresses traffic approaching lower speed limits by proposing a speed limit 10 mph higher than the speed limit in the next zone downstream (further along the route in the direction of travel). As a result, when a particular zone needs a reduced speed limit of 40 mph, for example, the first zone upstream is 50 mph, the second zone is 60 mph, and the third zone is 65 mph (or the maximum posted speed). This approach gradually warns and transitions drivers to lower speeds over a couple miles or more. The transition-based component does not address speed limits in the opposite direction, as nothing is gained by limiting the magnitude of a speed limit increase from one zone to the next when moving downstream.

4.1.2. Overweight Vehicle/Truck Component

Certain locations in Colorado with long downgrades, winding alignments, or tight curve geometries have lower speed limits for vehicles over 26,000 pounds GVWR. These vehicles are loosely defined as trucks but include any overweight vehicles. These VSL zones with separate overweight vehicle/truck speed limits generally reflect the potential for heavily loaded trucks to runaway due to brakes overheating or to overturn due to curves. VSL systems that choose to include separate overweight vehicle/truck speed limits will require VSL signs that are double in size. The upper display of the VSL sign is determined by the chosen VSL algorithm, and the lower display will either show the exact same speed limit or the maximum speed limit for overweight vehicles/trucks, whichever is lower. The overweight vehicle/truck speed limit must never be higher than the recommended passenger car speed limit. Figure 17 shows the VSL sign with lower overweight vehicle speed limits, sign code R2-20aP.

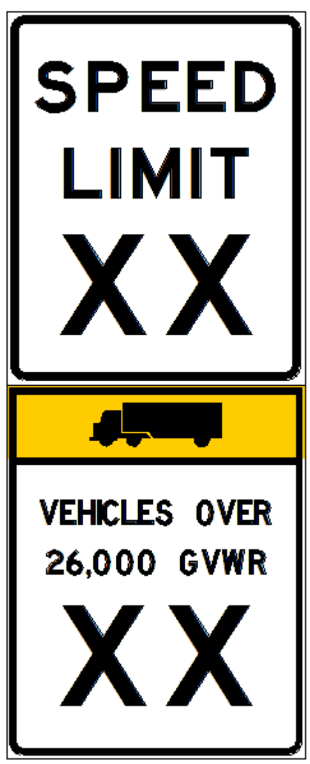


Figure 17. Dual VSL Sign with Lower Truck Speed Limit (Sign Code R2-20aP)

Table 7 lists all CDOT roadways with lower posted speed limits for overweight vehicles/trucks.

Table 7. Corridors with Lower Overweight Vehicle/Truck Speed Limits

Highway	Passenger Car Speed Limit	Overweight Vehicle/ Truck Speed Limit
I-70 in Glenwood Canyon	60	50
I-70 westbound descent from Vail Pass	65	45
I-70 westbound descent from the Eisenhower-Johnson Memorial Tunnels	60	35
I-70 eastbound descent from Georgetown Hill	65	45
I-70 westbound descent from Floyd Hill	55	45
I-70 eastbound in the Mount Vernon Canyon descent	65	45
US 160 westbound descent from Wolf Creek Pass	45	25

4.1.3. Determining Speed Limits for a Weather-Based System

The weather-based VSL algorithm will initially calculate a friction- and grade-based speed that is a multiple of five mph in the range of the maximum speed limit. It will then further reduce the speed based on the real-time observed visibility. All weather-based speed reductions are checked against the CDOT-defined minimum and maximum speed limits for various road conditions. For example, in the event of zero visibility the recommended speed limit would theoretically be zero, but an override is included in the algorithm that stops the incrementing at the CDOT-defined minimum speed limit for adverse conditions. Similarly, the proposed transition-based speed may be higher than the CDOT-defined maximum speed limit for passenger vehicles or overweight vehicles/trucks, so the overall algorithm must override the output of the transition-based component if necessary.

Figure 18 shows a flowchart that describes the process for determining the weather-based speed limit, accounting for all previously described calculations, algorithm components, and necessary overrides.

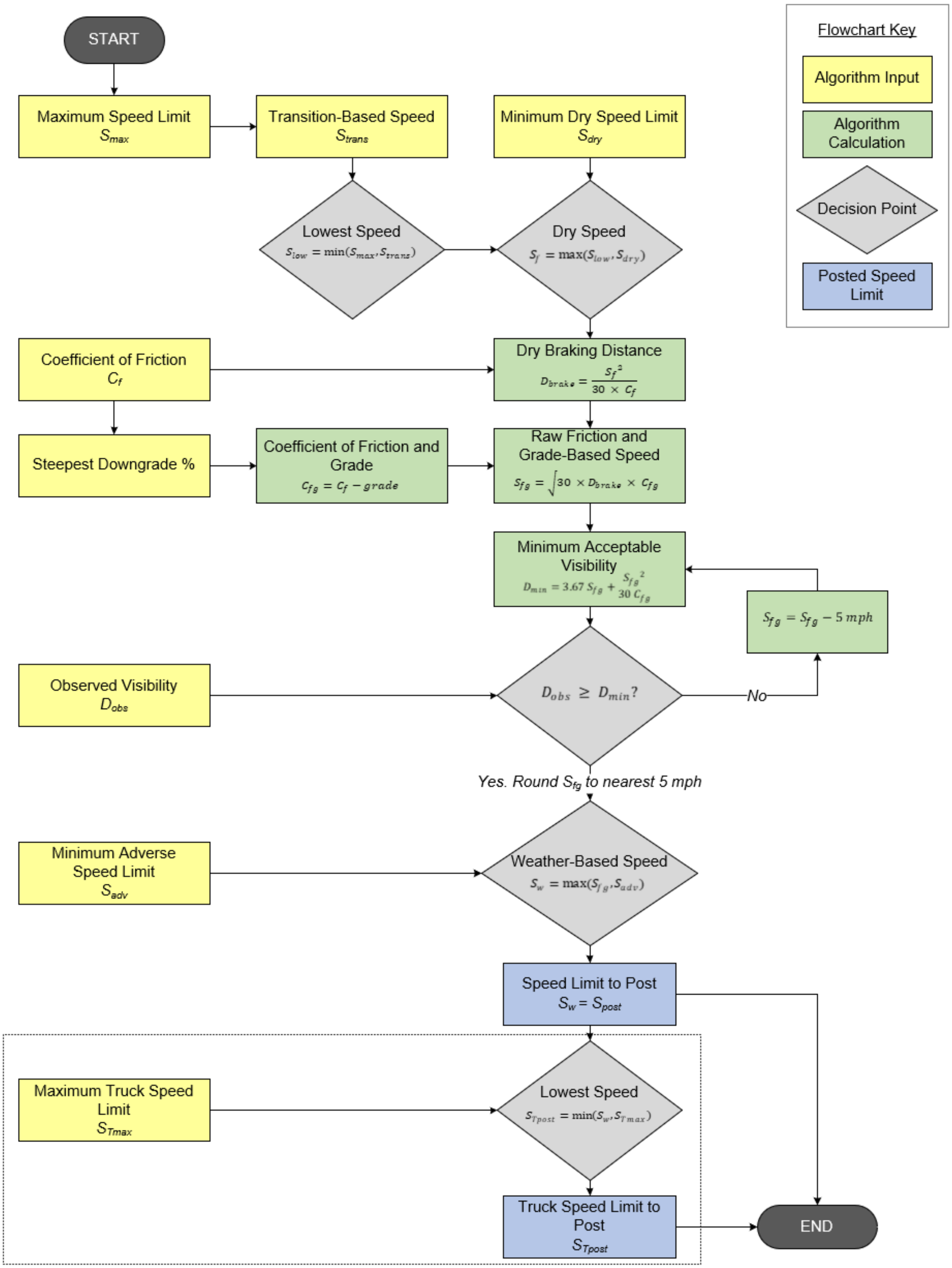


Figure 18. Flowchart for Weather-Based VSL Algorithm

(For VSL systems with different speed limits for overweight vehicles/trucks)

This flowchart describes how the weather-based VSL algorithm determines which speed limit to post. The algorithm will calculate the speed autonomously based on user-defined inputs and real-time data.

4.1.4. Weather-Based Algorithm Case Study

This case study uses the weather-based algorithm calculations described previously for an example corridor with assumed friction data to walk through the process of determining a weather-based speed limit.

Near-real-time data from deployed friction sensors is used as the basis of VSL speed limits during low-friction conditions. To determine the appropriate posted speed for various friction conditions, the braking distance is calculated from speed and road surface friction variables using Equation 1. Assuming a speed of 65 mph and a coefficient of friction of 0.82 (the dry friction coefficient for pavement in good condition that is used as a calibration constant for non-invasive friction sensors), the stopping distance is computed as 188 feet. This is the stopping distance at maximum deceleration effort, with no allowance for perception and reaction times.

Assuming the desired braking distance D is 188 feet for all road conditions, S can be calculated for any observed C_f. To calculate the appropriate posted speed S for various friction conditions, the terms are rearranged algebraically to form Equation 3. Values for S are rounded to the nearest 5 mph to arrive at a friction-based speed.

Table 8 shows friction-based speeds associated with various coefficients of friction and a 188-foot stopping distance, as calculated previously. The lowest friction-based speeds are in red, as they are lower than CDOT's minimum speed limit guidance and cannot be posted.

Table 8. Example Friction-Based Speed Limits

The speed that results in a stopping distance of 188 feet was calculated for a variety of friction coefficients, ranging from 0.75 (coefficient in dry conditions) to 0.05 (coefficient in snowy/icy conditions). This table shows the calculated speed that is then rounded to the nearest 5 mph and defined as the friction-based speed limit.

Approximate Road Condition	DRY			WET					SNOWY/ICY						
Friction Coefficient	0.75	0.7	0.65	0.6	0.55	0.5	0.45	0.4	0.35	0.3	0.25	0.2	0.15	0.1	0.05
Speed that can stop in 188ft	65.0	62.8	60.5	58.1	55.7	53.1	50.3	47.5	44.4	41.1	37.5	33.6	29.1	23.7	16.8
Friction-Based Speed Limit	**65**	**65**	**60**	**60**	**55**	**55**	**50**	**45**	**45**	**40**	**40**	**35**	**30**	**25**	**15**

For an assumed stopping distance of 188 feet, S is 65 mph (the existing speed limit) under dry conditions, 45 mph for the lowest friction corresponding to wet conditions, 45 mph on cold, very dry snow, and 30 mph (or slower) under the most slippery icy conditions. Those speed limits seem reasonable for a freeway with a maximum speed limit of 65 mph, assuming level ground and light traffic.

The raw, observed coefficient of friction assumes level ground, but if a grade is present, the algorithm must be modified to subtract the magnitude of the steepest downgrade from the friction coefficient. At this point, S represents the friction- and grade-based speed, which is calculated using Equation 3, where Cfg represents the coefficient of friction and grade (observed friction minus downgrade). Equation 3 may still be used to determine the appropriate speed limit, but the friction coefficient C_f is replaced with C_{fg}. The friction- and grade-based recommended speed can be further refined by considering flow within the corridor. For example, if flow is high enough that the flow-based speed is 45 mph, the dry braking distance D should be calculated for 45 mph rather than 65 mph. Assuming level ground and dry pavement (C_f = 0.82), the dry braking distance D is calculated using Equation 1, resulting in a dry braking distance D = 82 feet. The appropriate speed for a variety of coefficients of friction and grade, shown in Table 9, can then be calculated using D = 82 feet with Equation 3.

Table 9. Example Friction- and Grade-Based Speed Limits under High Flow Conditions

The speed that results in a stopping distance of 82 feet was calculated for a variety of friction and grade coefficients, ranging from 0.82 (coefficient in dry conditions on level ground) to 0.05 (coefficient in snowy/icy conditions). This table shows the calculated speed which also factors in a flow-based speed of 45mph. The calculated speed is then rounded to the nearest 5 mph and defined as the friction- and grade-based speed limit.

Approximate Road Condition	DRY			WET					SNOWY/ICY						
Friction and Grade Coefficient	0.82	0.7	0.65	0.6	0.55	0.5	0.45	0.4	0.35	0.3	0.25	0.2	0.15	0.1	0.05
Speed that can stop in 82ft	44.9	41.5	40.0	38.4	36.8	35.1	33.3	31.4	29.3	27.2	24.8	22.2	19.2	15.7	11.1
Friction- and Grade- Based Speed Limit	**45**	**40**	**40**	**40**	**35**	**35**	**35**	**30**	**30**	**25**	**25**	**20**	**20**	**15**	**10**

Similarly, queue-based and transition-based speeds may be used to calculate the dry braking distance D. To calculate speeds when flow, queue, and transition elements are present, the speed that should be used to calculate D is the lowest of the speeds proposed by the flow, queue, and transition component algorithms, or the lowest speed limit that CDOT would post on that facility under dry road conditions (likely 40 mph for a freeway), whichever is higher. This is called the dry speed, calculated using Equation 3, just as before, where Cfg represents the dry coefficient of friction and grade (0.82-grade). Then the appropriate speed S can be calculated for a variety of coefficients of friction and grade, and these speeds are rounded to the nearest 5 mph using with Equation 3.

Finally, low visibility in fog, smoke, dust, rain, or blowing snow may also be cause for slowing down. Visibility data is available in locations where CDOT RWISs include visibility sensors; in addition, all of CDOT's friction sensors are physically capable of reporting visibility, although this capability may require licensing changes to unlock.

Assuming the availability of visibility data, the appropriate speed may be refined for low-visibility conditions. This speed should be low enough that a driver can see, recognize, respond, and stop before striking something in the road under the prevailing visibility. Given specific speed, friction, and grade, the distance to stop can be calculated by determining the distance required to perceive and react, or minimum acceptable visibility (D_{min}) in feet using Equation 4, or the simplified Equation 5.

To solve for D_{min}, the observed friction minus downgrade (C_{fg}) is used, and S is the friction- and grade-based speed (which also considers flow-based speed). If the current observed visibility equals or exceeds D_{min}, then the friction- and grade-based speed becomes the weather-based speed; otherwise, S must be lowered 5 mph to solve for D_{min} again. The new D_{min} will be a shorter distance, reflecting the lower speed. This process iterates until D_{min} is less than or equal to the existing observed visibility. The value of S which achieves this result becomes the weather-based speed limit.

4.2. Flow-Based Algorithm

A flow-based VSL algorithm calculates the relationship between crash rate, volume per lane, and speed in a corridor to determine the appropriate speed limit. When high traffic volumes are moving at high speeds, a flow-based VSL algorithm intervenes by lowering the speed limit before crashes occur.

For each corridor where a flow-based algorithm is deployed, the relationship between flow in vphpl and crash rate per Million Vehicle-Miles of Travel (MVMT) is plotted from existing crash history, speed, and volume data. This plot is called a corridor-specific SPF curve. The SPF curve for eastbound I-70 from Genesee Park to Wadsworth Freeway corridor is provided as an example in Figure 19.

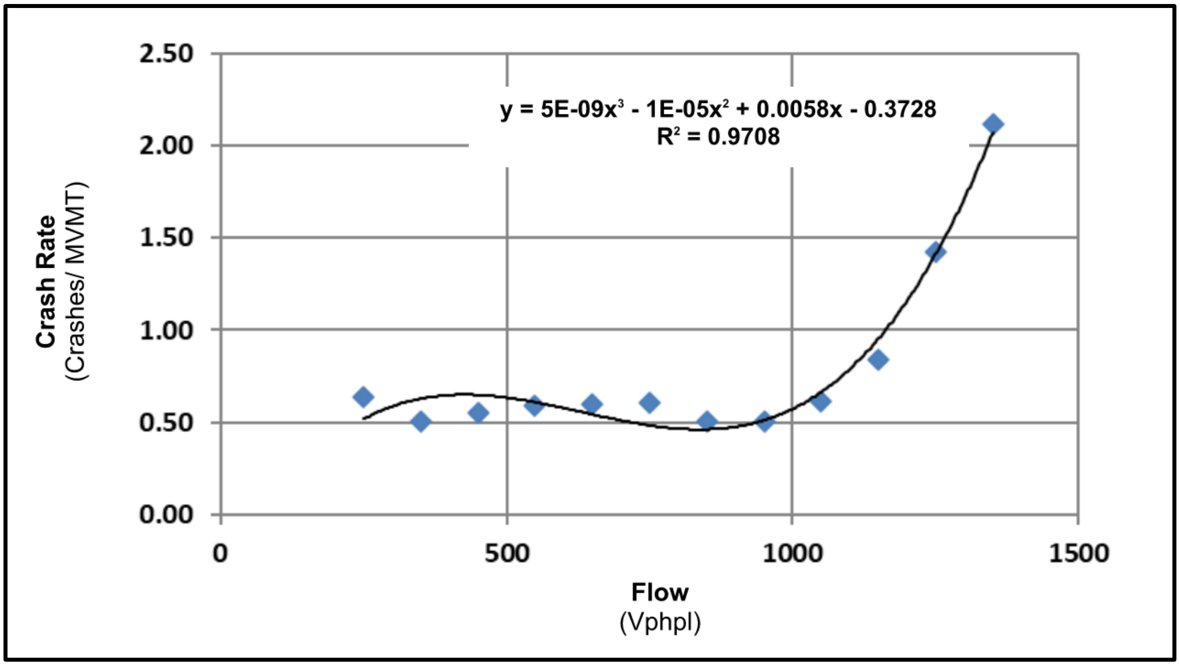


Figure 19. Example Corridor-Specific SPF Curve (I-70 eastbound Genesee to Wadsworth)

As shown in the example, the crash rate remains low and fairly uniform up to an inflection point flow rate of around 1,000 MVMT and then rises rapidly for higher flow. The “hockey stick curve” shape shows that drivers will continue to drive at high speeds as the flow and traffic density rise to a hazardous level. The hockey stick shape holds true for all freeway facilities, but the uniform crash rates and inflection point flow rate will vary between corridors.

The corridor-specific flow-based VSL algorithm uses the inflection point flow rate and the observed traffic speed in the corridor at the inflection point flow rate (which generally is the free flow speed of the corridor and can be gathered from MVRD data). Multiplying these two values yields the maximum flow momentum that the corridor can handle without experiencing a flow-based increase in crash rate.

Equation 6

$$Max. Flow\ Momentum\ (vehicle\ miles\ of\ travel\ per\ hour\ per\ lane\ [vmtphpl]) \\ = Observed\ free\ flow\ traffic\ speed\ (mph) \times Inflection\ point\ flow\ rate\ (vphpl)$$

Once the maximum flow momentum is defined, the VSL algorithm calculates the appropriate flow-based speed limit recommendation for various flow conditions by dividing the maximum flow momentum by the real-time observed flow, in vphpl, and rounding to the nearest 5 mph.

Table 10 shows an example of the recommended speed limits for various flow conditions when the maximum flow momentum is 68,250 vmtphpl and the maximum speed limit is 65 mph. This table is not directly utilized by the VSL algorithm, but can support in understanding the relationship between possible flow rates and recommended speed limits. These values can be identified without real-time data by dividing the maximum flow momentum by each potential posted speed limit minus 2.5 mph.

Table 10. Flow-Based Speed Recommendation

Given a maximum flow momentum of 68,250 vmtphpl, the VSL algorithm can recommend a speed limit based on the real-time observed flow conditions. This table displays the recommended speed limit for a variety of flow conditions.

Flow (vphpl)	Speed (mph)
Up to 1,092	65
1,093 – 1,187	60
1,188 – 1,300	55

Flow (vphpl)	Speed (mph)
1,301 – 1,437	50
1,438 – 1,606	45
1,607 or more	40

The recommended speed limits from the flow-based algorithm can be plotted on the speed-flow curve from the Highway Capacity Manual (HCM). This plot is not required for defining a flow-based speed limit but can offer a better understanding of the relationship between flow and crash rate. As shown in the curve, when flow in a corridor reaches unstable levels, average passenger car speeds should decrease accordingly, however, this is not always guaranteed. For instance, at a point with a flow rate of 1,600 passenger cars/hour/lane, the average passenger car speed remains at 68 mph. This high-speed, high-density operation corresponds with the steep part of the flow-specific SPF curve, where the crash rate increases rapidly in the absence of significant speed reduction.

Since the HCM uses passenger cars/hour/lane units for flow, the corridor-specific flows must be adjusted from vehicles to passenger car equivalents using the HCM methodology. This adjustment reflects the fact that overweight vehicles/trucks have more effect than cars in the traffic stream, and each overweight vehicle/truck is replaced with multiple passenger car equivalents, based on the grade. Figure 20 plots the speed recommendations provided in Table 10 above with a blue line, assuming 6.5 percent overweight vehicles/trucks and a -5.0% average grade, resulting in each overweight vehicle/truck being replaced by 2.222 passenger car equivalents.

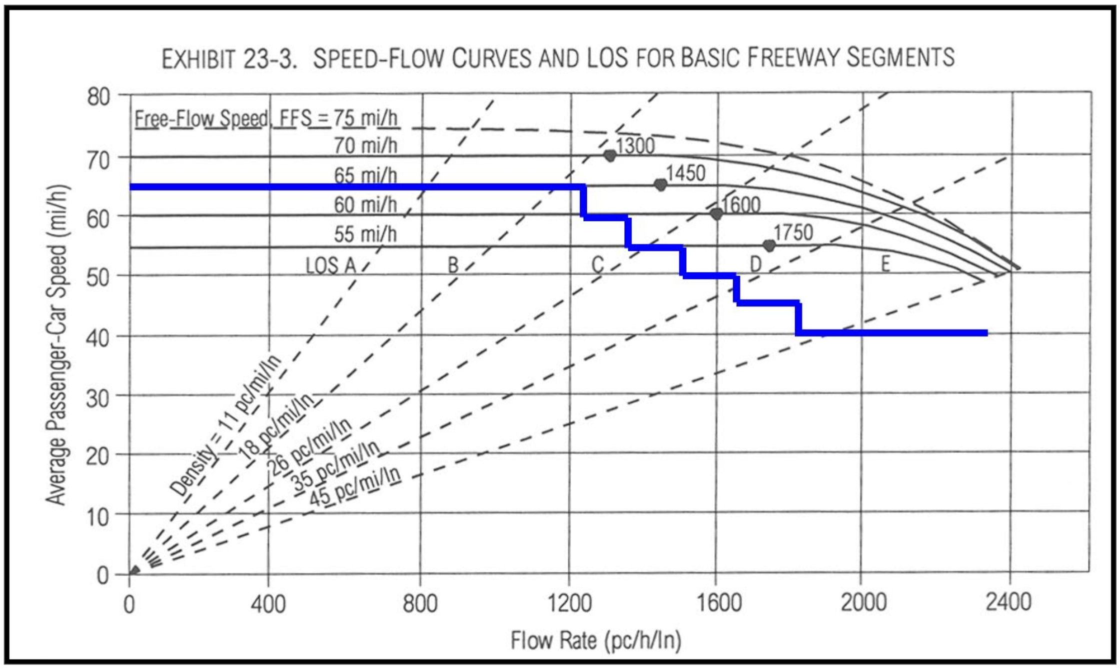


Figure 20. Flow-Based Proposed Speed Limits Overlaid on Speed-Flow Curve from the HCM

In summary, the Project Team must complete the following steps during the design of a flow-based VSL system:

1. Plot the corridor-specific SPF "hockey stick" curve using corridor crash and flow data.
2. Identify the inflection point flow rate from the SPF curve.

The VSL algorithm then utilizes the following steps to determine the flow-based recommended speed limit:

3. Identify the observed traffic speed at the inflection point flow rate from MVRD data.
4. Calculate the maximum flow momentum in miles of travel per hour per lane.
5. Determine the real-time observed flow in the corridor, in vphpl.
6. Divide the maximum flow momentum by the observed flow and round to the nearest 5 mph.

4.2.1. Queue-Based Component

In existing queue warning systems on US-36 and I-25 in Colorado, there is an emphasis on short zones between regularly spaced signs (half-mile or less), VMSs associated with every zone, and overhead lane use signage. There is also emphasis on designing the messaging and speed limits posted to achieve a low and steady deceleration rate approaching the queue location. Half-mile, regularly spaced zones and overhead signage are typically a luxury due to budget, resources, or space restrictions on highway corridors. As such, establishing specific deceleration rates requires a specialized algorithm for each VSL sign location, which is impractical.

Given these constraints, the queue-based algorithm component should help ensure that traffic in the zone just upstream of the back of the queue has a speed limit that is the greater of two considerations: between 5 and 10 mph higher than the speed in the zone with the queue or the minimum speed posted in dry or adverse conditions, depending on real-time weather data. The speed in the downstream zone (where the queue exists) is averaged over two, 30-second data collection cycles over all lanes, which prevents one slow-moving vehicle from lowering the speed limit. The queue-based speed is calculated by taking the observed average speed in the next zone downstream over the last available minute, adding 5 mph to that speed, and rounding up to the next multiple of 5 mph. For example, if the observed average downstream speed is 66 mph, the queue-based speed proposes a 75-mph speed limit.

While the flow- and weather-based algorithms only update speed limits on a six-minute cycle, the queue-based component is calculated every 30 seconds and can update posted speed limits as often as once per minute. This is the minimum time it takes to propagate and verify a speed limit change (i.e., data flows from the RTDH where speed data is stored, to OpenTMS where the algorithm calculates the appropriate speed limit, to the specific VSL signs that post the speed, back into OpenTMS to verify the correct speed was posted, and back to the RTDH to store the speed limit change). This allows the system to respond as rapidly as possible to detected slowing.

Once a zone responds to a detected queue (or slower traffic in general), the transition-based component algorithm will propagate any speed limit decreases further upstream.

4.2.2. Determining Speed Limits for a Flow-Based System

The flow-based speed calculation proposes a speed limit based on the observed corridor flow and the maximum flow momentum. At low volumes, the flow-based algorithm could propose very high speed (e.g., at 780 vphpl, if the maximum flow momentum value is 78,000, it will propose 100 mph). At very high volumes, the algorithm could propose very low speed limits (e.g., at 2,450 vphpl, it will propose 30 mph). However, the overall flow-based VSL algorithm overrides these high and low values with the CDOT-defined maximum or minimum speed limits for the corridor.

The flow-based VSL algorithm, which initially considers the CDOT-defined maximum speed limit, compares the calculated flow-based speed (Chapter 4.2) with the transition-based speed (Chapter 4.1.1) and queue-based speed (Chapter 4.2.1). The lowest of these speed limits is then run through the full weather-based algorithm (Chapter 4.1) to determine the final posted speed limit for the corridor. A lower speed limit for overweight vehicles/trucks can also be included in the algorithm, so long as it does not exceed the CDOT-defined maximum overweight vehicle/truck speed limit (Chapter 4.1.2).

Figure 21 shows the process for determining the final flow-based speed limit, accounting for all previously described calculations, algorithm components, and necessary overrides.

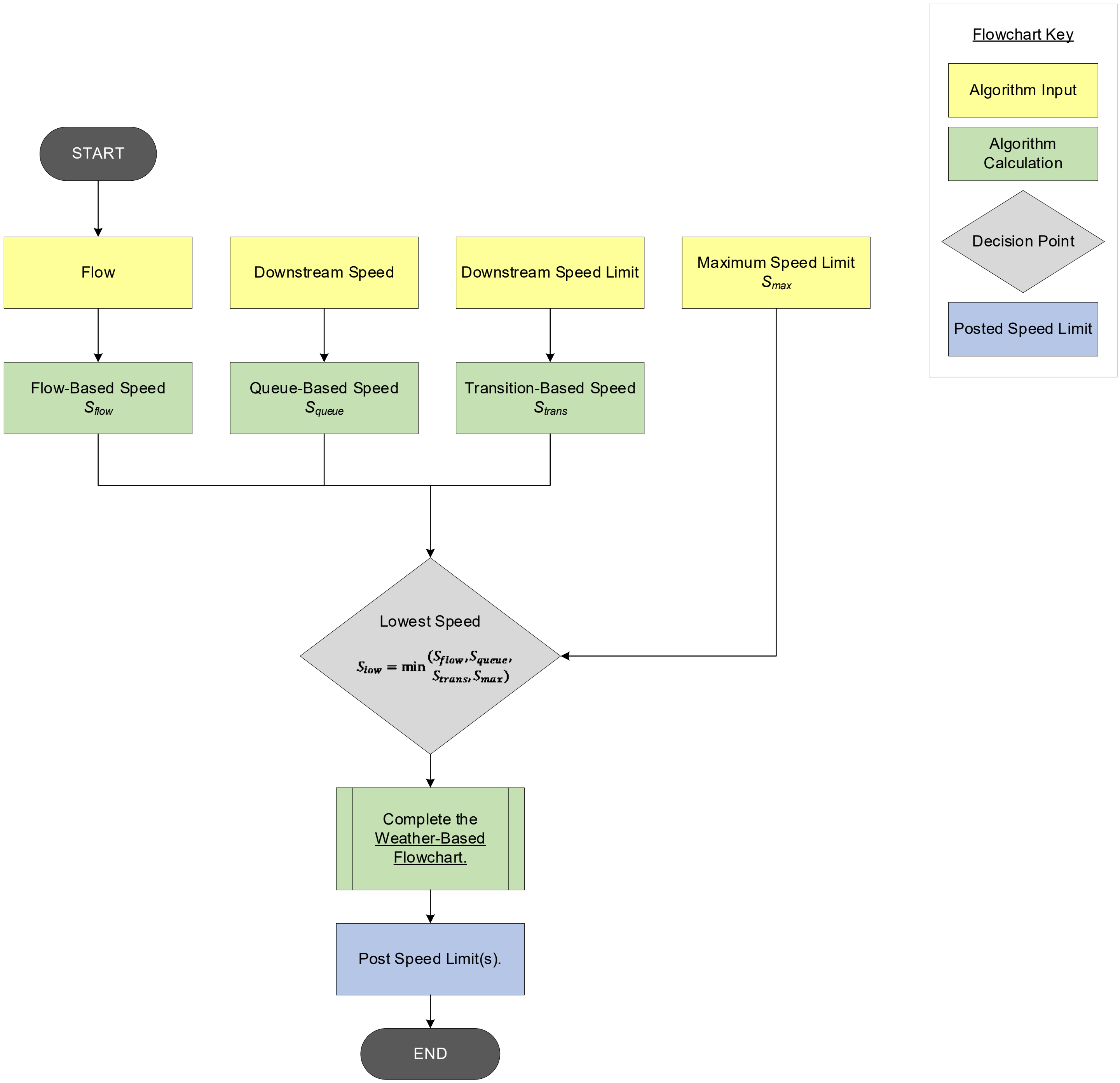


Figure 21. Flowchart for Flow-Based VSL Algorithm

This flowchart describes how the flow-based VSL algorithm determines which speed limit to post. The algorithm will calculate the speed autonomously based on user-defined inputs and real-time data.

4.3. Frequency of Measurements and Speed Limit Changes

The VSL algorithm resides in the RTDH and utilizes real-time data from MVRDs and RWISs that is collected through OpenTMS. OpenTMS polls the RWIS every 30 seconds, but the RWIS data only changes in 10-minute cycles. The minimum time for the RTDH and OpenTMS to push a speed limit change to the VSL signs and confirm that the new speed limit is posted is one minute. The VSL system generally updates speed limits once every six minutes or longer. Posted speed limits may be lowered as frequently as every one minute if the queue-based or transition-based components determine that a lower speed limit is necessary but may only be raised every six minutes.

Historic data shows that 30-second volume data can be very volatile. A change of plus or minus one vehicle in 30 seconds translates to a change of 120 vphpl since there are 120 30-second cycles in an hour. To avoid frequent and large speed limit changes being derived by the flow-based algorithm, the running average of the last 12 30-second cycles (six minutes) of volume data is used to determine the flow-based speed. Although a new flow-based speed is computed every 30 seconds, a new speed limit is only posted if the existing posted speed limit has been in place for at least six minutes. Similarly, the weather-based algorithm calculates weather-based speed every 30 seconds, but a new speed limit is only posted if the existing posted speed limit has been in place for at least six minutes.

5. VSL System Design

5.1. Preliminary/Conceptual Design

The conceptual design of a VSL project starts with defining the VSL corridor limits and establishing how the VSL system will function. The Project Team should complete the following preliminary design steps:

- Determine the total number of VSL zones within the corridor limits.
- Define the start and end MP for each VSL zone.
- Identify the required ITS devices for the selected VSL algorithm (weather-based or flow-based).
- Review the CDOT ITS Architecture Plan for all VSL-related devices.

These preliminary design steps will help the Project Team understand the infrastructure required to deploy a functioning VSL system. The Project Team will then need to investigate how the devices will communicate, what data they will collect, and how the data will be utilized to determine the appropriate posted speed limit. Understanding the VSL communication and data flow allows the Project Team to begin to identify all that is required for the system to operate as intended.

5.1.1. SEA System Functional Requirements

Once the preliminary questions outlined in Chapter 5.1 are answered, the Project Team can complete the **System Functional Requirements** SEA document utilizing the Programmatic VSL document as a framework (see Chapter 1.4).

5.1.2. SEA High Level System Design

Once the preliminary questions outlined in Chapter 5.1 are answered, the Project Team can also complete the **High Level System Design** SEA document utilizing the Programmatic VSL document as a framework (see Chapter 1.4).

5.2. Detailed System Design

5.2.1. ITS Device Requirements

VSL corridors can react to either weather conditions or a combination of both weather and traffic flow conditions. A weather-based VSL system requires RWISs. A flow-based VSL system requires RWISs and MVRDs. Either system can incorporate pan-tilt-zoom (PTZ) cameras or flashing warning beacons (FWB). These additional ITS devices should be evaluated during the project development process, as they provide significant benefit to the VSL system; however, they may be excluded due to project budget, environmental concerns, or other project priorities. Table 11 defines the purpose, mounting requirements, and maximum spacing for all ITS devices.

Table 11. ITS Device Requirements

This table describes the purpose of each required and recommended ITS device. Guidance is provided for mounting and spacing the devices in the corridor for optimal coverage.

ITS Device	Purpose	Device Mounting Requirements	Maximum Spacing
RWIS	RWISs provide real-time weather and road surface conditions. All RWISs must include friction and visibility sensors. **These units are required for all VSL systems.**	RWIS towers should be installed outside the clear zone. Remote, non-intrusive sensors should be placed on a separate pole closer to the roadway and located behind guardrail to minimize damage potential. If the RWIS tower cannot be installed outside the clear zone, it should be installed in a safe area and protected by guardrail. In this case, it should be located close enough to the roadway to allow non-intrusive infrared sensors to be installed on the same tower. RWISs should be installed in locations where the weather is frequently an issue and/or where roadway traction is an issue. Local maintenance patrols, CDOT ITS, CDOT Region Maintenance, and the State Meteorologist may be consulted in the identification of the installation location.	4 miles
MVRD	MVRDs measure traffic volumes and vehicle speeds. They can also classify vehicle types. **These units are required for flow-based VSL systems only.**	MVRDs should be pole-mounted 18–30 feet above the roadway. The exact height depends on the typical section of the VSL corridor, but the sensor must capture all lanes. Poles should be placed behind guardrail to help minimize damage potential.	½ mile
PTZ Camera	PTZ cameras allow visual observation of the VSL corridor for confirming weather and traffic conditions. They can also be used to confirm the posted speed on VSL signs, although it is not needed. **These units are highly recommended.**	PTZ cameras should be pole-mounted and located such that operators can view a VSL sign to confirm the posted speed limit. The maximum usable range for a PTZ camera is one mile in each direction but may need to be installed closer to clearly view the VSL sign. Additional PTZ cameras may be added at the project's discretion.	2 miles
FWB	FWBs provide enhanced warning to drivers in a VSL corridor. The beacons typically flash when the posted speed limit is reduced. **These units are highly recommended.** *Configuration of FWBs in the VSL algorithm is currently being developed (2023/2024). For the most recent details, see the SEA Programmatic templates.*	Warning beacons should be affixed to the top of VSL signs, per the MUTCD[10] requirements.	See VSL sign spacing in Chapter 5.2.3.

Every effort should be made to meet the device mounting and maximum spacing requirements. If an existing pole is not available to mount an ITS device, the project must include the installation of a pole in the Plans, Specifications, and Estimates (PS&E) package. The Project Team should discuss any need for exceptions to the spacing requirements with

[10] https://mutcd.fhwa.dot.gov/htm/2009/part4/part4l.htm

stakeholders and document decisions with justification in the **ConOps** SEA document, as it may require changes to the algorithm development process. All specifications for ITS devices can be found on the CDOT ITS specifications website.[11]

5.2.2. Algorithm Requirements

Once the VSL zones and ITS device quantities are finalized, the Project Team must define the corridor-specific inputs required for the VSL algorithm to operate.

If the VSL corridor is using a weather-based algorithm only (see Chapter 4.1), the following inputs are required:

- VSL zone name with starting and ending MP
- Steepest downgrade in each zone
- Minimum and maximum acceptable speed limits for dry weather conditions
- Minimum and maximum acceptable speed limits for adverse weather conditions
- Maximum acceptable speed limits for overweight vehicles/trucks, if applicable
- Location (MP), direction, and zone association for VSL signs and RWISs
- Coefficient of friction thresholds
- Lane topology information

If the VSL corridor is using a flow-based algorithm (see Chapter 4.2), these additional inputs are required:

- Corridor-specific SPF curve (“hockey stick” curve)
- Inflection point flow
- Location (MP), direction, and zone association for MVRDs

It is the responsibility of the Project Team to ensure the inputs align with CDOT’s VSL Algorithm Implementation Template[12] (see Appendix D), as these inputs may be subject to change. The algorithm also utilizes other inputs that are either defined by CDOT or gathered in real-time from deployed RWISs or MVRDs (see Chapter 6.1.2).

5.2.3. VSL Sign Requirements

The purpose of a VSL system is to adjust the posted speed limit in the corridor to meet changing road conditions automatically. This requires that VSL signs be spaced closely to improve driver compliance, provide regular reminders of current safe speed limits, and step down the speed limit appropriately in advance of unfavorable road conditions or queuing. A VSL system may be installed in both directions on a roadway or in a single direction. A VSL system fully replaces the static posted speed limit signs in a corridor.

Per the MUTCD, speed limit signs must be installed downstream of major intersections and at other locations where necessary to remind road users of the speed limit. VSL signs are typically spaced at least every mile but may be spaced more frequently (if funding is available to accommodate the increased maintenance costs associated with additional VSL signs). For example, signs can be installed at half-mile spacings upstream of known bottlenecks to help step down traffic that is approaching congested areas. Other considerations for more frequent signage may include locations with higher crash rates, complex roadway geometry, or steep grades. Exact sign locations and spacing can also vary to accommodate available power or communications. The final sign spacing should be determined through the project development process.

According to the MUTCD, double-posting regulatory signs along the outside shoulder of the roadway and in the median can enhance the sign’s visibility. Because VSL signs are regulatory, double posting VSL signs should be considered when increased conspicuity would be especially beneficial (e.g., downstream of interchange ramps and major access points on freeways and multi-lane highways). Double-posted VSL signs should be aligned so they are directly across from each other, whenever feasible. The maximum offset distance for double-posted VSL signs in the same direction should be discussed with CDOT Region Traffic and should consider maintenance access needs. It is recommended that signs be double-posted in locations that do not require a lane closure for maintenance and have sufficient shoulder width to minimize the potential of damage from vehicles. An alternative to double-posted VSL signs is overhead signage. Overhead VSL signs should be on a dedicated structure utilizing CDOT VSL signage above each lane and are intended to

[11] https://www.codot.gov/programs/intelligent-transportation-systems/specifications

[12] https://docs.google.com/spreadsheets/d/1mefPHbvZuORf-I-GIcs94x6e8W1BR3vtwGE1aWOTYaU/edit#gid=1544515188

be used when a different speed may be posted for each lane, such as with express lanes. The Project Team must coordinate with CDOT ITS and CDOT ODM to understand the current capabilities and limitations of the VSL algorithm programming with respect to overhead VSL signs and must provide clear justification for overhead signage through the SEA documentation. CDOT does not allow the posting of regulatory speed limits on VMSs.

VSL signs consist of an aluminum static speed limit panel with a full-matrix LED panel to display the two-digit speed limit. Character heights, sign size, color reflectivity, and illumination must conform to the CDOT standards and specifications. The LED panel of standard CDOT VSL signs uses white numbers on a black background. The size of a VSL sign will depend on if a separate speed limit for overweight vehicles/trucks is established. Single VSL signs are four feet wide and five feet tall, and dual VSL signs used for posting passenger vehicle and overweight vehicle/truck speed limits are four feet wide and 10 feet tall. The height of the VSL signs above the paved surface, which determines signpost pay length, needs to meet CDOT standard sign heights above the roadway per CDOT Standards. For project details and specifications examples, see Appendix E.

Each VSL sign requires a sign controller, dedicated fiber communication, and an uninterruptible power supply (UPS) capable of network connectivity and providing eight hours of battery backup power. This allows the VSL sign to maintain a posted speed limit for the corridor during a power failure. CDOT ITS Specifications for VSL signs and the UPS backup system can be found on the [CDOT ITS Specifications and Standard Procedures website](https://www.codot.gov/programs/intelligent-transportation-systems/specifications).[13]

A supplemental sign that identifies the beginning of a VSL corridor should be installed upstream of the first VSL sign to notify road users they are entering a VSL corridor and provide advance warning of potentially lowered speed limits. This sign should be statically posted approximately one half to one mile in advance of the first VSL sign and should also be considered at major intersections and ramps within the VSL corridor. A supplemental sign may be installed to denote the end of the VSL corridor as well. Figure 22 shows an example of the MUTCD supplemental signs for use upstream and downstream of the VSL corridor.

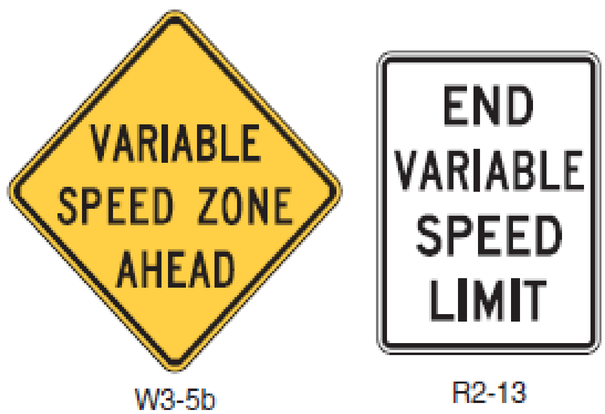


Figure 22: Supplemental Sign Examples for VSL Corridors

The use of supplemental signs within the VSL corridor should be discussed with CDOT Region Traffic. If a VMS already exists one half to one mile upstream of the first VSL sign, it may be used to post a message about the upcoming VSL zone, but a new VMS should not be installed for this sole purpose. For additional guidance on the use of VMSs, see CDOT's [VMS Guidelines.](https://www.codot.gov/programs/intelligent-transportation-systems/assets_its/updated-colorado-vms-guidelines.pdf)[14]

5.2.4. System Communication and Power

Because VSL systems require secure, continuous communication to ensure that the posted speed limit is appropriate for changing conditions in the corridor, fiber optic communication is required for VSL systems.

The Project Team must submit a Network Design and Fiber Assignment request via email to CDOT ITS (cdot_its_support@state.co.us)[15] as soon as device locations and splicing details are known. CDOT ITS will perform an

[13] https://www.codot.gov/programs/intelligent-transportation-systems/specifications

[14] https://www.codot.gov/programs/intelligent-transportation-systems/assets_its/updated-colorado-vms-guidelines.pdf

[15] cdot_its_support@state.co.us

audit that identifies the existing fiber optic communication hardware, node building equipment, and availability of connections for the VSL system. If the audit determines that additional communications or network hardware is required to implement a VSL system, the necessary equipment will need to be added to the VSL project PS&E package. It is important to note that the network design and fiber assignment request can take up to two months to complete. The Project Team is responsible for creating the network and splicing design drawings and plan sheets, which are required as part of the **Detailed Level System Design** SEA document (see Chapter 5.2.6).

If the CDOT ITS audit determines that the VSL corridor does not have available or sufficient fiber capacity, the CDOT PM must further coordinate with CDOT ITS to install new fiber as part of the project scope.

In addition to evaluating communications, the Project Team must identify the availability and locations of hard-wired electrical power sources in the corridor for all devices. Proposed additional power sources and relocations must be coordinated with CDOT ITS and the utility provider. During design, the CDOT PM must utilize the utility account matrix to provide CDOT ITS with the meter number and address for each existing electrical meter pedestal, including any removals and relocations, in accordance with PD 90.1. This information is also required as a part of the **Maintenance Plan** SEA document (see Chapter 5.3.2). During construction, the CDOT PM must utilize the utility account matrix to submit meter numbers for any newly installed electrical pedestals or any changes to the design to CDOT ITS after installation is complete, in accordance with CDOT PD 90.1. The CDOT PM must also work with the CDOT Region Utility Account Coordinator to ensure all billing is set up properly prior to project closeout.

5.2.5. Other Design Considerations

CDOT allows the modification of posted speed limits on roadways to address recurring safety conditions or applications that differ from traditional VSL corridors. Regardless of the application, appropriate posted speed limits must be established based on CDOT policies and Colorado State Law. Guidance is provided below on VSLs for chain stations, express lanes, and stand-alone safety applications.

VSL for Chain Stations

Posted speed limits around formal chain station locations may be reduced to enhance safety for drivers that are installing required traction devices. The typical speed limit reduction for chain stations is 10 mph and is only used when the chain law restriction is put into effect. Colorado's Chain Law website[16] should be referenced for the most up-to-date information. The design decision to install a VSL for chain stations must be made in coordination with CDOT ITS and CDOT Region Traffic, have a clear traffic safety justification, and take into consideration the availability of fiber, power, and local maintenance staff capabilities. VSLs should not be installed at a chain station if the chain station is within a VSL corridor.

VSL for Express Lanes

A VSL system can be modified to post different speed limits for express lanes and general-purpose lanes; however, the Project Team must coordinate with CDOT ITS and CDOT ODM to understand the current capabilities and limitations of the VSL algorithm programming. In order to post different speed limits for different lanes, a VSL corridor must utilize an overhead structure with a VSL sign above each lane, and the signage must be labeled to indicate the express lane. Additional MVRDs may be necessary to maintain full coverage of the express lane. When different speed limits are posted for express lanes and general-purpose lanes, it is strongly recommended that express lanes be physically separated or separated by a striped buffer from the general-purpose lanes. If an overhead structure is not used for VSLs, then only a single speed limit may be used for both express lanes and general purpose lanes.

Corridors with express lanes that are not separated from general-purpose lanes (e.g., I-70 Mountain Express Lanes, I-25 North Express Lanes between 84th Avenue and 120th Avenue) should not provide separate VSL signs for express lanes. As technology evolves and devices become more reliable, system requirements may be adjusted accordingly. The Project Team should discuss the operations of VSL systems for express lanes with relevant stakeholders and implement based on a safety analysis and engineering judgment for each project.

VSL for Specific Safety Issues

Posted speed limits may be reduced to address various known safety issues on a roadway. Specific safety issues could include recurring limited visibility, high wind conditions, or icing conditions; bridges that freeze regularly; or locations that warrant reduced nighttime speed limits. These stand-alone VSL applications typically require CDOT RTO to modify the posted speed limit on VSL signs based on established internal CDOT ITS standard operating procedures or when notified

[16] https://www.codot.gov/travel/colorado-chain-law

by CDOT Region Maintenance. The authorized speed limit reduction should be studied and approved by CDOT HQ Traffic and identified in a VSL Corridor Justification Memorandum, as defined in Chapter 3.5 of these guidelines. The installation and application of these stand-alone VSL devices must be closely coordinated with CDOT ITS and vetted through the standard SEA process (i.e., the Programmatic VSL SEA documents cannot be utilized in this kind of scenario).

5.2.6. SEA Detailed Level System Design

Once the project has progressed to approximately 90% of the final design, the Project Team can complete the **Detailed Level System Design** SEA document utilizing the Programmatic VSL document as a framework (see Chapter 1.4). The following information is required for the document submission:

- Device type and compliance with the Quality Manufacturers and Products (QMP)
  - If a device is not on the QMP, then compliance with the Colorado Information Security Policies (CISPs) must be verified.
- Device location (stationing and MP)
- Device communication method and verification of system capacity
- Additional fiber or network gear that is needed for device communication
- All required modifications to OpenTMS software or the VSL algorithm
- Network and splicing diagrams with project plan sheets
- VSL algorithm inputs (as defined in Chapter 6.1.2)
- VSL Corridor Justification Memorandum (as defined in Chapter 3.5)

5.2.7. SEA Testing and Integration

After approval of the **Detailed Level System Design** SEA document, the Project Team can complete the **Testing and Integration** SEA document, utilizing the Programmatic VSL document as a framework (see Chapter 1.4). This document uses the testing procedures and deliverables checklists for all ITS devices in the ITS Construction Testing, Integration, and Acceptance Requirements Specification[17] to ensure the smooth integration of the VSL System with the CDOT ITS Network during construction. The information in the **Testing and Integration** document should also be used by the Project Team to modify the Testing and Acceptance project special provision, as needed (see Chapter 5.4.1).

5.3. System Life Cycle Planning

5.3.1. Continued Stakeholder Engagement

It is important for projects to consider and plan for the long-term operations and maintenance of the VSL system. The project stakeholders identified earlier in Chapter 3.6 should continue to be engaged in order for the Project Team to identify agreements that need to be executed, standard operating procedures, maintenance requirements, and any potential necessary design changes. For instance, law enforcement stakeholders need to be aware of a new VSL corridor and may identify the need to design and construct pullouts, both for the construction period and long-term deployment, to allow them to operate safely in the corridor. Stakeholders in CDOT RTO may identify key considerations for posting information to devices.

5.3.2. SEA Agreements with Partners, Standard Operating Procedures, and Maintenance Plan

As stakeholders continue to be engaged, the Project Team can complete the non-sequential documents in the SEA process. The non-sequential **Agreements with Partners**, **Standard Operating Procedures**, and **Maintenance Plan** SEA documents may be submitted at any time by the Project Team following approval of the **ConOps** SEA document. These documents should be developed utilizing the Programmatic VSL document as a framework (see Chapter 1.4). When developing these three SEA documents, the following elements should be clearly defined:

- Identification of access for maintenance and repair activities
- Identification of all operations and maintenance activities (for more on what this might include, see Chapter 7)
- Identification of personnel responsible for operation and maintenance, such as CDOT RTO and CDOT Region Traffic
- Identification of documents used in operations and maintenance, such as relevant agreements, policy directives, system configuration documentation, and device or communication manuals
- Identification of funding sources for ongoing operations and maintenance

[17] https://drive.google.com/file/d/1ekq2bmFyYDOsT4x-iD_yGWSVg7LYE2l5/view

- Identification of required human resources and facilities, including tools and personnel training
- Identification of personnel for annual algorithm verification, which must be a collaborative effort with CDOT Region Traffic, CDOT ITS, and CDOT ODM

The description of operations and maintenance activities should cover both preventive and reactive scenarios. Activities should include, but are not limited to, regular cleaning of VSL signs and ITS equipment, repair of all VSL-related equipment, validation of the algorithm, and regular checks with data collection for system health and performance monitoring. The life expectancy of the VSL system should be considered, with a plan for end-of-life replacement and upgrade processes.

5.4. Final Design Details

5.4.1. Project Specifications

The latest version of the project specifications for ITS devices (i.e., MVRDs, RWISs, PTZ cameras, and VSL signs) must be incorporated into the project special provisions in the PS&E package. These documents can be obtained by the Project Team from the CDOT ITS Specifications and Standard Procedures website[18] or by direct coordination with CDOT ITS. It is critical for all devices to conform to the project specifications, as they provide detailed procedures and requirements for device integration and testing.

All testing and integration requirements should also be detailed in the appropriate project special provisions to ensure responsibilities are clearly defined for the construction period. For instance, the specified warranty period that commences after the validation period is required to ensure that the Contractor maintains and replaces all ITS devices, as needed, during the system testing process (see also Chapter 6.1.1). The Project Team should consider adding milestones and working days to the commencement and completion project specification stipulating that the Contractor is responsible until VSL testing and integration is complete and the system completes the Go-Live process.

5.4.2. Plan Sheet Requirements

Design of the VSL system may be incorporated in roadway, signing and striping, ITS, utility, or other relevant subsets of the final plans. Cross-section drawings should be included where applicable. This installation of VSL structures is only required when existing structures are not present in the desired device locations. The final project plan sheets must include installation of guardrail and end sections to protect VSL signs and ITS devices, as well as installation of additional poles and foundations to mount VSL devices. Access for maintenance and repair at each site must be considered during the design, and documented in the plan sheets wherever possible. The final plan quantities should consider the need for additional traffic control days during construction and initial VSL testing, such as during the 30-day burn-in process for ITS devices (see Chapter 6.1).

5.4.3. SEA Validation Plan

The Project Team must complete the **Validation Plan** SEA document utilizing the Programmatic VSL document as a framework (see Chapter 1.4). The **Validation Plan** can be completed any time after approval of the **ConOps** SEA document but is typically completed as the last SEA document. The **Validation Plan** verifies that the selected stakeholder wants and needs were addressed in the VSL system design, and it captures all significant design changes that have occurred during the project development process. As such, this document is typically submitted after all other SEA documents have been approved and signifies completion of the SEA process.

[18] https://www.codot.gov/programs/intelligent-transportation-systems/specifications

6. VSL System Configuration and Testing

6.1. Overview of Construction Timeline

By the time a project moves to construction, the VSL system design is finalized, and all SEA documents are complete and accepted. During and after the construction phase, the Contractor, CDOT PM, CDOT ITS, CDOT Region Traffic, CDOT ITS (OpenTMS Team), and CDOT ODM (RTDH Team) use the project specifications and the ITS Construction Testing, Integration, and Acceptance Requirements Specification[19] to ensure the VSL system works as intended. Table 12 shows the key milestones for configuring, testing, and integrating the VSL system.

Table 12. VSL System Construction Timeline

This table outlines the sequential tasks completed by the Project Team, Contractor, or CDOT for a VSL corridor to be tested and integrated. These steps are vital to ensuring the VSL system is ready for deployment upon construction completion.

Step	Description	Associated Timeline
1	Project Team provides list of devices, algorithm inputs, and zone information to CDOT ITS.	During the design phase/SEA process
2	Contractor installs all VSL-related devices (i.e., RWISs, MVRDs, PTZ cameras, FWBs, and VSL signs) and submits 1411s.	*Contractor must notify CDOT ITS 2 weeks prior to starting 1411 submittals*
3	CDOT ITS processes all submitted 1411s in App Sheet and initiates VSL corridor configuration.	Up to 30 days per 1411
4	CDOT ITS runs daily EFRs to identify device issues during a 30-day burn-in test procedure. Contractor responds within 24 hours to troubleshoot and correct any faults.	30 days *(Can occur concurrently with steps 5–6.)*
5	CDOT ITS and CDOT ODM verify OpenTMS/RTDH device mappings and integrate the applications.	2 months *(Can occur concurrently with step 4.)*
6	Soft deployment to produce speed recommendations.	
7	CDOT Region Traffic conducts dim testing with support from CDOT ITS and CDOT ODM to ensure the correct speed limits are being produced and displayed.	3 months
8	CDOT Region Traffic or CDOT PM provides a Go-Live date with input from CDOT HQ Traffic, CDOT ITS, CDOT ODM, and CDOT PIO.	After all testing is complete

Although most steps in the VSL system configuration are intended to be sequential, the VSL algorithm development in OpenTMS and the RTDH can occur concurrently with the 30-day burn-in testing of VSL devices.

6.1.1. Responsibilities during Construction

The Contractor is responsible for maintaining all ITS devices during the initial VSL system testing and configuration process, per the project PS&E package. Temporary power sources are not allowed during ITS device testing to ensure devices are not damaged and manufacturer warranties are not voided. If a device is inoperable and must be replaced, the Contractor is liable until the VSL system completes testing and integration and the Go-Live process is complete. In addition, the Contractor is required to maintain and replace all ITS devices, as needed, during the specified warranty period after Go-Live (see also Chapter 5.4.1).

The Contractor is responsible for the submittal of CDOT's 1411 form for each device used in the VSL system. This form must be submitted to CDOT ITS via App Sheet to ensure that each device is properly identified and integrated in the CDOT ITS Network. These submittals and the coordination to integrate the new ITS devices should be considered in the construction project schedule.

[19] https://docs.google.com/document/d/1xeFqznH7Q3n4t_lpTd5c7U8W7ievFM__/edit

6.1.2. OpenTMS and RTDH Integration

Table 13 summarizes all data that is required for configuring the VSL corridor in OpenTMS and the RTDH. All information required for the algorithm is determined by the Project Team, collected in real time by ITS devices, calculated from the device data, or pre-defined by CDOT. To provide redundancy, accuracy, and resiliency to the algorithm, multiple ITS devices within the specified range have their measurements averaged as part of the calculation. As the algorithm is refined through VSL system deployments, the information required for the algorithm is subject to change. The Project Team must confirm that the inputs align with CDOT's VSL Algorithm Implementation Input Template[20] (see Appendix D), as these inputs may be subject to change.

Table 13. Required Algorithm Inputs

This table summarizes all inputs that are needed to operate the VSL system in OpenTMS and the RTDH. These inputs extend beyond those required by the Project Team, as defined in Chapter 5.

OpenTMS Inputs	RTDH Inputs
For all VSL systems (regardless of algorithm type): • Device name (from CDOT 1411 form) • Device locations (MP) • Sign name and type • Minimum and maximum speed for passenger vehicles (CDOT-defined) • Minimum and maximum speed for overweight vehicles/trucks (CDOT-defined) • Corridor start and end mile marker • Lane topology information	For all VSL systems (regardless of algorithm type): • VSL zone name • Zone starting and ending MP • Maximum speed for passenger cars and overweight vehicles/trucks • Minimum speed for passenger cars and overweight vehicles/trucks during dry conditions • Minimum speed for passenger cars and overweight vehicles/trucks during adverse conditions • VSL sign name, location (MP), direction, and zone association • VSL sign dual indicator (passenger car only, both passenger car and overweight vehicle/truck)
	For weather-based VSL systems: • Steepest downgrade • RWIS name, location (MP), direction, and zone association
	For flow-based VSL systems: • Inflection point volume • MVRD name, location (MP), direction, and zone association

[20] https://docs.google.com/spreadsheets/d/1mefPHbvZuORf-I-GIcs94x6e8W1BR3vtwGE1aWOTYaU/edit#gid=1544515188

7. VSL System Long-Term Operations and Maintenance

The effectiveness of a VSL system during construction, initial testing, and long-term operations is dependent on coordination between a variety of stakeholders. Whether at the project, CDOT Region, or State level, each stakeholder has defined responsibilities that are crucial for the success of the overall VSL corridor.

Project Team is responsible for:

- Identifying primary system operations during the SEA and project planning process.
- Discussing system operations with CDOT Region Traffic and CDOT RTO.
- Identifying the parties responsible for replacing VSL assets and documenting these responsibilities in the Maintenance Plan SEA document (e.g., CDOT ITS, CDOT Region Traffic, CDOT HQ Traffic, etc.).

CDOT HQ Traffic is responsible for:

- Sharing the results of any post-deployment studies with each CDOT Region and CDOT ITS to learn from previous VSL corridors.

CDOT ITS is responsible for:

- Completing the Network Design and Fiber Assignment request from the CDOT PM during the project design process.
- Performing final inspection and acceptance of ITS devices installed by construction projects along State highways. (Acceptance is only for the device and integration, not for the functionality of the algorithm.)
- Coordinating project work inside tunnels or near tunnel approaches.
- Monitoring the health of the CDOT ITS Network and functionality of the individual CDOT ITS-owned devices within the VSL system.
- Tracking identified or reported device and network issues.
- Providing initial remote troubleshooting of VSL device, network switch, and communication issues.
- Escalating device issues for equipment repair and dispatching maintenance teams, as needed.
- Providing corrective, scheduled, and preventive maintenance for all ITS devices and auxiliary equipment (network switches, communication cables, equipment cabinets, and structures used to mount ITS devices) that are part of VSL systems across the State.
    - For VSL corridors located more than two hours (with traffic delays) from the CDOT ITS Maintenance Patrol Yards in Golden and Grand Junction, CDOT ITS may request support from CDOT Region Traffic to provide emergency maintenance.
- Providing temporary traffic control needed for safe site access for device maintenance and operations.
- Ensuring that each ITS device can provide data to be archived in the ITS device database that is accessed by the VSL algorithm.
- Managing licensing and software updates for VSL signs and ITS devices.
- Updating specific ITS device drivers and ensuring that each updated device maintains communication with the CDOT ITS Network.

The CDOT ODM (RTDH Team) is responsible for:

- Generating speed recommendations for VSL signs and sharing a report of these recommendations with Region Traffic Engineers.
- Maintaining a database for archiving the date and time period that speed limit changes were posted in the VSL corridor.
    - Maintaining a log of each speed limit change and the corridor conditions that dictated the change.
    - Storing the speed limit changes in the Advanced Data Analytics Platform (ADAP).
- Providing VSL system data storage and reporting that is accessed by the VSL algorithm.
- Providing information for CORA requests if a speeding citation issued by law enforcement is challenged in a court of law (see Chapter 8.3.1).
- Generating a report with the status of VSL devices and VSL algorithm at the time of citation.

CDOT RTO is responsible for:

- Observing VSL corridors and checking the visibility and correct display of the posted VSL speed limit (only applies to corridors where cameras for viewing VSL speed limit signs are included).
- Submitting tickets through OpenTMS when issues are identified.

- Managing VSL system operations manually and through daily automated device health checks (depending on VSL corridor location).
- Monitoring the VSL system as defined in the **Standard Operating Procedures** SEA document for the project.
  - Monitoring the system daily as well as upon a change to the posted speed limits.
  - Monitoring functionality and operational status of VSL signs.
  - Monitoring visibility and correct display of posted speed limits (only applies to corridors where cameras for viewing VSL speed limit signs are included).
- Submitting tickets via email to CDOT ITS (cdot_its_support@state.co.us)[21] when system issues are found.

CDOT Region Traffic is responsible for:

- Determining the appropriate frequency for monitoring VSL system status and validating the VSL algorithm for each VSL corridor within the CDOT Region.
- Monitoring the VSL system status and coordinating necessary repairs with CDOT ITS by submitting a ticket via email to CDOT ITS (cdot_its_support@state.co.us).[22]
- Monitoring the performance and effectiveness of VSL systems installed in their respective CDOT Regions and providing VSL system status reports to CDOT ITS.
- Validating that the VSL algorithm is querying device data and producing the correct speed limit recommendations based on device data.
  - Initiating manual override to post the static speed limit if the VSL system is malfunctioning by submitting a ticket via email to CDOT ITS (cdot_its_support@state.co.us).[23]
- Validating all traffic data being input to the VSL system algorithm and the speed limits being output.
  - Providing notification for any traffic data issues by submitting a ticket via email to CDOT ITS (cdot_its_support@state.co.us).[24]
- Monitoring conditions after the VSL system is implemented and conducting post-deployment studies to measure effectiveness (on an as-needed basis as determined by CDOT Region Traffic for each VSL corridor). This should be done in coordination with CDOT HQ Traffic.
  - Identifying changes needed for the VSL system itself or related law enforcement efforts for the system to operate effectively.
- Sharing the engineering speed study with Law Enforcement.

CDOT Region Maintenance is responsible for:

- Providing corrective, scheduled, and preventive maintenance of roadway, right-of-way (ROW) area, static signs, and striping.
- Supporting CDOT ITS in providing emergency maintenance for ITS devices and auxiliary equipment that are part of VSL systems located more than two hours (with traffic delays) from the CDOT ITS Maintenance Patrol Yards in Golden and Grand Junction.
- Providing support to CDOT ITS Field Operations as requested for major infrastructure needs such as light standards, signposts, and electrical power.
- Providing temporary traffic control needed for safe site access for device maintenance and operations.
- Removing snow as needed for CDOT ITS Field Operations to safely access devices.
- Supporting CDOT ITS with temporary traffic control needed for safe site access for emergency device maintenance and operations.

Law Enforcement is responsible for:

- Reviewing the engineering speed study provided by CDOT.
- Accessing the VSL system, in coordination with CDOT HQ Traffic and CDOT ODM (RTDH Team), to request the date and time period that speed limit changes were posted in the VSL corridor.
- Enforcing static and variable speed limits.

---

[21] cdot_its_support@state.co.us

[22] Ibid.

[23] Ibid.

[24] Ibid.

7.1. Data Archival

For VSL corridors, there is a need to quickly query time-stamped, VSL-posted speed limits to enforce citations being challenged in a court of law. There is also a need to query data to establish roadway conditions that require a speed limit change. The CDOT ODM (RTDH Team) is responsible for establishing an archival system for data, and CDOT is responsible for establishing how long the data will be maintained in the archive.

7.2. Maintenance

7.2.1. Response Times for Device and System Outages

It is important to quickly resolve device outages in a VSL system due to their role in establishing real-time regulatory speed limits on a roadway. Although the ITS devices that provide real-time data to the VSL algorithm (i.e., MVRDs and RWISs) are not regulatory, they greatly impact the reliability and accuracy of the VSL system. Device outages that directly impact the posted speed limit in a VSL corridor require immediate resolution, as do any system failures (e.g., corridor-wide application programming interface (API) failure), while other outages may allow a more lenient response time. The maintenance staff response times for VSL corridor repairs will vary depending on location, road conditions, and available CDOT ITS resources.

CDOT ITS is responsible for providing emergency maintenance for all ITS devices and auxiliary equipment (network switches, communication cables, equipment cabinets, and structures used to mount ITS devices) that are part of VSL systems across the State, but when VSL corridors are located more than two hours (with traffic delays) from the CDOT ITS Maintenance Patrol Yards in Golden and Grand Junction, CDOT ITS may request support from CDOT Region Traffic to provide emergency maintenance. In the event of a device outage, establishing communications between CDOT RTO and CDOT Region Traffic is critical for reporting VSL system/ITS device health and ensuring efficient response time for repairs. Automated EFRs are sent via email to CDOT ITS and CDOT Region Traffic. The required method for reporting device failures not identified in the EFR is to submit a ticket via email to CDOT ITS (cdot_its_support@state.co.us).[25]

During the design phase, the Project Team should have collaborated with CDOT Region Traffic, CDOT RTO, and CDOT ITS to document all maintenance concerns, including required response times for device outages, in the project-specific **Standard Operating Procedures** SEA document (see Chapter 5.3.2).

7.2.2. Ongoing Testing and Algorithm Review

CDOT Region Traffic should proactively coordinate with CDOT ITS, CDOT HQ Traffic, and CDOT ODM to review the algorithm in order to ensure the VSL system is performing as intended, with speed limits being adjusted appropriately based on the VSL data. Algorithm reviews should be conducted 12 months after the VSL system goes live and again prior to device retirement and replacement, with additional reviews conducted at a frequency to be determined by CDOT Region Traffic. CDOT HQ Traffic has allocated $15,000 for annual testing of the algorithm and any necessary updates. In addition to the algorithm review, periodic software upgrades are required for individual ITS devices. Thorough testing should be conducted to ensure all devices are communicating in OpenTMS and the RTDH after upgrading the software and drivers, as it is unknown how these upgrades may impact the VSL system.

7.2.3. Post-Deployment VSL Corridor Study

The VSL system should be evaluated once sufficient crash data is available to measure its effectiveness in meeting the safety goals of the corridor. During a project's SEA process, CDOT Region Traffic will determine a plan for when a post-deployment evaluation should be conducted. A post-deployment study should assess the safety impacts as crash data becomes available and evaluate if changes are necessary to the VSL system itself, law enforcement efforts, or public education. Post-deployment studies will be initiated by CDOT Region Traffic in coordination with CDOT HQ Traffic. CDOT HQ Traffic will share the results of any studies with all CDOT Regions and CDOT ITS to learn from previous deployments.

7.2.4. Device Retirement and Replacement

CDOT ITS is responsible for replacing ITS devices throughout the State according to the Transportation Asset Management Plan (TAMP). A pre-determined replacement timeframe has been established for ITS devices included in the VSL system based on the average lifespan of each device. The expected lifespan, replacement cost, replacement priority, and anticipated funding needs for each ITS device should already have been documented by the Project Team in the **Maintenance Plan** SEA document (see Chapter 5.3.2).

[25] Ibid.

Because CDOT ITS does not receive annual funding for the proactive replacement of these signs, replacement responsibilities and funding sources should also be identified and documented in the **Maintenance Plan** SEA document. If CDOT ITS does not have adequate funds to replace devices that have reached the useful life threshold, CDOT ITS must work with CDOT Region Traffic to either identify alternative funding sources or discuss removal of the system.

8. Public Information and Law Enforcement

8.1. Roles and Responsibilities

The purpose of the VSL system is to slow traffic to mitigate crashes during adverse weather or flow conditions. Driver compliance to the newly posted speed limit is critical for both the safety and efficiency of the VSL corridor, but it requires robust public information outreach to educate drivers. Public outreach requires close coordination with CDOT stakeholders to ensure that the information presented to travelers is accurate and addresses any concerns.

The CDOT PM is a critical stakeholder for public education during the project design and construction. The CDOT PM is responsible for:

- Justifying the implementation of a VSL system in the proposed corridor due to existing safety issues, consistent weather issues, low visibility, recurring congestion, or a combination thereof.
- Explaining how the VSL system addresses safety concerns in the corridor for public messaging purposes.
- Coordinating corridor-specific talking points with CDOT PIO and the CDOT Region Customer Service Team.
- Providing answers to technical questions that may arise during public information outreach.
- Providing information that can supplement standard VSL messaging to the public.
- Distributing pictures of VSL signs or videos demonstrating how the system operates. The videos should demonstrate how posted speed limits change throughout the corridor to address weather or traffic conditions.

CDOT PIO is another stakeholder that manages public outreach prior to implementation, during live testing, and following construction of the VSL corridor. CDOT PIO is responsible for:

- Leading coordination at both the Region and Statewide levels for the safety strategic planning initiative.
- Developing a messaging strategy to inform the public of VSL corridors.
- Sharing all information and corridor-specific talking points with the CDOT Region Customer Service Team.
- Pushing information to the public via news outlets or social media.

During and after construction, the CDOT Region Customer Service Team communicates directly with the traveling public. The CDOT Region Customer Service Team is responsible for:

- Responding to or redirecting questions from the traveling public that come in via phone or email.
- Coordinating with CDOT HQ Traffic or the CDOT PM as needed for questions requiring technical support.

8.2. Education for the Traveling Public

It is important to educate the traveling public about VSL corridors prior to implementation. An effective messaging strategy and outreach not only informs the public of upcoming changes, but also educates drivers on the importance of VSL systems and driver behavior with changing speed limits. While much of this messaging is standard information used to describe all CDOT VSL systems, each corridor may have safety or traffic flow characteristics that are unique and require a more targeted messaging strategy.

As the CDOT PM analyzes the corridor, they are responsible for identifying specific locations with crash patterns, existing safety concerns, or hazardous roadway conditions during severe weather. These key locations and characteristics can then be used to develop a corridor-specific outreach to the public. The CDOT PM should coordinate closely with CDOT PIO and the CDOT Region Customer Service Team throughout the project development process to tailor the public information messages. Messaging specific to the corridor can be developed using the results of the VSL Feasibility Workshop detailed in Chapter 2 and VSL Safety Assessment in Chapter 3.

In addition to analyzing the corridor characteristics, it is important for the CDOT PM and CDOT PIO to anticipate questions from the traveling public. The questions and sample responses shown in Table 14 should be considered to develop an effective messaging strategy.

Table 14. Sample Questions and Responses for VSL System Public Messaging
This table provides responses to commonly asked questions about VSL.

Anticipated Question	Sample Response
Why is the speed limit being reduced when there is no traffic around me?	• CDOT's VSL system is designed to be responsive to changing weather and traffic conditions to address travel conditions in real time. • The VSL system reduces the posted highway speed limit to reflect the appropriate speed for current roadway conditions caused by extreme weather, including low visibility and wet or icy pavement conditions. • The VSL system slows drivers down before they run into unforeseen congestion, reducing the potential for rear-end crashes. • Reducing speeds helps to safely dissipate and maintain stable traffic flow, improving the efficiency of the highway facility. • In high-traffic-volume or dense-traffic-flow conditions, the VSL system adjusts the speed limit to prevent crashes as the headway between vehicles is reduced at high speeds.
How should drivers behave and why?	• When drivers comply with posted speed limits, it improves the safety of the traveling public by protecting them from unknown or changing roadway conditions. • VSL signs are regulatory, so law enforcement can issue traffic citations.
Why is there VSL in this corridor?	• VSL corridors can be implemented in highway corridors with recurring weather patterns that limit visibility (e.g., sun glare, blizzard conditions, fog conditions) or cause other hazardous road conditions. Reducing speed limits in these corridors ensures that drivers have the appropriate sight and braking distance for their traveling speeds. • VSL corridors are selected through a specific safety analysis process, which uses recent crash data to identify specific crash patterns or traffic flow conditions that can be mitigated by changing the posted speed limit when these specific circumstances exist.
What will the public see in a VSL corridor?	• The public will see advanced permanent signs in both directions informing drivers that they are entering and exiting the VSL corridor. • The public will see VSL signs that show the current speed limit using changeable LED displays, which display white numbers on a black background. • The public may see flashing beacons above VSL signs alerting drivers when the speed limit is reduced. • The public may see additional sensors or cameras placed throughout the corridor that are used to inform the VSL algorithm.

8.2.1. Public Outreach Methods and Timeline

It is important for CDOT to provide public information through a variety of media sources to reach as much of the traveling public as possible. Information can be provided to the public using public service announcements (PSAs) on news outlets, social media, YouTube videos, other internet sources, or other mediums. Public outreach should start about two weeks before construction to inform drivers in the corridor of the upcoming project, including what devices will be installed and how the VSL system will improve safety in the corridor. After project construction is complete, CDOT PIO may need to inform the public about system testing prior to activating VSL signs. If VSL signs are posting static speed limits for testing purposes, it may also be necessary to communicate why speed limits are not changing and when the system will be fully activated.

8.3. Enforcement Needs

Enforcement is a necessary and integral part of developing driver compliance in a VSL corridor. Both CSP and local law enforcement must be included as stakeholders at the beginning of any VSL project. As a partner of the highway corridor, they are acutely aware of specific safety challenges and are responsible for enforcing posted speed limits.

Close coordination between CDOT Region Traffic and law enforcement is critical to ensure that each clearly understands the other's needs in a VSL corridor. Coordination may include, but is not limited to, the following questions:

- How and why is CDOT applying VSL to the corridor?
- How will CDOT Region Traffic inform law enforcement of speed limit changes?
- Will law enforcement need to query VSL posted speed limits?
- How will law enforcement access VSL information?

The answers to these questions, as well as other issues identified for VSL operations, should be discussed in detail and incorporated into the project design as is feasible. It is important to remember that law enforcement can still issue citations for drivers traveling too fast for current road conditions, regardless of the posted speed limit.

8.3.1. CORA Request

A CORA request can identify how the speed limit was established in a VSL corridor and is particularly useful when a speeding citation is challenged in a court of law. A CORA request may be submitted online26 by the public to access VSL information, including the needed time, date, and location information. A CORA representative requests all relevant materials in PDF format from the CDOT HQ Traffic Field Regulatory Operations Team. The requested materials will include the current strip map, traffic investigation for altering speeds memo, VSL Corridor Justification Memorandum, and VSL speed limit data from CDOT ODM (RTDH Team). The CORA representative then sends documents to the user who submitted the request.

The Colorado Department of State requires the relevant CDOT department to respond to a CORA request within three business days. In extenuating circumstances, the department may have an additional seven business days to respond. The responding CDOT department must understand where the VSL system information is stored and how to retrieve it to resolve the request. CDOT must establish a procedure, data retention policy, and contact list for each corridor to address any VSL-related CORA information requests.

[26] https://www.codot.gov/topcontent/cora

Appendix A. Planning Level Cost Estimate Examples

The following examples show the estimated overall and per-mile cost of deploying a VSL corridor. Each example includes the optional flashing warning beacons and PTZ cameras to show the upper limit cost. The estimate assumes the minimum recommended spacing for all devices, as outlined in Chapter 5.2.1.

These costs are planning level estimates only and do not include all pay items that are associated with a VSL project. These planning level estimates assume that fiber optic communication is available in the corridor to facilitate the transfer of ITS device information to and from the CTMC. Unit prices identified in these estimates need to be updated regularly using current bid price information.

The table below lists all assumptions used in creating the planning level estimates.

Item	Assumptions
RWIS	Weather station with friction/visibility sensors that includes tower and installation. Recommended spacing = 4 miles
MVRD	Sensor used for flow-based VSL systems that includes pole and installation. Recommended spacing = 1/2 mile
VSL Signs	Sign with small full color, full matrix insert that includes sign structure and installation. Recommended spacing = 1 mile, double-posted
UPS	Required for each pair of VSL signs (double-posted).
Flashing Warning Beacon - *optional*	Assumes each VSL sign is equipped with a flashing beacon for enhanced warning purposes.
PTZ Camera - *optional*	Recommended spacing = 2 miles
Communications	For each device (MVRD, RWIS, pair of VSL signs) installed and includes switch, cabinet, conduit, pull box, fiber, and splicing.
Power	For each device installed and includes new power meter, wiring, conduit, pull boxes, utility provider costs.
Guardrail Modifications	Providing additional guardrail (type 3) to extend existing or install new for the purpose of protecting ITS devices, not including end sections. Assume 100 feet per device.
VSL Corridor Configuration	Provides budgeted funding for CDOT to set up the VSL corridor in OpenTMS and the RTDH. This cost may vary and should be coordinated with CDOT ITS.

Example 1: A weather-based VSL system estimate.
This example provides a cost estimate for a 1 mile long corridor that is deploying a weather-based VSL system. It does not include MVRDs but does include all other optional devices. Factoring in device, communication, power, structure, and algorithm configuration costs yields an estimate of approximately $600,000 for one direction or $800,000 for both directions.

Item	Units	Unit Cost	Quantity (Direction 1)	Quantity (Direction 2)	Total Cost (Direction 1)	Total Cost (Direction 2)
RWIS	Each	$80,000.00	1.00		$80,000.00	
MVRD	Each	$25,000.00	0.00		$0.00	

VSL Signs	Each	$45,000.00	2.00	2.00	$90,000.00	$90,000.00
UPS	Each	$10,000.00	1.00	1.00	$10,000.00	$10,000.00
Flashing Warning Beacon - *optional*	Each	$1,000.00	2.00	2.00	$2,000.00	$2,000.00
PTZ Camera - *optional*	Each	$52,000.00	1.00		$52,000.00	
Communications	Each	$35,000.00	2.00	1.00	$70,000.00	$35,000.00
Power	Each	$20,000.00	2.00	1.00	$40,000.00	$20,000.00
Guardrail Modifications	Linear Foot	$35.00	100.00		$3,500.00	
VSL Corridor Configuration	One-Time	$100,000.00	1.00		$100,000.00	
Total VSL Corridor Estimate (One Direction)		$581,750.00	**Cost Per Mile**		$581,750.00	
Total VSL Corridor Estimate (Both Directions)		$785,850.00	**Cost Per Mile**		$785,850.00	

Example 2: A weather-based VSL system estimate.
This example provides a cost estimate for a 4 mile long corridor that is deploying a weather-based VSL system. It does not include MVRDs but does include all other optional devices. Factoring in device, communication, power, structure, and algorithm configuration costs yields an estimate of approximately $300,000 for one direction or $500,000 for both directions.

Item	Units	Unit Cost	Quantity (Direction 1)	Quantity (Direction 2)	Total Cost (Direction 1)	Total Cost (Direction 2)
RWIS	Each	$80,000.00	1.00		$80,000.00	
MVRD	Each	$25,000.00	0.00		$0.00	
VSL Signs	Each	$45,000.00	8.00	8.00	$360,000.00	$360,000.00
UPS	Each	$10,000.00	4.00	4.00	$40,000.00	$40,000.00
Flashing Warning Beacon - *optional*	Each	$1,000.00	8.00	8.00	$8,000.00	$8,000.00
PTZ Camera - *optional*	Each	$52,000.00	2.00		$104,000.00	
Communications	Each	$35,000.00	5.00	4.00	$175,000.00	$140,000.00

Power	Each	$20,000.00	5.00	4.00	$100,000.00	$80,000.00
Guardrail Modifications	Linear Foot	$35.00	100.00		$3,500.00	
VSL Corridor Configuration	One-Time	$100,000.00	1.00		$100,000.00	
Total VSL Corridor Estimate (One Direction)		$1,261,650.00	**Cost Per Mile**		$315,412.50	
Total VSL Corridor Estimate (Both Directions)		$2,078,050.00	**Cost Per Mile**		$519,512.50	

Example 3: A flow-based VSL system estimate.
This example provides a cost estimate for a 1 mile long corridor that is deploying a flow-based VSL system. It includes all ITS devices. Factoring in device, communication, power, structure, and algorithm configuration costs yields an estimate of approximately $800,000 for one direction or $1,000,000 for both directions.

Item	Units	Unit Cost	Quantity (Direction 1)	Quantity (Direction 2)	Total Cost (Direction 1)	Total Cost (Direction 2)
RWIS	Each	$80,000.00	1.00		$80,000.00	
MVRD	Each	$25,000.00	2.00		$50,000.00	
VSL Signs	Each	$45,000.00	2.00	2.00	$90,000.00	$90,000.00
UPS	Each	$10,000.00	1.00	1.00	$10,000.00	$10,000.00
Flashing Warning Beacon - *optional*	Each	$1,000.00	2.00	2.00	$2,000.00	$2,000.00
PTZ Camera - *optional*	Each	$52,000.00	1.00		$52,000.00	
Communications	Each	$35,000.00	4.00	1.00	$140,000.00	$35,000.00
Power	Each	$20,000.00	4.00	1.00	$80,000.00	$20,000.00
Guardrail Modifications	Linear Foot	$35.00	300.00		$10,500.00	
VSL Corridor Configuration	One-Time	$100,000.00	1.00		$100,000.00	
Total VSL Corridor Estimate (One Direction)		$798,850.00	**Cost Per Mile**		$798,850.00	
Total VSL Corridor Estimate (Both Directions)		$1,002,950.00	**Cost Per Mile**		$1,002,950.00	

Example 4: A flow-based VSL system estimate.
This example provides a cost estimate for a 4 mile long corridor that is deploying a flow-based VSL system. It includes all ITS devices. Factoring in device, communication, power, structure, and algorithm configuration costs yields an estimate of approximately $500,000 for one direction or $700,000 for both directions.

Item	Units	Unit Cost	Quantity (Direction 1)	Quantity (Direction 2)	Total Cost (Direction 1)	Total Cost (Direction 2)
RWIS	Each	$80,000.00	1.00		$80,000.00	
MVRD	Each	$25,000.00	8.00		$200,000.00	
VSL Signs	Each	$45,000.00	8.00	8.00	$360,000.00	$360,000.00
UPS	Each	$10,000.00	4.00	4.00	$40,000.00	$40,000.00
Flashing Warning Beacon - *optional*	Each	$1,000.00	8.00	8.00	$8,000.00	$8,000.00
PTZ Camera - *optional*	Each	$52,000.00	2.00		$104,000.00	
Communications	Each	$35,000.00	13.00	4.00	$455,000.00	$140,000.00
Power	Each	$20,000.00	13.00	4.00	$260,000.00	$80,000.00
Guardrail Modifications	Linear Foot	$35.00	900.00		$31,500.00	
VSL Corridor Configuration	One-Time	$100,000.00	1.00		$100,000.00	
Total VSL Corridor Estimate (One Direction)		$2,130,050.00		**Cost Per Mile**	$532,512.50	
Total VSL Corridor Estimate (Both Directions)		$2,946,450.00		**Cost Per Mile**	$736,612.50	

DiExSys
Road Safety Analytics

Updated Safety/Operational Assessment I-25 MP 158.00 – 181.00 Baptist Road Interchange to Plum Creek Interchange

Reproduction of any Portion of this Document is Prohibited without Expressed Written Authority from the Douglas County Department of Public Works

Appendix C. VSL Corridor Justification Memorandum Template

Replace header with the appropriate Region, complete information within the angle brackets, check all applicable boxes, attach all required documentation.

COLORADO
Department of Transportation
Office of the Chief Engineer

DATE: Month <XX>, <XXXX>
TO: <State Traffic Engineer>, <Region Traffic Engineer>, <ITS Branch Manager>
FROM: <Project Manager>
SUBJECT: **VSL Corridor Justification –** <Project Name/Number>

Following the CDOT Variable Speed Limit (VSL) Guidelines, Region <X> has completed the following steps to evaluate a VSL corridor along <highway number> between MM <X> and MM <Y> in the <eastbound/northbound> and/or <westbound/southbound> directions:

- ☐ Performed a VSL Feasibility Workshop.
- ☐ Determined if the weather algorithm is applicable.
- ☐ Determined if the flow algorithm is applicable.
- ☐ Determined the Benefit/Cost justification of designing, implementing, and operating a VSL corridor.
- ☐ Performed a traffic investigation to identify the appropriate maximum and minimum speed limit for the VSL system, per CRS 42-4-1102.
- ☐ Identified design, construction, integration, and testing funding for the VSL corridor.
- ☐ Completed a Systems Engineering Analysis (SEA) through at least the Detailed Level Design at the time of submittal.

The Project Team will be implementing the following into the project to support the VSL corridor:

- ☐ <X> Single VSL Signs and Structures
- ☐ <X> Dual VSL Signs and Structures
- ☐ <X> Flashing beacons for VSL Signs
- ☐ <X> MVRDs
- ☐ <X> RWISs
- ☐ <X> PTZ cameras
- ☐ <X> Overhead Sign Structures for Express Lanes

The outputs from the analysis, including algorithm selection, signed traffic investigation setting the speed limit parameters, VSL Safety Assessment with Benefit/Cost analysis, and SEA documents completed thus far for the project, are included with this memo or can be found here <Project file link>.

The funding for the design, construction, integration, and testing of the VSL corridor has been identified as <type of funding> and is ready to be budgeted into the project subaccount.

If there are any questions, please reach out to <PM name> at <PM email>.

Project Manager Signature:	Date:
State Traffic Engineer Signature:	Date:
Region Traffic Engineer Signature:	Date:
ITS Branch Manager Signature:	Date:

Appendix D. Algorithm Implementation Input Template

The following images are excerpts from the CDOT's VSL Algorithm Implementation Input Template[27] provided by the RTDH Team. This template defines all inputs required to operate the VSL algorithm for the corridor. The latest version of this template will also be linked in the Programmatic VSL Detailed Level System Design SEA document.

Spreadsheet Tab #1: Corridor Description

Algorithm Name	<Corridor Name>
Algorithm Description	<Corridor Description>
Algorithm Calculation Area	**Rules**
Overall Calculation	Start calculation at the most downstream zone in the corridor
Friction	Use average of values from 2 closest weather station devices (either upstream or downstream) within 5 miles from the Zone VSL
Visibility	Use value from the closest Weather Station within 5 miles
Volume	Use average of values from all MVRDs within the zone. All MVRDs has mile marker strictly greater than the Zone VSL and has mile marker less than or equal to the zone end mile marker. If no MVRDs are found in a zone using the above logic, find the next down stream MVRD within 3 miles of the Zone VSL mile marker (Upstream mile marker of the zone)
Downstream Speed	Use minimum of speed values from all MVRDs within the next zone downstream. (MM equal to or greater than VSL immediately downstream of this zone and less than MM of the following VSL downstream. If no MVRDs are found in a zone using this logic, find the next downstream MVRD within 2 miles of the VSL at the upstream end of the next zone downstream.
Flow Based Speed	Find flow parameter by zone, if not match found, use downstream flow parameter
Queue Based Speed	Use downstream observed speed to compute queue based speed. Round the downstream observed speed to the nearest multiple of 5 + 5 Downstream Observed + (5 - MOD(Downstream Observed, 5)) + 5
Speed Transition	Use downstream observed posted/calculated to compute queue transition speed. Downstream Posted + 10

[27] https://docs.google.com/spreadsheets/d/1mefPHbvZuORf-I-GIcs94x6e8W1BR3vtwGE1aWOTYaU/edit#gid=1544515188

Spreadsheet Tab #2: Corridor Outline

The **max speed truck** column is only required for VSL systems that include a separate speed limit for overweight vehicles. The **inflection** column is only required for flow-based VSL systems and the input (i.e., inflection point flow rate) is defined in Chapter 4.2. The **steepest downgrade** column is required for all VSL systems and is defined in Chapter 4.1.

Route	Direction	Zone Name	Start Mile Marker	End Mile Marker	Max Speed Car	Max Speed Truck	Min Speed Dry	Min Speed Adverse	Inflection	Steepest Downgrade
I-70	Eastbound	E1	116.00	116.87	60	50	40	30	65000	0.032
I-70	Eastbound	E2	116.88	118.18	60	50	40	30	65000	0.000
I-70	Eastbound	E3	118.19	118.97	60	50	40	30	65000	0.044
I-70	Eastbound	E4	118.98	121.72	60	50	40	30	65000	0.040
I-70	Eastbound	E5	121.73	123.19	60	50	40	30	65000	0.044
I-70	Eastbound	E6	123.20	126.06	60	50	40	30	65000	0.056
I-70	Eastbound	E7	126.07	127.54	60	50	40	30	65000	0.022
I-70	Eastbound	E8	127.55	128.86	60	50	40	30	65000	0.034
I-70	Eastbound	E9 - Overflow	128.87	132.00	60	50	40	30	65000	0.020
I-70	Westbound	W1	132.00	131.06	60	50	40	30	65000	0.016
I-70	Westbound	W2	131.05	129.72	60	50	40	30	65000	0.024
I-70	Westbound	W3	129.71	128.14	60	50	40	30	65000	0.046
I-70	Westbound	W4	128.13	124.51	60	50	40	30	65000	0.072
I-70	Westbound	W5	124.50	122.46	60	50	40	30	65000	0.038
I-70	Westbound	W6	122.45	120.64	60	50	40	30	65000	0.060
I-70	Westbound	W7	120.63	118.21	60	50	40	30	65000	0.046
I-70	Westbound	W8	118.20	117.69	60	50	40	30	65000	0.028
I-70	Westbound	W9 - Overflow	117.68	116.00	60	50	40	30	65000	0.024

Spreadsheet Tab #3: General Configuration

#	Input Parameter	Description		Default Values
1	Speed	Frequency in seconds, units	seconds	30
2	Volume	Frequency in seconds, count	seconds	30
3	Visibility	Frequency in seconds, units	seconds	600
4	Friction	Frequency in seconds, friction coefficient (0 - 1)	seconds	600
5	Downstream Speed	Frequency, aggregate time for smoothing	seconds	189
6	Downstream Speed Limit	Frequency, units of the downstream zone	mph	10
7	Minimum Acceptable Visibility (MAV)	Distance in feet	feet	5,000
8	Output calculation	How often should the recommended speed be calculated?	seconds	30
9	Cycle Posting Window	The interval between posting VSL to signs. Will never return zero or negative number	cycles	6
10	Max Weather Station Distance	Max weather station distance	miles	3
11	Max Speed for Any VSL in the Corridor	Default max speed to be used for any VSL	mph	65
12	Min Speed in Adverse Conditions	Minimum adverse road conditions speed	mph	30
13	Max MM Range for Friction	Max distance to search for a friction sensor input	miles	5
14	Max Friction Input Values	Maximum friction sensor input values to use when computing friction value for a zone	# of sensors	2
15	Max MM Range for Visibility	Max mile marker range (from upstream MM) to search for visibility sensors	miles	2
16	Max Visibility Input Values	Maximum number of visibility sensors that should be included in the viability calculation for a given zone	# of sensors	1
17	Max MM Range for Volume	Max mile marker range (from upstream MM) to search for volume sensors	miles	3
18	Volume Smoothing Record Count	Number of historical records to use while calculating volume value for a given sensor	# of records	10
19	Max MM Range Speed	Returns the max mile marker range (from upstream MM) to search for downstream speed sensors. NOTE - This value is only used for fallback scenarios when NO MVRDs can be located in the immediate downstream zone. In such cases, the next downstream zone is searched for up to 2 mms from the upstream location of that zone	miles	2
20	Downstream Speed Smoothing Record Count	Number of historical records to use while calculating downstream speed data value for a given sensor	# of records	2
21	Downstream Observed Speed Rounding	Number to which to round up the downstream observed speed value while computing Speed Queue values	value	5
22	Downstream Posted Speed Rounding	Number to which to round up the downstream posted speed value while computing Speed Queue values	value	10

Spreadsheet Tab #4: Friction Table

As discussed in the template, the friction grade coefficient is compared with a series of threshold values to determine the friction-based speed for cars. The friction grade coefficient is defined in Chapter 4.1.

#	Speed to Post for Cars	Friction Grade Coefficient (>=)
1	65	0.7
2	60	0.6
3	55	0.5
4	50	0.42
5	45	0.34
6	40	0.27
7	35	0.2
8	30	-1
#	**Speed to Post for Trucks**	**Friction Grade Coefficient (>=)**
1	65	0.7
2	60	0.6
3	55	0.5
4	50	0.42
5	45	0.34
6	40	0.27
7	35	0.2
8	30	-1

The following images from tabs 5-7 of the spreadsheet are nearly identical, as they are defining the inputs for the deployed MVRDs, VSL signs, and RWISs.

Spreadsheet Tab #5: Detectors

This tab is only required for flow-based VSL systems.

Zone Name	Detector Name	Detector MM	Detector Direction	ATMS Prod ID	ATMS Test ID	ATMS Dev ID
Zone A [231.3 - 231.74]	070E232 1.0MI E OF HERMAN GULCH RD. (MEDIAN) (10051)	231.75	East	To Be Entered by ITS	To Be Entered by ITS	To Be Entered by ITS
Zone B [231.75 - 232.54]	070E232 0.4 MI E OF US-40 (10052)	232.25	East	8102		
Zone C [232.55 - 233.59]	070W233 0.2 MI E OF EMPIRE (10053)	232.6	West	8088		
Zone D [233.6 - 234.54]	070E233 04 MILES E OF (10054)	233.3	East	8705		
Zone D [233.6 - 234.54]	070E234 0.5 MILES E OF (10055)	232.6	West	8132		

Spreadsheet Tab #6: VSL Signs

This tab is required for all VSL systems.

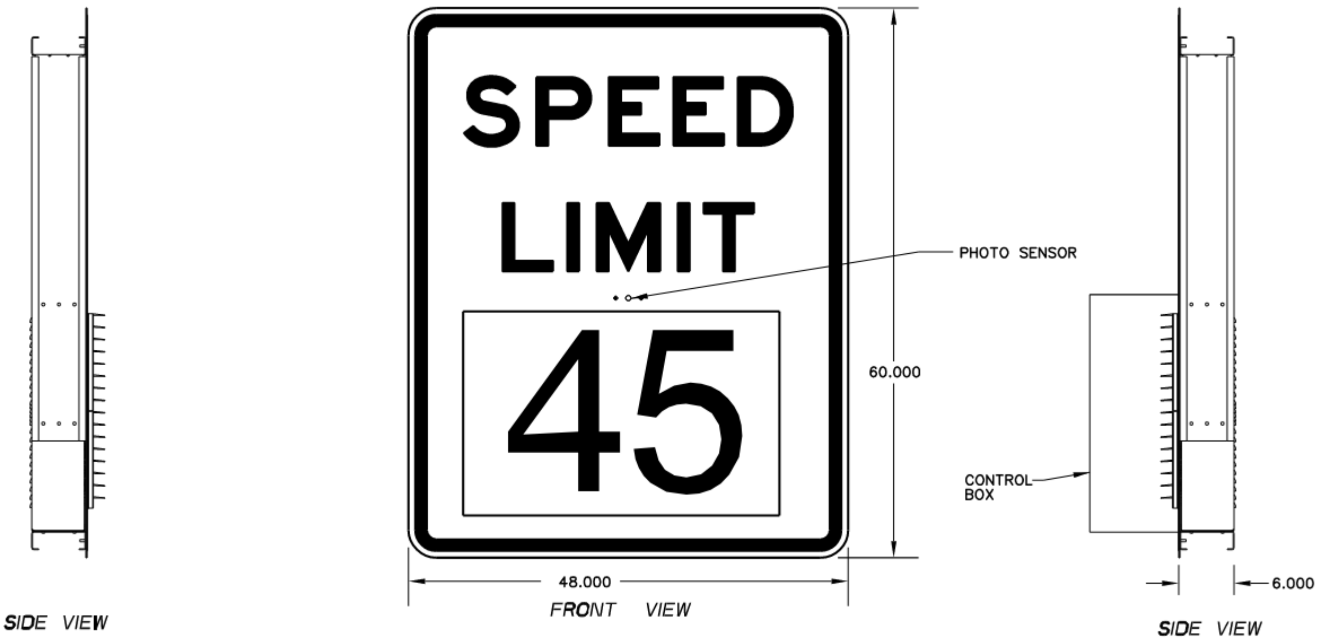
Zone Name	Detector Name	Detector MM	Detector Direction	ATMS Prod ID	ATMS Test ID	ATMS Dev ID
Zone A [231.3 - 231.74]	070E23125VSL1MED : 0.6 mi W of US-40	231.2	East	OpenTMS-Sign475224		
Zone A [231.3 - 231.74]	070E23125VSL1RHS : 0.6 mi W of US-40	231.2	East	OpenTMS-Sign475239		
Zone B [231.75 - 232.54]	070E23175VSL1MED : 0.1 mi W of US-40	231.8	East	OpenTMS-Sign475269		
Zone B [231.75 - 232.54]	070E23175VSL1RHS : 0.1 mi W of US-40	231.8	East	OpenTMS-Sign475284		

Spreadsheet Tab #7: Weather Stations

This tab is required for all VSL systems.

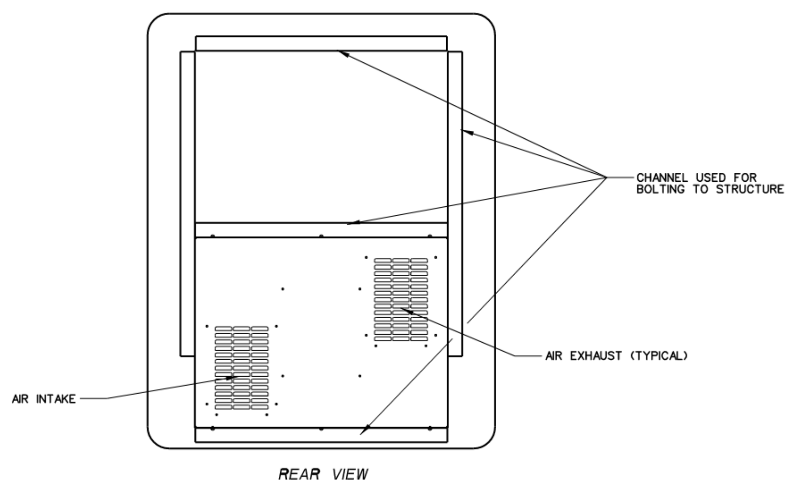
Zone Name	Detector Name	Detector MM	Detector Direction	ATMS Prod ID	ATMS Test ID	ATMS Dev ID
Zone A [231.3 - 231.74]	070E23125VSL1MED : 0.6 mi W of US-40	231.2	East	OpenTMS-Sign475224		
Zone A [231.3 - 231.74]	070E23125VSL1RHS : 0.6 mi W of US-40	231.2	East	OpenTMS-Sign475239		
Zone B [231.75 - 232.54]	070E23175VSL1MED : 0.1 mi W of US-40	231.8	East	OpenTMS-Sign475269		
Zone B [231.75 - 232.54]	070E23175VSL1RHS : 0.1 mi W of US-40	231.8	East	OpenTMS-Sign475284		

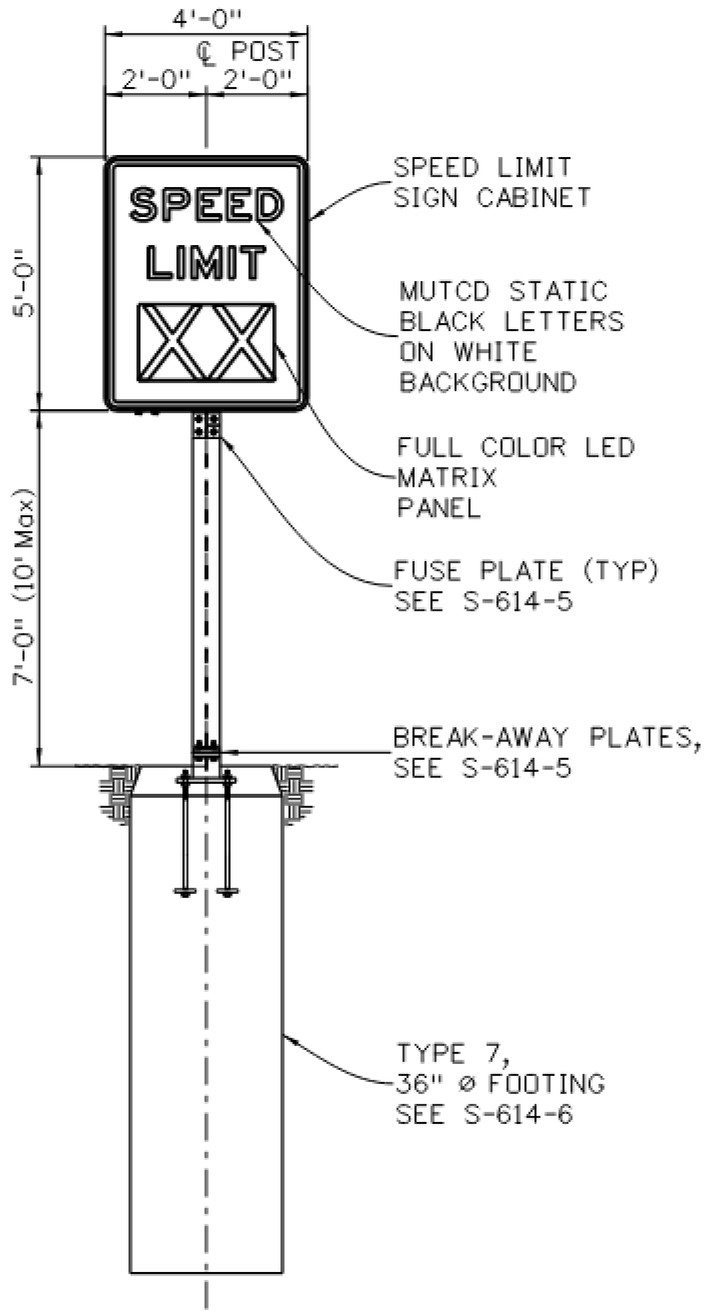
Appendix E. Project Details and Specification Examples



NOTES:

1. SEE R2-1 OF THE STANDARD HIGHWAY SIGNS FOR SIGN LAYOUT DETAILS.
2. THIS SIGN SHALL BE INSTALLED IN ACCORDANCE WITH THE PROJECT SPECIAL PROVISION, REVISION OF 614, VARIABLE SPEED LIMIT SIGN INCLUDED IN THE SPEC PACKAGE, AND THE PROJECT DETAIL FOR SINGLE SIGN SUPPORT DETAILS INCLUDED IN THIS PLAN SET.
3. DISPLAY SHALL BE CAPABLE OF POSTING 55, 50, 45 and 40





FRONT ELEVATION

The latest version of the VSL project specification along with the other necessary project special provisions can be found in the latest [CDOT Standard Specifications Book](https://www.codot.gov/business/designsupport/cdot-construction-specifications/2022-construction-specifications/2022-specs-book)[28] and the [CDOT ITS specifications website](https://www.codot.gov/programs/intelligent-transportation-systems/specifications).[29] The selected specifications should be confirmed with CDOT ITS.

Typical VSL project will include the following project special provisions:

Revision of Section 108 – Disincentive for Offline ITS Devices
Revision of Section 108 – Fiber Procedures Notification Without Outages
Revision of Section 612 – Location Markers
Revision of Section 613 – Electrical Conduit
Revision of Section 613 – Electrical Conduit (Liquidtight Flexible Metal)
Revision of Section 613 – Pull Boxes
Revision of Section 613 – Electrical Conductor Identification
Revision of Section 613 – Troubleshooting (ITS)
Revision of Section 614 – Communications Cabinet (Type 2) (Ground Mounted)
Revision of Section 614 – Variable Speed Limit Sign
Revision of Section 614 – Weather Monitoring System
Revision of Section 614 – Microwave Vehicle Radar Detector
Revision of Section 614 – Telemetry (Master)
Revision of Section 614 – Telemetry (Field)
Revision of Section 614 – Small Form Factor Pluggable Optic Modules
Revision of Section 614 – Optical Attenuator
Revision of Section 614 – Fiber Optic Cable (Single Mode)
Revision of Section 614 – Fiber Optic Termination Panel
Revision of Section 614 – Fiber Optic Splice Closure
Revision of Section 614 – Fiber Optic Splice Closure Lock
Revision of Section 614 – Test Fiber Optic Cable
Revision of Section 614 – Ethernet Switch Type II
Revision of Section 614 – ITS System As-Built Documentation
Revision of Section 614 – Global Positioning System (GPS)
Revision of Section 614 – Grounding and Bonding
Revision of Section 614 – Testing and Acceptance
Revision of Section 614 – Equipment Procurement and Configuration
Revision of Section 625 – Asset Geospatial Data Collection

Please note that the project special provision list will be specific to each individual project and will be dependent on the fiber network that is available in the project corridor.

[28] https://www.codot.gov/business/designsupport/cdot-construction-specifications/2022-construction-specifications/2022-specs-book

[29] https://www.codot.gov/programs/intelligent-transportation-systems/specifications