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Operational and Safety Analysis Tool for Various TSMO Active Traffic Management Strategies

Requested by

Yusuf Shatnawi, Division of Traffic Operations

Prepared by

Bach Duong, Division of Research, Innovation & System Information

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Executive Summary

Background

Active Traffic Management (ATM) strategies such as dynamic speed limits, adaptive ramp metering, queue warning systems, and dynamic lane management are increasingly used by Caltrans to improve freeway operations and safety. However, evaluating the long-term operational and safety benefits of these strategies, especially when deployed in combination, remains challenging. Existing tools and data sources do not provide a consistent statewide method for estimating speed improvements, delay reduction, or crash modification factors associated with ATM deployments. This limits Caltrans' ability to conduct data-driven evaluations for SHOPP Operational Improvement (OI) and Safety Improvement (SI) projects. Districts are currently faced with challenges of analyzing and estimating long-term operational and safety benefits of various ATM strategies, highlighting the need for a unified analysis approach. Developing a statewide operational and safety analysis tool would support more consistent project review, improve benefit estimation, and strengthen TSMO decision-making across the state.

The Preliminary Investigation (PI) will review existing national and international research, tools, and best practices related to evaluating ATM strategies to inform the development of a comprehensive Caltrans analysis tool.

Summary of Findings

Related Research and Resources

NCHRP Research Report 1120 (2024): Active Traffic Management Strategies - A Planning and Evaluation Guide

NCHRP 1120 is the most comprehensive national reference for planning and evaluating Active Traffic Management (ATM) strategies. The guide defines ATM within an "active management continuum," ranging from static operations to fully proactive, predictive control. It outlines how agencies should link goals, benefits, performance measures, and data requirements when evaluating strategies such as variable speed limits, adaptive ramp metering, queue warning, dynamic lane-use control, and part-time shoulder use. The report also categorizes analysis tools from sketch planning to high-fidelity simulation and highlights the limitations of existing tools in capturing multi-strategy interactions, reliability benefits, and driver compliance.

Record URL: <https://www.nationalacademies.org/read/27871/chapter/4>

Record URL: <https://www.nationalacademies.org/read/27871/chapter/6>

Record URL: <https://www.nationalacademies.org/read/27871/chapter/7>

Record URL: <https://www.nationalacademies.org/read/27871/chapter/8>

Research Finding: This guide provides the strongest national framework for ATM evaluation but does not offer a ready-made tool. It highlights the exact gaps Caltrans faces, especially the need for integrated operational and safety evaluation and the ability to model reliability and bundled strategies.

FHWA Active Traffic Management Feasibility and Screening Guide (FHWA-HOP-14-019)

The FHWA ATM Feasibility and Screening Guide offers a structured process for identifying candidate corridors and determining whether ATM strategies are appropriate for a given location. The guide focuses on early-stage screening rather than detailed predictions, providing high-level benefit ranges, cost considerations, and strategy suitability criteria. It includes examples from multiple states, including

Caltrans, and emphasizes the importance of understanding corridor characteristics before committing to design or implementation. While the guide is useful for determining whether ATM should be considered, it does not provide the analytical depth needed to quantify operational or safety impacts for project development

Record URL: <https://ops.fhwa.dot.gov/publications/fhwahop14019/index.htm>

Research Finding: This guide is valuable for early corridor screening but does not provide the detailed operational or safety evaluation capabilities needed for Caltrans' statewide analysis tool.

FHWA TOPS-BC (Tool for Operations Benefit Cost Analysis), Version 4.0

TOPS-BC is a sketch-planning benefit–cost tool designed to help agencies compare TSMO strategies using standardized assumptions and default impact ranges. The tool provides order-of-magnitude estimates for operational and safety benefits and supports early programming decisions. However, TOPS-BC relies heavily on national default values and simplified assumptions, and it cannot model interactions among ATM strategies, reliability improvements, or corridor-specific behavioral factors. Its strength lies in rapid screening rather than detailed analysis.

Record URL: <https://ops.fhwa.dot.gov/plan4ops/topsbctool/>

Research Finding: TOPS-BC offers a useful structure for early benefit–cost discussions but is insufficient for evaluating ATM bundles or California-specific operational and safety impacts.

FHWA (2021) Developing Crash Modification Factors for Variable Speed Limits (FHWA-HRT-21-053)

This FHWA study provides one of the most rigorous evaluations of Variable Speed Limits (VSL) in the United States. Using multi-state data from Virginia, Wyoming, and Georgia, the research team applied advanced statistical methods including interrupted time series analysis and generalized estimating equations to estimate crash modification factors for VSL under various conditions. The study found substantial crash reductions in Wyoming and Georgia but inconclusive results in Virginia due to limited activation data and corridor-specific operational patterns. The report also includes benefit–cost analyses demonstrating strong economic justification where VSL is effective.

Record URL: <https://highways.dot.gov/sites/fhwa.dot.gov/files/FHWA-HRT-21-053.pdf>

Research Finding: This study provides defensible CMFs for VSL but also shows that effectiveness depends heavily on activation logs, corridor context, and system usage highlighting the need for Caltrans to incorporate operational realism into any statewide tool.

CMF Clearinghouse (ATM-Related Crash Modification Factors)

The CMF Clearinghouse compiles safety effectiveness estimates for a wide range of traffic strategies, including ATM components such as ramp metering, variable speed limits, hard shoulder running, and bundled ATM systems. For example, VSL CMFs range from 0.66 for total crashes in Wyoming to 0.35 for rear-end crashes, while California ramp metering studies report CMFs around 0.64. Bundled ATM deployments, such as those combining VSL, lane-use control, and shoulder running, show mixed results depending on corridor characteristics and operational design. The Clearinghouse provides applicability conditions and study meta data, allowing agencies to assess transferability.

Record URL: https://cmfclearinghouse.fhwa.dot.gov/study_detail.php?stid=637

Research Finding: The Clearinghouse offers essential safety inputs, but the CMFs vary widely by context, and many are based on simple before/after studies. California-specific calibration will be necessary for accurate statewide evaluation.

VDOT / VTRC Evaluation of the I-66 ATM System (Phase II)

Virginia's evaluation of the I-66 ATM system is one of the most detailed real-world assessments of a bundled ATM deployment in the U.S. The system included advisory variable speed limits, lane-use control signals, and hard shoulder running (HSR). Using empirical Bayes methods and Virginia-specific safety performance functions, the evaluation found that HSR produced the strongest operational and safety benefits, while segments with only VSL and lane use control showed limited measurable improvements. The study also highlighted the importance of segment-level analysis, as benefits varied significantly along the corridor.

Record URL: https://cmfclearinghouse.fhwa.dot.gov/study_detail.php?stid=571

Research Finding: This evaluation demonstrates that ATM benefits are not evenly distributed across components or segments. It reinforces the need for a Caltrans tool that can evaluate bundled strategies and differentiate impacts by location.

FDOT (2020) TSM&O Strategies Assessment Tool

Florida DOT developed a spreadsheet-based tool that integrates operational and safety impacts for multiple TSMO strategies, including ramp metering, dynamic message signs, Road Rangers, express lanes, transit signal priority, and adaptive signals. The tool uses Florida-specific Mobility Enhancement Factors (MEFs) and Crash Modification Factors (CMFs) to estimate benefits and support project prioritization. The methodology combines travel time reliability measures, crash risk analysis, and incident clearance metrics, offering a practical example of how statewide evaluation can be operationalized.

Record URL: <https://fdotwww.blob.core.windows.net/sitefinity/docs/default-source/research/reports/fdot-bdv29-977-46-rpt.pdf>

Record URL: https://cmfclearinghouse.fhwa.dot.gov/study_detail.php?stid=609

Research Finding: This is the closest existing model to what Caltrans seeks. However, Florida's performance factors are state-specific and cannot be directly applied to California without recalibration.

MnDOT (2023) Evaluation and Refinement of Minnesota Queue Warning Systems

Minnesota's evaluation of its queue warning algorithm (MN-QWARN) focused on algorithm performance rather than crash outcomes due to low crash frequencies. The study assessed detection rates, false alarms, and over-warning conditions, and recommended recalibration for new sites. The evaluation also documented a shift from video-coded near-crash analysis to data-driven algorithm performance metrics, reflecting the difficulty of using crash data for short-duration or low-volume deployments.

Record URL: https://rosap.ntl.bts.gov/view/dot/67836/dot_67836_DS1.pdf

Research Finding: This study highlights the need for surrogate safety and algorithm-performance metrics when crash data is insufficient and important consideration for Caltrans' tool, especially for queue warning and similar strategies.

FHWA (2025) Traffic Management Systems Actively Managing Queue Warning Messages

This FHWA brief synthesizes national practices for queue warning systems, focusing on operational implementation, message selection logic, and the role of TMC operators. It documents examples of crash and injury reductions but cautions that benefits may be overstated when queue warning is not deployed as a standalone strategy. The brief emphasizes the importance of automation supported by operator oversight and highlights challenges in attributing safety benefits to a single component within a larger ATM system.

Record URL: <https://highways.dot.gov/media/58936>

Research Finding: This resource reinforces that queue warning effectiveness depends on operational reliability and integration with other ATM strategies. It also underscores the difficulty of isolating safety benefits in bundled deployments.

ATDM Analysis Brief #4: Example Application (Ramp Metering and Demand Management) - FHWA Office of Operations

This FHWA brief shows how agencies can evaluate bundled ATDM/ATM strategies using a scenario-based reliability architecture built around FREEVAL-ATDM and an ATDM Analyzer. The workflow generates a large scenario space across demand, weather, incidents, and work zones (10,192 combinations), selects 30 representative scenarios, and runs automated HCM-based analyses for “before” and “after” cases. Reported measures of effectiveness include VHT, VHD, average speed, and Planning Time Index (95th-percentile TTI). In the worked example, adding dynamic ramp metering and employer-based TDM on top of a HOT lane conversion reduced vehicle-hours of delay by ~37%, increased average speed by ~14%, and improved reliability by ~24%. The approach explicitly captures disruption variability and strategy interactions without requiring full microsimulation.

Record URL: <https://ops-dr.fhwa.dot.gov/publications/fhwahop13037/index.htm>

Research Finding: This brief provides a computational engine template for Caltrans: a practical, reliability-first method to test combined ATM strategies using HCM + SHRP2 reliability extensions; it is not a crash-prediction tool and does not produce CMFs.

Development of Active Traffic Management Strategies for Minnesota Freeway Corridors (MN/RC 2015-26) Minnesota DOT / University of Minnesota Duluth

This MnDOT-sponsored project pairs field evaluation with algorithm enhancement. On I-35W, the team assessed a Variable Advisory Speed Limit (VASL) system using real detector data and found statistically significant reductions in maximum deceleration and substantial improvements in travel time reliability (95th-percentile buffer index) after activation. In parallel, they enhanced and deployed a coordinated adaptive ramp-metering method on Hwy 100 NB, reporting mainline and ramp performance gains versus a prior “stratified” algorithm. The report documents operational constraints (e.g., queue storage, min/max metering rates) and sensitivity to detector quality, illustrating how real-world limitations must be encoded in any statewide evaluation tool.

Record URL: <https://rosap.ntl.bts.gov/view/dot/32168>

Research Finding: A strong state DOT analogue: shows how to evaluate and tune ATM algorithms with archived field data and reliability metrics; emphasizes that algorithm + constraints + data quality are inseparable in estimating benefits.

Surrogate Safety Assessment Model and Validation (FHWA-HRT-08-051) FHWA Turner-Fairbank Highway Research Center

This FHWA research effort establishes a validated methodology for safety evaluation using microsimulation-based surrogate conflicts rather than long-term crash data. The project tested SSAM across multiple simulation platforms and conducted field validation using 83 real intersections, demonstrating that conflict-based indicators can reliably distinguish design or operational alternatives when crash data are sparse. The report also documents key sensitivities such as simulation calibration quality and vendor-specific trajectory outputs showing how surrogate-based safety assessment can be integrated into operational analyses where traditional crash-based CMFs are infeasible.

Record URL: <https://highways.dot.gov/sites/fhwa.dot.gov/files/2008-ssam-validation-final-report.pdf>

Research Finding: Provides a defensible, FHWA-validated approach for analyzing safety impacts in ATM/TSMO projects when crash samples are insufficient; establishes a transferable surrogate-safety module for any Caltrans microsimulation-based evaluation workflow.

Smart Motorway Safety: Evidence Stock take and Action Plan UK Department for Transport (2020)

This major national review synthesizes safety performance across the UK's smart motorway configurations, including variable mandatory speed limits, lane-use control, and hard-shoulder running concepts. The report applies before/after studies, counterfactual modeling, statistical testing, and national casualty databases (STATS19) to assess risk changes using metrics such as casualty rates per vehicle-mile and the Fatal and Weighted Injuries (FWI) index. The findings highlight mixed impacts: overall casualty reductions on some corridors but increases in hazard-specific risks such as stopped-vehicle exposure. The report emphasizes statistical uncertainty due to limited post-opening years and provides a transparent model for communicating safety results in politically sensitive contexts.

Record URL: <https://assets.publishing.service.gov.uk/media/5e5e0f1ce90e072f2813f7a3/smart-motorways-evidence-stocktake-and-action-plan.pdf>

Research Finding: Offers a rigorous evaluation template combining counterfactuals, FWI metrics, and transparent uncertainty discussion highly relevant to Caltrans when assessing lane-use or shoulder-use ATM strategies that carry distinct hazard-specific risks.

Evaluation of a Variable Speed Limit System Using a Hierarchical Framework Under a Connected-Vehicles Environment (Seattle I-5) IET Intelligent Transport Systems (2020)

This peer-reviewed field study evaluates a Variable Speed Limit (VSL) system deployed on Seattle's I-5 corridor in a connected-vehicle environment. Using integrated traffic sensor data and CV trajectory data, the research applies a hierarchical evaluation framework covering maneuvering, safety, and operational performance. Results show that VSL improves operational measures and driver compliance even at low CV penetration rates, while some segments showed decreased flow stability based on safety-surrogate metrics such as speed variance. The study also highlights evaluation challenges including missing "system-off" periods and demonstrates how stability and variance indicators must complement traditional speed and delay metrics.

Record URL: <https://ietresearch.onlinelibrary.wiley.com/doi/10.1049/iet-its.2019.0462>

Research Finding: Demonstrates a transferable CV-era evaluation structure emphasizing operational, safety-surrogate, and stability metrics; reinforces the need for activation logs and baseline data for VSL assessments relevant to future Caltrans deployments.

Gaps in Findings

Right now, there isn't a ready-to-use, off-the-shelf tool for evaluating ATM.

- NCHRP 11-20 is helpful as a framework, but it's not an implementable evaluation tool. It even flags limitations around bundled strategies, reliability, and compliance.
- The FHWA screening tools and TOPS-BC are a good starting point, but they're still too high-level for project-development decisions.

Caltrans lacks a clear method for evaluating how ATM strategies interact when deployed as bundled systems

- Real-world deployments (like I-66) show benefits vary by corridor segment and by individual component.
- Using component-only CMFs can be misleading when strategies are combined, because most sketch tools assume benefits are additive or independent and that often isn't true.

Reliability benefits are widely acknowledged, but they're not modeled consistently.

- ATDM reliability workflows are promising, but they don't tie cleanly into safety prediction and aren't widely operationalized statewide.
- Many tools still struggle to quantify reliability improvements for multi-strategy ATM deployments.

Safety evaluation is basically split into two camps, and neither is a perfect statewide solution.

- In the CMF world (Clearinghouse + FHWA VSL CMF work), results can be useful but vary a lot by context and often come from simpler study designs.
- In the simulation/surrogate world (SSAM and similar methods), you can evaluate sparse-crash situations, but scaling it is hard because it requires calibration and consistent trajectory outputs.

Data is one of the biggest practical barriers.

Multiple sources emphasize that ATM/VSL effectiveness depends heavily on:

- strong activation logs (when/where/how the system ran),
- reliable "system off" periods for comparison,
- good detector health and complete archived data.

Next Steps

Recommendations for research include but are not limited to:

- Determine how to operationalize a statewide ATM evaluation framework within Caltrans, including governance, IT/security considerations, procurement, deployment, and long-term maintenance.
- Determine whether and how the technology can be incorporated into Caltrans processes and procedures (data readiness, workflow integration, piloting, and validation).

Contacts

State Agencies

Research, Innovation and System Information

2963 R St, Sacramento, CA 95816

(916) 654-2852 Public Affairs/Media Line:(916) 657-5060

Caltrans Contact

DRISI contacted Caltrans staff to gather information for this investigation. Currently, there is no additional research internally from Caltrans but recommendations for Headquarters Division of Traffic Operations staff, and District staff that work with/in the TMCs to be involved as the technical advisory group members.

1. Islam, Akm Akm.Islam@dot.ca.gov
2. Duong, Bach Bach.Doung@dot.ca.gov