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16. ABSTRACT

Fatal and serious injury (FSI) crashes in California have increased by 51.9% in the past decade. To curb this growth, Director's Policy 36 was issued for Caltrans to adopt the Safe System Approach, an approach that has proven to reduce FSI crashes by large margins in countries and cities that have adopted it. Following this, two Safe System-aligned countermeasures, cable-barriers and roundabouts, are evaluated to assess the obstacles towards their wider implementation in California. Next, training material and curriculum were created on Safe System, and some entry-level trainings of Caltrans were reviewed to assess compatibility with the Safe System Approach. In this effort, a key contribution was creating Caltrans's Safe System Framework, which builds on the Safe System Pyramid and the FHWA Road Design hierarchy concept of ordering interventions based on effectiveness. Finally, following a literature review of the state of the art in kinetic energy assessment models of intersections and risk-based network screening, a spreadsheet-based model was created based on FHWA's Safe System for Intersections. Further work on this was suspended to avoid duplication, as FHWA proceeded to create a spreadsheet-based tool on that model. Further research needs, to enable Caltrans to reach its goal of zero FSI crashes by 2050, were identified.

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Safe System Research and Implementation

FINAL REPORT

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Contract No. 65A0960

by

Ipsita Banerjee, Qianhua Luo, Jacob Champlin, Julia Griswold
Safe Transportation Research and Education Center, University of California, Berkeley
Meghan Mitman
Fehr & Peers

UC Berkeley SafeTREC

Fehr & Peers

for

California Department of Transportation

Caltrans

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Acronyms

AV	autonomous vehicle
CalSTA	California State Transportation Agency
CMF	crash modification function
CMF	crash modification function
CO	crossover
DP-36	Director's Policy 36
FHWA	Federal Highway Administration
FSI	fatality and serious injury
HQ	headquarters
HTCB	high-tension cable barrier
ISOAP	Intersection Safety and Operational Assessment Process
KEMM	Kinetic Energy Management Model
KEMM-X	Kinetic Energy Management Model for Intersections
MoI	magnitude of improvement
NHTSA	National Highway Traffic Safety Administration
OTS	California Office of Traffic Safety
SHS	State Highway System
SHSP	Strategic Highway Safety Plan
SSA	Safe System Approach
SSI	Safe System for Intersections
SWITRS	Statewide Integrated Traffic Records System
SWOT	strengths, weaknesses, opportunities, and threats
TSSG	Traffic Safety Systems Guidance
TWTL	two-way two-lane
VMT	vehicle miles traveled
VRU	vulnerable road user
X-KEMM-X	Extended Kinetic Energy Management Model for Intersections

Executive Summary

California continues to face a high rate of fatalities and serious injuries (FSIs) from roadway crashes, with over 4,500 deaths in 2022 alone, representing more than 10% of all U.S. traffic deaths. Vulnerable road users (VRUs) such as pedestrians, bicyclists, motorcyclists, and older adults have experienced particularly steep increases in FSIs over the past decade. Recognizing this, Caltrans is advancing its commitment to achieving Vision Zero, the elimination of FSIs on California's roadways, through the adoption and integration of the Safe System Approach (SSA). The Director's Policy 36 (DP-36) communicates a vision to eliminate FSIs on California's roadways by 2050 and provide safer outcomes for all communities. It requires all divisions to align their programs, procedures, and practices with the SSA as appropriate to their division. This report supports that commitment by proposing tools, frameworks, and recommendations to help embed Safe System principles throughout Caltrans's policies, programs, training, and infrastructure investments.

The Safe System Approach reflects a global paradigm shift in transportation safety, grounded in the understanding that people will make mistakes and that those mistakes should not result in death or serious injury. The approach emphasizes system design and management to reduce kinetic energy in crashes. Caltrans's role in implementing SSA includes improving roadway design, managing speeds, supporting safe behavior, accommodating safer vehicle technologies, and enhancing post-crash care.

This report aims to:

- Define a Safe System Approach from the perspective of Caltrans.
- Evaluate the alignment of a Caltrans safety program and project with the Safe System Approach.
- Evaluate two effective countermeasures, cable barriers and roundabouts, aligned with SSA, for their applicability to the State Highway System (SHS) of California.
- Review Caltrans's training programs and propose recommendations to better align with the Safe System principles; develop a training curriculum and module on Safe System.
- Recommend tools for system-wide kinetic energy risk assessment and management

Define a Safe System Approach from the perspective of Caltrans

The introduction of the report details how these five SSA elements are being operationalized across Caltrans's programs, partnerships, and planning efforts, while also identifying current limitations, such as data availability for VRUs and speed management constraints, and future opportunities. These efforts are grounded in a commitment to equity and system-wide transformation, reflecting international best practices such as Vision Zero in Sweden and Safe System strategies in New Zealand and Australia.

Evaluate the alignment of existing programs with SSA

To incorporate the Safe System Approach in Caltrans's programs and practices, the report introduces two evaluation methods:

1. **Program Evaluation Method**
   Assesses the SSA alignment of safety monitoring programs based on crash type prioritization, location identification criteria, location identification approach, and countermeasure recommendations. As a case study, this method was applied to the 2020 Cross Over Collision Monitoring Program.

2. **Project Evaluation Method**
   A modified version of Austroads's Safe System Matrix is used to assess safety improvement projects in different categories of crashes based on the magnitude of improvement (MoI) across exposure, crash likelihood, and crash severity.

Together, these tools help Caltrans identify which programs and projects are most aligned with SSA and most capable of reducing FSI.

Evaluate the application of cable barriers and roundabouts as safety countermeasures

Two high-impact and SSA aligned countermeasures were evaluated for their applicability to the California SHS. Cable barriers and roundabouts reduce kinetic energy and enhance safety system-wide. High-tension cable barriers on the median and roadside have been found to substantially reduce FSIs. Being flexible, these absorb much of the crash energy, transmitting minimum energy to the vehicle occupants. These countermeasures do not obstruct sight lines, allowing water and small animals to pass through and emergency vehicles to conveniently access the opposite side of the road by removing some posts from the sockets. However, depending on post spacing and cable tension, these barriers could allow large deflections of vehicles on impact which could cause the vehicles to cross into the opposite traffic stream. To eliminate that possibility, cable barriers are currently recommended in California on medians that are 46' or wider. By adjusting specifications to keep deflections to a minimum, cable barriers could be used on narrower medians for two lane roads in which the impact angle for hitting the median in the event of a crash would be small, which causes minimal deflection. The barriers are high maintenance, as posts might need to be repaired and the cable tension adjusted after hits. Recommendations include pilot installations on 4'–8' medians, studying Oregon DOT practices, updating specifications for motorcyclist safety, and exploring use on the right roadside and for separating Class II bike lanes. Recommendations also include studying the possibility of converting two-way two-lane roads (TWTLs) into 2+1 roads with cable barriers, to allow vehicles to pass safely.

Roundabouts are consistent with SSA because they reduce the number of conflict points and crash severity by lowering slower speeds and reducing crash angles. Multilane roundabouts witness more severe crashes than single-lane types, but design modifications such as Turbo Roundabouts can improve safety in multilane roundabouts. The report recommends broader implementation, design consideration for pedestrians and bicycles, inclusive design for older adults and people with disabilities, and the use of the Intersection Safety and Operational Assessment Process (ISOAP) tool for site selection.

Review training and educational activities & identify future research needs

A key contribution of the effort is the development of the Caltrans Safe System Framework, which synthesizes best practices and SSA concepts into a structured tool for recommending plans, policies, and countermeasures to improve safety based on context and effectiveness. Based on three roadway contexts of local access, transition, and mobility corridors, the appropriate interventions are prioritized in the following order: reducing exposure, speeds, and conflicts; improving vehicle safety and post-crash care; and ensuring redundancy through signs, education, and enforcement.

The Framework emphasizes prioritization based on effectiveness and population-level benefit, encouraging systemic safety investments that reduce the likelihood and severity of crashes. It serves as both a reference and a decision-making tool for Caltrans staff.

A 90-minute training module on the SSA and a curriculum for a 6-hour extended training were developed under this effort. Additionally, some of Caltrans's foundational training programs were reviewed to assess their alignment with SSA. These include the Basic Traffic Safety Investigator Training, Complete Streets Training, Traffic Safety Workshop, Project Engineer Academy, and Project Engineer Fundamentals. To better align these training courses with the Safe System principles, the report recommends:

- Integrating a 90-minute SSA module at the beginning of all training courses.
- Selecting FSI crash locations or locations with FSI potential as case studies.
- Discussing the process of identifying the highway context using DIB-94 and prioritizing alternative strategies to improve safety using the Safe System Framework.
- Developing proactive non-crash data sources and including information from community members and road users in decision making

These updates would ensure that Caltrans staff across roles and regions share a consistent understanding of Safe System principles.

Based on the understanding of Caltrans programs and procedures, we recommend future research needs to achieve Caltrans Vision Zero goal by 2050.

Models to advance SSA: Kinetic Energy Risk Assessment at intersections and network

The report highlights the importance of system-wide tools for evaluating kinetic energy and crash risk. It reviews models—such as KEMM-X, X-KEMM-X, and Safe System for Intersections (SSI)—that assess intersections based on speed, angle, movement complexity, and user exposure, and can help identify opportunities for kinetic energy reduction. Tools such as ViDA (iRAP) and RB-RNWS allow for proactive, network-wide screening of road segments by using the kinetic energy assessment metric including exposure, likelihood, and severity, proactively prioritizing high-risk areas for treatment without having to use crash data.

Based on Federal Highway Administration (FHWA)'s SSI, a spreadsheet-based model was developed that calculates the SSI score for a T-intersection based on a set of input values and default values. This effort was reported along with its sensitivity to various input values. Additionally, the beta version of FHWA's SSI tool was summarized.

This report provides a roadmap for institutionalizing the Safe System Approach at Caltrans. Caltrans can lead a statewide transformation in roadway safety by updating training programs, using proven safety countermeasures, adopting proactive data tools, implementing the proposed Framework, and prioritizing high-impact interventions. Achieving Vision Zero will require sustained commitment, cross-agency coordination, and ongoing investment in people and systems. With the current steps and the future research outlined, it is within reach.

1 Introduction & Definition of Safe System Approach from Caltrans's perspective

Nationwide fatalities and serious injuries (FSI) from vehicle crashes in the United States have remained high, totaling over 42,514 deaths in 2022 (NHTSA 2024). Of these, 9.9% occurred in California alone, resulting in the loss of 4,214 lives (TIMS, 2024), equivalent to about 12 fatalities per day. The magnitude of FSI crashes in California and the drastic need to further improve California's traffic safety.

The mission of the California Department of Transportation (Caltrans) is to improve lives and communities through transportation (About Caltrans, n.d.). This includes facilitating safe and reliable movement of goods and people for personal and commercial purposes, providing access to employment, healthcare, education, and other essential services, and supporting the economic and social development of communities.

While the importance of providing reliable movement is of great value, this document focuses on considerations for developing a safe world-class transportation system in California. Traditionally, while federal, state, and local agencies have recognized safety as a part of a transportation system, the focus has primarily been on the "movement" of goods and people such that the traditional performance measures spoke to "safer travel," rather than "safe" travel. This document provides an opportunity to better define a safe world-class transportation system, and how the development of a safe transportation system in California can be informed by ongoing efforts at the international and national levels.

At the heart of such a system is an aspirational objective to establish a system on which no road user can suffer catastrophic outcomes. It aims for a transportation system that does not involve trade-offs between safety, health, and mobility, nor assume an acceptable level of morbidity and mortality as part of travel. The Safe System Approach (SSA) provides both the foundation to move away from such tradeoffs and a set of principles to help agencies develop their road safety action plans. Applied in practice, the SSA principles mean that no traffic crash should be more severe than the tolerance of the human body to prevent an injury that can cause a loss of life or long-term health.

Preventing deaths and serious injuries is not only a moral imperative but also an economic one. In 2021, road crashes in the U.S. claimed the lives of 42,939 people. Of those victims, 28,358 were drivers or occupants of a motor vehicle, 7,388 were pedestrians and 7,193 were motorcyclists, bicyclists, and other non-occupants (Stewart, T., 2023). In 2019, when traffic fatalities totaled 36,096 (National Center for Statistics and Analysis, 2020), the estimated economic cost of all motor vehicle traffic crashes in the United States was $340 billion (Blincoe et al., 2022), so this cost is undoubtedly higher today.

In February 2022, Caltrans released a new Director's Policy (DP-36) to communicate its vision to eliminate fatalities and serious injuries on California's roadways by 2050 and provide safer outcomes for all communities. DP-36 requires all divisions to align their programs, plans, policies, procedures, and practices with the SSA as appropriate to their division. As stated before, this document provides important support to the DP-36 effort.

1.1 Existing Conditions

According to preliminary data from the Statewide Integrated Traffic Records System (SWITRS), there were 19,553 fatal or serious injury crashes on California roads in 2022. This is the second highest total in the past ten years, surpassed only by the 19,554 fatal or serious injury crashes in 2021. Fatal and serious injury crashes have risen 42% in the past decade. In the same period, the number of crashes with an injury of any severity fell slightly. The same pattern is reflected in injured victims, with FSI rising 42% while the number of all injured victims fell by a little less than 2%. In all, there were 5,782 more victims of fatal or serious injuries in 2022 than in 2013 in California.

These trends suggest that increasing crash severity is a leading factor in safety. One potential contributing factor is the increasing number of FSI to vulnerable road users (VRUs), such as older adults. Adults 65 and over make up a growing share of California's population. In 2022, there were 2,500 fatalities or serious injuries among older adult victims of crashes. This is a 85% increase from 1,351 such victims in 2013.

The number of FSIs among other VRUs, particularly pedestrians and bicyclists, are also increasing. These road users lack the protection of a motor vehicle and are more reliant on roadway design and driver behavior for safety. In 2022, there were 3,716 FSIs among pedestrians, an increase of 55.4% from 2,392 in 2013. Among bicyclists, there was an 27.7% increase in FSIs over the past decade, climbing to 1,456 in 2022. Motorcyclists, also lacking the protection of typical motor vehicles, suffer a high rate of FSIs. In 2022, there were 4,203 FSIs among motorcyclists, an increase of 59% from 2,643 in 2013.

Road user behaviors also contribute to increased crash severity. Higher speeds not only make crashes more difficult to avoid but also make the ensuing crashes more severe. There were 5,793 FSIs in speeding-related crashes in 2022, 59.6% greater than the number in 2013. Some motor vehicle occupants may not use vehicle safety devices such as seat belts correctly, which can contribute to increased injury severity if a crash occurs. In 2022, there were 2,743 fatally or seriously injured unrestrained occupants. This was 61.1% greater than the number in 2013.

Impaired driving also contributes to fatal and serious crashes. While the problem of alcohol-impaired driving is widely understood, state and local agencies continue to grapple with drug testing and drug-involved driving policies. In 2022, there were 4,819 FSIs in alcohol-involved crashes, up 44.2% from 3,342 in 2013. In 2022, the most recent year of final SWITRS data, there were 865 drug-involved FSI crashes, the only priority area that recorded a decrease, of 22.3%, from 2013.

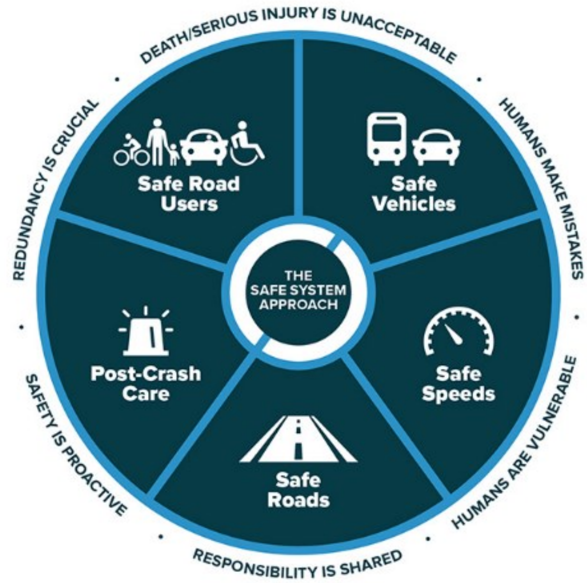
Drivers face distractions from vehicle technology or other sources. Understanding these distractions and attempts to measure their effect continue to develop as technology changes. In 2022, 699 people were fatally or seriously injured in distracted driving crashes. This is a slight increase of 16.02% from 649 in 2013, but both estimates are likely an undercount due to the challenges of gathering this information after a crash.

This burden of lost lives and sustained injuries is not equally shared. People of color, especially Native and Black Americans, are more likely to die while walking than any other race or ethnic group (Smart Growth America, 2022). Fatality rates in California among Black and Hispanic Americans have been 9 and 7 percent more, respectively, than White Americans between 2009-2018, according to Fatality Analysis Reporting System data and the American Community Survey. The same rates have been 16 percent more among American Indians and Alaskan Natives. People walking in lower income communities are also killed at far higher rates than people in more affluent areas, and less likely to have sidewalks, marked crosswalks, and infrastructure that supports safer, slower speeds. Rates of fatalities for census block groups with average household income less than $50,000 are a staggering 50 percent higher than rates in census block groups that have higher average household income (SHSP, 2022).

In a report released in early 2021, a group of leading highway engineers, scientists, and public health professionals called for a re-imagining of road safety and equity in the United States, with recommendations to adopt the SSA as a way to both improve safety and to address equity in historically marginalized and underserved communities (Safe System Consortium, 2021). Following their adoption of Safe System in 2021 as per Directors Policy 36 (DP-36), Caltrans has shifted towards a safety first vision that prioritizes road safety, aims to eliminate FSI crashes, and moves to dismantle disparities in road safety outcomes (Caltrans 2022). Similar frameworks, such as Sweden's Vision Zero, have successfully reduced their crash fatalities to 2 inhabitants per 100,000 people in 2020, compared to 12 inhabitants per 100,000 people in the United States (OECD 2021).

1.2 The Safe System Approach

The SSA is an approach to achieve the goal of zero traffic fatalities or serious injuries. California aims to achieve this goal by 2050. As described by the Federal Highway Administration (FHWA), the SSA is based on six principles that guide how to address the five elements: Safe Roads, Safe Speeds, Safe Road Users, Safe Vehicles, and Post-Crash Care as shown in Figure 1-1. Equity is a consideration throughout. Below, each principle is defined, along with its relationship with equity.



Source: FHWA.

Figure 1-1 FHWA Safe System Wheel

Death/serious injury is unacceptable. Fatalities and serious injuries are unacceptable for all communities. Caltrans will only reach the goal of zero deaths and serious injuries and ensure equity in reaching that goal by addressing disproportionate traffic injury outcomes in underserved communities.

Humans make mistakes. Unsafe behavior due to lapses in attention should not result in death or serious injury. An individual's behavior is key, but these behaviors are also influenced by the built environment.

Humans are vulnerable. Human bodies have physical limitations for tolerating crash forces without death or serious injury; therefore, it is critical to design and operate a transportation system that is human-centric and accommodates physical human vulnerabilities. Caltrans will plan and engineer the transportation system to prevent or minimize the vulnerabilities for all road users. Engaging with all road users across all communities that have suffered historical inequity—specifically tribal, low-income, and communities of color—to understand their specific concerns and priorities, and then funding, planning and implementing solutions with the communities, can minimize vulnerabilities.

Responsibility is shared. All stakeholders, including government at all levels, industry, non-profit and advocacy, researchers, and the general public are vital to preventing FSIs on our roadways. The road users, road designers, city planners, system operators as state and local agencies, and emergency medical service are all responsible. The experiences of individuals living in communities and the knowledge of experts beyond the transportation discipline must be integrated into the planning, design, and operations of a safe transportation system. Early, meaningful, and continuous public involvement can bring diverse viewpoints and values into the transportation system. To build equity into this process, communities directly affected by disparities and underinvestment in safety efforts must be integrally and meaningfully involved in these efforts.

Safety is proactive. Focusing on systematic and predictive data (such as speed, near-misses, hard-braking, and similar potential conflicts), rather than reactive (crash) data, can help identify focus areas for implementation of countermeasures. Prioritizing underserved communities and using demographic, social, and public health data in identifying risk and implementing countermeasures will help to redress disparities experienced by these communities.

Redundancy is crucial. Reducing risks requires that all elements in the transportation system be strengthened, so that even if there are multiple failures, there is sufficient safety built in to protect people across all communities.

1.2.1 Five Elements of the Safe System

The five elements of the SSA (also known as pillars in some countries) are its foundation, and the following sections discuss Caltrans' role in supporting the Safe System through those elements.

1.2.1.1 Safe Roads

The Safe Roads element recognizes the central opportunities of roadway environments to mitigate human mistakes and account for injury tolerances. Design can also serve as a mechanism to encourage safer behaviors and to facilitate safe travel by the most vulnerable users.

Safe Roads is the SSA element most relevant to Caltrans, as the steward of the State Highway System and the organization responsible for developing roadway design guidelines for the state. While "responsibility is shared," this element is a primary responsibility of Caltrans. Activities like Caltrans' safety improvement programs play a prominent role, but safety efforts should also be infused in the processes and activities of other divisions for the Department to be proactive in addressing safety concerns. This means shifting the focus toward managing crash forces to allow for human error, identifying locations with hazardous conflict points, and then addressing the location or concern regardless of crash history. Caltrans's role in land development review provides an opportunity to create the land use mix adjacent to state highways that reduce vehicular trips, thus reducing exposure. Caltrans can address historic inequities in roadway design by prioritizing safety improvements in low-income communities of color.

A few international examples support this element well. Austroads asserts that "it continues to be recognized that designing a road to standards and guidelines alone does not give a safe road system." (Hillier, 2022) Under Vision Zero, Sweden uses the principle of "Integration and Separation"; they integrate traffic elements that are compatible and separate elements that are incompatible. (Johansson, 2009) In practice, an example is 2 + 1 roads with median barriers, which are 3-lane roads that provide alternating passing lanes between the two directions of traffic but have a median barrier to eliminate the risk of head-on crashes. Sweden converted over 1,000 miles of rural roads to 2 + 1 roads within the first 10 years and saw a 79 percent reduction in fatalities on those roads. (Belin et al., 2022) In urban settings, it is important to separate vulnerable road users from high speed (greater than 20-mph) traffic. This can be done through grade separation, shortening of crossing distances, and slowing of traffic near crossings.

Caltrans' safety monitoring programs target crash types and road users associated with more serious injuries. Programmatically, these programs should prioritize roads with a high number of fatal and serious injury crashes, rather than those with high numbers of all crashes, in the location selection process; some programs have already transitioned to this prioritization. The bicyclist and pedestrian programs have begun including population characteristics in their location selection process to prioritize equity, and similar approaches may also be appropriate for the motor vehicle programs. Where possible, the safety monitoring programs could also shift to a more proactive safety approach by identifying locations with the highest risk, rather than focusing exclusively on crash history. Safety investigations should be conducted with consideration of the five SSA elements to identify how road users may be interpreting the road and how enhancements could be made to mitigate impact forces.

Caltrans also has a role in promoting the SSA statewide through its leadership and participation in the Strategic Highway Safety Plan (SHSP). This federally mandated effort requires collaboration and coordination across multiple stakeholders, including state departments and agencies as well as local agencies and organizations. In 2022, the SHSP made a "pivot" in response to rising fatalities and serious injuries by establishing guiding principles, among others, that include a focus on equity and the SSA. This pivot also established High Priority Challenge Areas to allow focus on roadway programs addressing lane departure, impaired driving, speed management and aggressive driving, pedestrians and bicyclists, and intersections.

Good quality data is critical to evaluating the safety of the transportation network so that Caltrans can proactively address hazards. Robust safety analysis requires motor vehicle and VRU exposure (volume) data, infrastructure data, and crash data. VRU data of all types pose an additional challenge due to limited availability, which has prevented Caltrans from developing safety performance functions or crash prediction models for bicyclists or pedestrians. The SWITRS team at the California Highway Patrol is an important collaborator with the Traffic Accident Surveillance and Analysis System branch for crash data on the State Highway System, but further collaboration with the California Department of Public Health and the California Emergency Medical Services Authority to match hospital and EMS data could mitigate underreporting, particularly of pedestrian and bicyclist crashes. The Crash Medication Outcomes Data Project (CMOD), a pilot program between the California Office of Traffic Safety (OTS) and California Department of Public Health, is exploring integration of medical and crash data.

1.2.1.2 Safe Speeds

The Safe Speeds element is based on the foundation that humans are less likely to survive crashes that occur at high speeds. Lower speeds can accommodate human tolerances for injury by reducing the impact forces, allowing drivers adequate time to stop, and improving visibility of VRUs and road elements.

The SSA requires a significant rethinking of how agencies set speed limits in California. Currently, speed limits are based on existing driver behavior, allowing the majority to determine appropriate speeds for a facility. If an agency wants to set a safer (i.e., lower) speed limit, they are required to install traffic calming countermeasures that slow traffic to the desired speed. In contrast, the SSA looks at what speeds are appropriate given the types of road users, the context, and the types of crashes that could occur and encourages setting speed limits so that no fatal or serious injuries could occur. With this approach, a lower speed limit is the starting point that should be increased only when there are Safe System countermeasures that separate VRUs and mitigate hazards at crossings. In New Zealand, the approach to Safe Speeds also includes consideration of underserved communities and the importance of providing "equitable access to a variety of safe and healthy transport options (Waka Kotahi NZ Transport Agency, 2022)."

Caltrans has a direct role in setting speed limits in California, by setting speed limits on the State Highway System (SHS) and defining a uniform procedure for setting speed limits throughout the state through guidance such as the California Manual for Setting Speed Limits at the Headquarters level. Statutory requirements in the California Vehicle Code, however, limit the ability of Caltrans or local agencies to apply speed limits consistent with the Safe Speeds element. When locations do not have an applicable prima facie or statutory speed limit, the speed limit must be set based on the 85th percentile speed from an engineering and traffic survey (E&TS). The Zero Traffic Fatalities Task Force, a panel of experts convened by the California State Transportation Agency (CalSTA) in 2019, identified a number of shortcomings of the 85th percentile approach and recommended developing a "context-sensitive approach to establish speed limits that prioritizes the safety of all road users." In response, the State Assembly passed Assembly Bill (AB) 43 (2021) and AB 1938 (2022) as an interim strategy to allow some discretion for local agencies to lower speed limits below the 85th percentile under certain contexts or conditions.

Caltrans is working within the statutory constraints to advance Safe Speeds in California. First, it has funded research to examine international practice, propose an SSA to setting speed limits for California (65A0808), and identify the next steps for implementation. This research is the first step towards Safe Speed limits for California and will eventually require legislation to implement. Under a second effort, the Safe Speeds T3 Project (50A0015), Caltrans has funded the development of a toolkit, web-based training, and technical assistance to disseminate the research conducted under the Zero Traffic Fatalities Task Force and provide guidance on the current prima facie and statutory speed limits in the California Vehicle Code to local agencies.

Speed management is a necessary effort, while speed limit compliance continues to be a problem. California Highway Patrol and its allied agencies are key partners for speed enforcement on the State Highway System and local roads, respectively, but these activities are labor intensive and may be subject to budget constraints. Automated speed enforcement, recently piloted in some cities in the state, is an important tool for addressing limited enforcement capacity, as well as potentially for issues related to equitable enforcement. Further, automated speed enforcement can be targeted on the roadways where it can most effectively reduce the risk of FSI crashes. Automated speed enforcement deployment must consider the disproportionate burden of traffic fines on low-income communities and the historic relationships between police and communities of color. Installing traffic calming countermeasures or building “self-enforcing” roads to reduce speed is another approach to speed management. It can be difficult to disentangle Safe Speeds from Safe Roads, which is why some countries like New Zealand consider them together in the same pillar. OTS is another important partner funding education programs, research and outreach surveys, and enforcement efforts to understand attitudes about traffic safety within the state and can play an important role in creating support among the public for speed limit and enforcement changes. These efforts are consistent with SHSP activities as well.

Caltrans’ new Speed-Related Monitoring Program, which is currently under development, provides an important opportunity to focus on high impact force crashes through coordination between Caltrans, California Highway Patrol, and OTS. The initial stage of this program relies exclusively on police-reported injury crash data, analysis of which has identified some challenges. Current guidance for reporting advises use of California Vehicle Code §22350 “speed greater than is reasonable or prudent” for all speeding crashes. This code acknowledges that there are conditions under which the posted or prima facie speed limit is not a reasonable speed. It does not, however, distinguish between drivers intentionally traveling over the posted speed limit and those who misjudged the appropriate speed for the given conditions. This distinction would be useful for better understanding crash mechanisms without reviewing crash narratives and help to distinguish between locations where infrastructure countermeasures might be more effective than enforcement or other behavioral approaches.

1.2.1.3 Safe Road Users

The Safe Road Users element encourages alert, compliant, and responsible behavior by people who use the roads. This element does not expect road users to behave perfectly, and misjudgments are expected.

Focusing on Safe Road Users involves encouraging safe roadway behavior and providing conditions that make individuals’ ability to travel safely a priority. The premise of this element is the fact that no road user makes perfect decisions 100% of the time. It is a given that drivers, pedestrians, bicyclists, and others will make momentary lapses in judgment at any one point in time. Others may choose to engage in risky behavior. The SSA puts forth that these mistakes should not result in their or other road users’ death or serious injury.

While Caltrans’ focus is on the SHS, its mission to “provide a safe and reliable transportation network that serves all people and respects the environment” and its “safety first” goal inherently include the Safe Road Users element of the SSA. Caltrans DP-36 outlines the agency's commitment to zero fatalities and the SSA as a strategy for achieving this safety goal.

Shared responsibility is a Safe System principle that too often implies that each road user—driver, pedestrian, and bicyclist—has equal responsibility to behave safely. However, shared responsibility does not mean equal responsibility. It is also not limited to roadway behavior. While all stakeholders—from drivers to system managers, vehicle manufacturers, policy makers, and pedestrians and bicyclists—are integral in reducing FSI crashes, Caltrans has underscored that shared responsibility refers to the "larger context and network of factors" contributing to roadway deaths and serious injuries, rather than individual road user behaviors (DP-36). Within California, the larger context and network may refer to policy decisions from Caltrans, SHSP actions and goals, and roadway design at a state and regional levels.

California's adoption of the SSA has brought opportunities for an extended partnership between Caltrans and OTS, the Governors Highway Safety Office in California. OTS is responsible for distributing grant funding from the National Highway Traffic Safety Administration (NHTSA) to support traffic safety education and enforcement programs. Through the SHSP—from the policy level (Executive Leadership Committee) to management (Steering Committee) to planning and implementation (Challenge Areas)—Caltrans and OTS could deepen linkages in planning and implementing evidence-based behavioral safety programs with infrastructure safety programs. One example of this linkage is Caltrans's and OTS's collaboration on public education efforts, such as the Go Safely California campaign, which features education campaigns and informational resources (templates, flyers, videos, etc.). These joint campaigns also include Changeable Message Signs addressing impaired driving, speeding, motorcycle safety, holiday messaging, etc.

The Safe Road Users focus of the SSA, as FHWA and Caltrans describes, involves the context and network in which all road users travel. The US Department of Transportation (USDOT) in its National Roadway Safety Strategy (NRSS) identifies the following as the frequent and sustained behavioral elements found in fatal crashes (US Department of Transportation, 2022):

1. Non-use of seat belts
2. Alcohol-impaired driving
3. Speeding

The connection between safe infrastructure and safe road users is clear. Caltrans sponsors several programs that are examples of "crossover" strategies between safe infrastructure and safe people. Examples of strategies include to expand the Multidisciplinary Accident Investigation Team program to examine the role of built environment and roadway environment in promoting or allowing safe behavior; explore adding pedestrian and bicycle infrastructure and volume data to the Model Inventory of Roadway Elements (MIRE) and MIRE Fundamental Data Elements; and attend equity by understanding how people (particularly pedestrians and bicyclists in communities of color) use the road; and invest in communities affected by redlining policies and consequently experiencing disproportionate pedestrian deaths (Taylor et al., 2023). Throughout all programs, promoting evidence-based approaches is critical to ensuring that road safety funds are allocated to effective programs and projects (Shelton et al., 2021).

1.2.1.4 Safe Vehicles

This SSA element focuses on the availability of vehicle systems and features that help to prevent crashes and minimize the impact of crashes on vehicle occupants and non-occupants.

Vehicle safety features are primarily regulated nationally through the Federal Motor Vehicle Safety Standards and at the state level through regulations in the California Vehicle Code. Caltrans has a limited role in these standards, which, at the state level, are enforced by the Department of Motor Vehicles (DMV) and other agencies. However, Caltrans can lead by adopting vehicle safety technologies, such as intelligent speeds assistance (ISA) and advanced driver assistance system (ADAS) features in their own vehicle fleet.

Caltrans has a greater role in partnerships to advance the safe development and deployment of autonomous vehicles (AVs). These efforts are led by CalSTA through the AV Strategic Framework and partners include federal, state, and local agencies as well as industry. Caltrans can support AVs through infrastructure accommodation and adaptation of road markers, as recently included in updates to the California Manual on Uniform Traffic Control Devices (CA MUTCD). While AVs have the potential to reduce the relevance of human error in the transportation system, safety data on AVs must be publicly available to allow for objective analysis and to ensure trust in and public support for this new technology. Equity impacts must also be considered in the funding of new technologies, when current efforts may be underfunded, as well as in the eventual access to new technologies.

Advances in vehicle technology, like the shift towards electric vehicles, can have unintended safety consequences. Electric vehicles tend to weigh several hundred to thousands of pounds more than their gasoline-powered equivalents, and research has shown that increases in weight, while safer for the vehicle occupants, significantly increases the fatality risk for the other parties in a crash (Anderson & Auffhammer, 2014). Additionally, electric motors have more powerful acceleration than gasoline engines. These factors combine to increase the potential impact forces, which may in turn be mitigated by the additional safety features included in these newer vehicles. Regardless, these fleet changes reinforce the need for “Integration and Separation” as described under Safe Roads, particularly for VRUs.

Caltrans and other state agencies can also take action within their vehicle fleets to encourage safe speeds by requiring speed limiter devices in all fleet vehicles. These devices use GPS and technology that reads speed limit signs to prevent vehicles from surpassing the speed limit. The European Union (EU) has required this technology on new motor vehicles since 2022. While similar regulations would likely meet resistance in the US, application to fleet vehicles can improve safety while also reducing state spending on fuel and improving climate goals.

Ignition interlock devices (IIDs) that prevent a vehicle from starting if alcohol is detected on the driver’s breath are encouraged as a Vision Zero countermeasure in Sweden for both fleet vehicles and driver’s suspected of alcohol-impaired driving. In California, installation of IIDs can be ordered by a court or may be required for certain driving under the influence (DUI) offenders to retain driving privileges through the DMV. Equity needs to be considered here, e.g., when offenders are required to purchase their own IIDs.

1.2.1.5 Post-Crash Care

This SSA element seeks to enhance the survivability of crashes through expedient access to emergency medical care, while creating a safe working environment for vital first responders and preventing secondary crashes through robust traffic incident management practices.

Post-crash care is critical in a Safe System. Timely trauma care at a Level I trauma center improves chances of survival from a serious injury crash by up to 25 percent (USDOT, 2022). In the US, only 19 percent of the population lives in rural areas, yet over 50 percent of traffic fatalities are in rural areas (Doggett et al., 2019). Distance from and scarcity of trauma centers and EMS activation, response, and transport time are factors in disproportionate rural mortality risk.

Caltrans may work to prevent secondary crashes, such as traffic death and injury among first responders through continued implementation of its "Move Over, Slow Down" provisions, expanded in 2021 to include local streets and roads in addition to freeways.

Continued coordination of Caltrans with SHSP and Traffic Records Coordinating Committee (TRCC) partners to improve rural roads will help achieve Safe System goals.

1.3 Summary

The introduction provides an overview of some of the progress made by Caltrans and the other state agencies toward implementing a Safe System Approach. It identifies further considerations for achieving a Safe System and the role of equity in that system. Caltrans could consider conducting further research to identify detailed measures to integrate the Safe System Approach in all its internal functions as well as external road safety engagement efforts.

This study has six chapters that help define an SSA from the perspective of Caltrans. This research aims to distinguish the SSA from traditional safety frameworks and reviews its core principles and applicability to Caltrans. Chapter 2 describes the development of an evaluation method for quantifying the alignment of existing Caltrans safety programs and projects with the SSA. Chapter 3 and 4 respectively evaluate two safety countermeasures that have been widely accepted to reduce FSI, cable barriers and roundabouts respectively, for their suitability with roads and intersections in California. These evaluations analyze case studies of their implementation in other state transportation departments and look at best practices, their benefits, and potential drawbacks. Chapter 5 documents the evaluation of Caltrans's traffic safety training and educational activities that was conducted to assess their current alignment with SSA and provide recommendations on potential improvements. This chapter additionally discusses Caltrans's future research needs to achieve Caltrans Vision Zero by 2050, including recommendations for development of technical models for application in Caltrans safety assessments. Chapter 6 provides a review of currently available kinetic energy management models for intersections, other intersection assessment processes and tools, state of the art in network evaluation, and a recent method for risk-based network screening. Benefits, challenges, and best practices of these models are provided to further inform traffic safety experts of possible integration of these models into Caltrans's processes. Chapter 7 describes an early-stage spreadsheet-based version of FHWA's Safe System for Intersections (SSI) model developed by SafeTREC, as well as the beta version of the tool based on SSI developed by FHWA. Chapter 8 concludes this research effort.

2 Evaluation of Alignment of a Program and a Project with the Safe System Approach

This chapter focuses on developing a method to evaluate Caltrans's safety monitoring programs for alignment with the Safe System Approach (SSA). The proposed method consists of two evaluation frameworks—one for evaluating safety monitoring programs at the statewide program-level and the other for evaluating safety improvement projects proposed in the monitoring program by districts, at the individual project level. The two evaluation frameworks are explained through case studies by evaluating the 2020 Cross Over Collision Monitoring Program for the program-level evaluation, and one project location for the project-level evaluation.

The details of the location for project evaluation and the outcome of evaluation are not published to ensure data privacy for Caltrans.

2.1 Background

The Federal Highway Administration (FHWA) has the vision of zero deaths on the nation's roadway system and recognizes Safe System as the way to get there. Caltrans has issued the first Director's Policy on Road Safety (DP-36) with the expressed goal of eliminating fatalities and serious injuries on California roads by 2050 through the adoption of the SSA. The SSA is a worldwide movement that has been practiced for more than 30 years with significant long-term reductions in fatalities and serious injuries. It is grounded in an ethical imperative that no one should be killed or seriously injured when using the roadway system. The SSA has a fundamental objective to eliminate fatal and serious injuries for all road users by accommodating human errors, incorporating redundancies, and keeping impacts on the human body at tolerable levels. The core principles of a Safe System are as follows: 1) Death/serious injury is unacceptable; 2) Humans make mistakes; 3) Humans are vulnerable; 4) Responsibility is shared; 5) Safety is proactive; 6) Redundancy is crucial. These principles are used as guidelines to address issues related to the five SSA elements: safe roads, safe speeds, safe road users, safe vehicles, and post-crash care. To reach a safe transportation network, all five elements should be considered and implemented (FHWA, n.d.).

To implement the SSA, it is critical to understand how well the current safety policies, procedures, and practices are aligned with the SSA, such that areas for potential improvements can be identified. Several practices exist to evaluate the alignment of existing programs or projects with the SSA. For example, at the program level, FHWA qualitatively analyzes the Highway Safety Improvement Program in comparison against the six principles of the SSA and assigns it a level of alignment ("Full Alignment", "Partial Alignment", or "Minimal Alignment/Not Applicable") (Finkel et al., 2020).

On the project level, Austroads, the peak organization of Australasian road transport and traffic agencies, developed a Safe System assessment framework that can help assess how closely road design and operations are aligned with the Safe System objectives of eliminating fatal and serious injuries (Turner et al., 2016). The major component of the assessment framework is the Safe System Matrix, which quantitatively determines how well a given project is aligned with the Safe System principles. Specifically, the matrix assesses different major crash types that contribute to fatalities and serious injuries (FSIs) against three risk elements: exposure to that crash risk, the likelihood of it occurring, and the severity of the crash should it occur. Seven crash types are considered in the matrix, including run-off-road, head-on, intersection, other (incorporating all same direction, maneuvering, overtaking, on path and miscellaneous crashes), and crashes related to vulnerable road users: pedestrian, cyclist, and motorcyclist. Each column in the matrix corresponds to a crash type and each row corresponds to one of the three risk factors they are evaluated against. Each cell is assigned a score from 0 to 4, based on subjective assessment of different factors, such as roadway environment, infrastructure, and traffic operation. A score of zero indicates the system is fully aligned with the Safe System vision for that component of the given crash type. The product of each column represents the alignment with Safe System for that specific crash type, with a rationale behind multiplication that if any risk element (i.e., exposure, likelihood, or severity) of a crash type receives a score of zero, that crash type should be seen as having reached a Safe System and thus eliminated from the score. And the sum over all the crash types is the final score for the whole system. The total score is out of a possible 448, representing the safer speed, safer roads, and roadsides pillars. The closer the score is to zero, the more aligned the project is with Safe System principles.

Caltrans has a vision of zero road FSIs by 2050, and the SSA is how Caltrans intends to achieve this vision. One vital part of achieving this goal is through the set of safety monitoring programs. Safety monitoring programs take a data-driven approach to reduce fatalities and serious injuries and provide a regular mechanism for monitoring the safety of the State Highway System. Each program focuses on resolving issues related to a specific type of crash associated with higher fatalities and serious injuries. Headquarters (HQ) first identifies a list of locations that have potential safety issues related to the target crash type, using a specific set of screening criteria. HQ then provides Districts with the list of identified locations to investigate, along with a list of recommended countermeasures that can be considered to address issues related to the crash type. Districts then complete a site investigation and safety analysis for locations on the list, document the investigation in a Traffic Investigation Report with the identified issues at each location, and propose safety improvements if they think it is necessary.

DP-36 directs, “All Divisions shall align their programs, plans, policies, procedures and practices with the SSA as appropriate to their division” to achieve Caltrans’ Vision Zero. With their critical role in the path to Vision Zero, safety monitoring programs thus should fully align with SSA. As such, part of this report proposes an assessment method to evaluate the alignment of Caltrans safety monitoring programs with the SSA. In addition, because the safety improvement projects proposed by the districts are critical to advancing the investigated locations towards a Safe System outcome, this chapter also proposes an assessment method to evaluate the Safe System benefit of safety improvements projects.

In the following sections, we first present the proposed SSA alignment evaluation method, which consists of a program evaluation method and a project evaluation method, followed by the scoring system of the method and the scoring table. Then, we apply the program evaluation method to the 2020 Crossover (CO) Collision Monitoring Program as a case study to evaluate its alignment with the SSA. Subsequently, the project evaluation method is applied to one location identified by the program to evaluate the Safe System benefit of the safety improvement project proposed by the district. Finally, we conclude the report by discussing the recommendations on increasing the SSA alignment of the CO monitoring program, potential usage of the proposed evaluation method, caveats on applying the project evaluation method, and possible improvements to overcome the subjectivity in project evaluation.

2.2 Method to Evaluate Alignment with SSA

In this section, we present the SSA alignment evaluation method that we propose. It consists of two evaluation methods, one for the safety monitoring program and one for the safety improvement projects proposed by the districts under the program. Table 1 shows the detailed information on the two evaluation methods that we propose.

2.2.1 Program Evaluation Method

For the ***program*** evaluation, we propose to evaluate the SSA alignment of a ***safety monitoring program*** based on four aspects:

- targeted crash type;
- location identification criteria;
- location identification approach; and
- countermeasure recommendations.

Each aspect is examined against one or more relevant Safe System principle.

Targeted crash type: We examine targeted crash type against the principle of "death and serious injury is unacceptable" by checking whether it is a major contributor to FSIs in California. A safety monitoring program that focuses on a crash type that contributes to a high proportion of statewide FSI can be of greater help in eliminating FSI within the system.

Location identification criteria: We examine the location identification criteria against the principle of "death and serious injury is unacceptable" by assessing the extent of priority given to FSI crashes in the screening procedure. A SSA aligned program would prioritize locations more likely to have FSI crashes.

Location identification approach: We examine the location identification approach against the principle of "safety is proactive" by checking how proactive the method is in identifying locations with latent safety issues. Instead of solely relying on historical data, an SSA aligned safety monitoring program would be able to identify locations with high crash risk based on its characteristics (e.g., geometric design and traffic operations). This would enable Caltrans engineers to identify issues with locations that might have limited crash data but high crash risk.

Countermeasure Recommendations: We examine the proposed countermeasures against the principle of “human is vulnerable” by checking whether Safe System treatments are included in the list. While various safety countermeasures exist, those that can prevent an FSI crash or reduce the severity of a crash have a greater benefit in protecting humans and progressing towards Vision Zero. For example, median barriers are a Safe System treatment effective in reducing head-on FSI crashes (Beer, 2021). As such, those could be recommended for locations that are at a higher risk for such crashes.

To summarize, within the proposed program evaluation methodology, safety monitoring programs that do the following would be considered in higher alignment with the SSA: targeting crashes that result in greater FSIs, prioritizing locations with high FSI risk, proactively selecting possible locations of such crashes based on site characteristics, and recommending countermeasures to prevent FSI crashes or to reduce their impact.

2.2.2 Project Evaluation Method

At the ***project*** level, we propose to evaluate whether the ***safety improvement projects*** proposed by the districts will produce a better Safe System outcome for the investigated location. Specifically, we propose to quantify the Safe System benefit of the ***safety improvement projects*** using a modified version of the Safe System Matrix from Austroads**.**

2.2.2.1 The Modified Safe System Matrix

Like the original Safe System Matrix, the modified Safe System matrix evaluates the ***seven major crash types*** (run-off road, head-on, intersection, other crashes, pedestrian, cyclist, motorcyclist) against the ***three risk elements***: exposure, crash likelihood, and severity based on factors that can potentially affect the risk element (see Factor Inventory in Table A3-1). A score between zero and four is assigned based on the evaluation of the factors according to the scoring system (Table A3-2), with a zero indicating a full alignment with the Safe System vision for that component of a given crash type, and a four indicating the worst alignment.

To incorporate objectivity in the evaluation, the modified matrix evaluates the severity of a type of crash, based on the probability of an FSI for the target vehicle/vulnerable road users under the current speed limit. An FSI is defined as clinically serious injury, Maximum Abbreviated Injury Score of 3 or more (MAIS3+) here. According to the KABCO-to-MAIS Translators by NHTSA , the proportion of No Injury (O), Possible Injury (C), Non-Incapacitating (B), Incapacitating (A), Fatality (K), and Injured, Severity Unknown (U) in KABCO reported as MAIS3+ is 0.37%, 2.364%, 4.741%, 31.441%, 100%, and 3.5%, respectively (Wang, 2023).

Given the speed of the bullet vehicle, the P(FSI) is approximated with the risk curve developed by Jurewicz et al. (Jurewicz, 2016), and a score from 0 to 4 is assigned based on the approximated P(FSI) (See Table A3-2 for details).

2.2.2.2 Safe System Benefit - Magnitude of Improvement (MoI) at the Location

To quantify the Safe System benefit of a ***safety improvement project***, a before-after analysis is conducted on the investigated location with the modified Safe System Matrix to obtain the Safe System score of the investigated location before ($Score_{i,before}$) and after ($Score_{i,after}$) implementing the proposed safety improvement project. The Safe System benefit of the proposed project, denoted as the magnitude of improvement (MoI) on location i, is then calculated as:

$$MoI_i = \frac{Score_{i,before} - Score_{i,after}}{448} * 100\%$$

The safety improvement projects proposed by the districts should alleviate issues related to the targeted crash type while not increasing the possibility of occurrence or impact of the other crash types (i.e., not worsening the safe system alignment of the other crash types). As such, a safety improvement project that will benefit the investigated location will have a positive *MoI*. The higher the MoI, the greater the Safe System benefit is. Table 2-1 lists the evaluation methodologies for Programs and Projects.

Table 2-1 Evaluation Methodologies for Programs and Projects

Method	Aspect	Details	Safe System Principle
Program	Targeted Crash Type	How much FSI is attributed to this type of crash	Death/Serious Injury is Unacceptable Responsibility is shared
	Location Identification Criteria	Whether FSI crashes are the focus	Death/Serious Injury is Unacceptable Humans make mistakes
	Location Identification Approach	Whether the approach is reactive or proactive	Safety is Proactive
	List of countermeasures	Whether Safe System countermeasures are promoted	Humans are vulnerable Redundancy is crucial
Project	Safe System benefit (MoI)	Whether the safety improvement project will produce a better Safe System outcome for the investigated location	Death/Serious Injury is Unacceptable Humans are vulnerable

2.2.3 Scoring System

The scoring system of the two evaluation methodologies is shown in Table 2-2. We develop an evaluation matrix to rate 1) ***the alignment of the examined aspects*** of the safety monitoring program with the corresponding Safe System principle and 2) ***the overall Safe System benefits*** of all the safety improvement projects proposed under the program. The rating is on a scale from 1 to 4, with a 4 indicating a high SSA alignment/overall Safe System benefit and a 1 indicating the opposite.

2.2.3.1 Program

For the ***crash type targeted*** in the program, we assign the score based on the proportion of roadway FSI crashes in California this crash type represents. If the targeted crash type accounts for more than 30% FSI crashes in California in the past 5 years, improvements that help reduce the number and severity of this type of crash help move towards Vision Zero. Therefore, the program target will score a 4 for its SSA alignment. On the contrary, if the targeted crash type accounts for less than 5% of FSI in California, a focus on this crash type will probably not help much in achieving the Vision Zero goal and thus will score a 1.

For ***location identification criteria***, the criteria will score a 4 if locations are screened with an emphasis on FSI crashes, while a 1 if no emphasis is placed on crash severity level. As for the ***location identification approach***, systemic and robust location identification approaches contribute more to proactive safety. A program that adopts the Highway Safety Manual's crash prediction module, which combines safety performance function (SPF) and crash modification function (CMF) to predict crash risk, in the location identification process will score a 4, as it proactively identifies locations with potential high crash risk based on roadway features. In contrast, a program that identifies locations based on historical crash records alone can only reactively address spot-related issues and thus will score a 1.

Lastly, for ***countermeasure recommendations***, the list of recommendations will score a 4 if it is dominated by Safe System countermeasures (e.g., cable barriers), a 3 if it is dominated by highly effective conventional countermeasures, a 2 if it is dominated by effective conventional countermeasures, and the lowest score of 1 if the countermeasures recommended are not specific to the crash type and/or their effectiveness is unknown.

2.2.3.2 Project

The overall Safe System benefit is defined as the average of the MoIs across all the investigated locations under the safety monitoring program, which represents the average Safe System benefits of all the safety improvement projects proposed under the program. A score from 1 to 4 is assigned based on the magnitude of the average MoI. An average MoI greater than 50% means all the safety improvement projects proposed by the districts together have a great Safe System benefit in reducing FSIs and will be assigned a score of 4. In contrast, an average MoI less than 0 means the safety monitoring projects proposed by the districts together will not help Caltrans move towards the goal of eliminating FSI crashes within the system, and will be assigned a score of 1.

Table 2-2 Scoring System

Method	Aspect	1	2	3	4
Program	Targeted Crash Type	Accounts for ≤5% total FSI	Accounts for <5% and ≤10% total FSI	Accounts for <10% and <30% total FSI	Accounts for >30% total FSI
	Location Identification Criteria	Don't consider crash severity	Partly consider crash severity	Consider both fatality and injuries	Consider fatality and serious injuries
	Location Identification Approach	Spot	Corridor	Systemic matrix	Crash prediction module
	Countermeasures	Any countermeasures	Effective countermeasures	Highly effective countermeasures	Safe System countermeasures
Projects	Overall Safe System benefits: Average MoI (%)	≤0	>0 and ≤25%	<25% and ≤50%	>50%

2.2.4 Evaluation Table

Table 2-3 shows the evaluation table. Each aspect has a maximum score of 4. The total score for the program evaluation is 16 and the score for the overall Safe System benefits across all safety improvement projects is 4, which sum up to a total score of 20.

Table 2-3 Safe System Approach Alignment Evaluation Table

Method	Aspect	Details	Score
Program	Targeted Crash Type	For example, Cross over crashes	/4
	Location Identification Criteria	For example, All and fatal crashes	/4
	Location Identification Approach	For example, Historical crash data	/4
	Countermeasures	See Table 2-4	/4
Projects	Overall Safe System benefits: Average MoI (%)	Scoring exposure, likelihood and severity of different crash types before & after	/4
Overall score			**/20**

2.3 Case Study of the Proposed Evaluation Method

In this section, we apply the program evaluation method to the 2020 Cross Over (CO) Collision Monitoring Program as a case study to assess its alignment with the Safe System Approach. In addition, we apply the project evaluation method to one investigation in District 7 to evaluate the Safe System benefit of a safety improvement project proposed by the district. Caltrans engineers, with access to all the Traffic Investigation Reports, can apply the project evaluation method to all the locations identified by the districts to obtain the overall Safe System benefits of all the safety improvement projects proposed under the program.

2.3.1 Program Evaluation

Vehicles crossing into an opposing lane and colliding head-on with vehicles traveling in the oncoming direction often result in more FSIs than other types of crashes do. To reduce FSIs in the road system, it is critical to address issues related to crossover crashes. The 2020 Cross Over (CO) Collision Monitoring program is part of such an ongoing effort. The purpose of the program is to reduce the number and severity of crashes that involve two or more vehicles traveling in opposite directions.

Caltrans HQ screened locations using historical crash data from Traffic Accident Surveillance and Analysis System.

To reduce crossover crashes, the program suggested a list of incremental safety countermeasures, shown in Table 2-4, for districts to consider. Districts are encouraged to implement incremental safety countermeasures, either independently or in combination at the identified location, based on their engineering judgement on necessity and appropriateness.

Table 2-4 Type of Improvements

Countermeasures	Details
Inside shoulder rumble strips	Standard Modified (sinusoidal)
Inside edge line rumble strips	Standard Modified (sinusoidal)
Centerline rumble strips	Standard Modified (sinusoidal)
Channelizers for conventional highways	
Buffer zones in combination with rumble strips	
Reduce/eliminate passing areas or improve passing sight distance	
Lane and inside shoulder widening to incorporate above improvements	Lane
Median barriers	Cable barriers Concrete Beam guardrail

2.3.2 Project Evaluation

We apply the project evaluation method to the investigated location as a case study to evaluate the Safe System benefit of its proposed safety improvement project.

2.3.2.1 Location Description (A Two-lane Mountain Road)

The investigated location is a 5.25-mile segment. It is a two-lane mountain road. The segment consists primarily of asphalt concrete pavement, with vertical alignment of positive (ascending) and negative (descending) grade in east and west bound directions, and horizontal alignment of reverse curves and tangent sections. The east and westbound lanes are both 12 feet wide, divided by double yellow striping with recessed pavement markers. Both the north and south borders of the travel way are bounded by a solid painted white line, with varying width of asphalt and dirt shoulder. There are two passing lane sections in the eastbound directions. A few turnouts are presented in each direction within this segment. The posted speed limit in the area is 40 mph and the curve advisory speed is 25 mph and 35 mph. However, as indicated by the report, the operating speed can be greater than or equal to 45 mph. Investigators conducted a field review and found striping, pavement markers and pavement in standard condition. Signs were found in either standard, good, missing, or damaged conditions.

2.3.2.2 Safety Improvement Project

A total of four crossover fatal crashes occurred in this segment during the investigated 5-year period. After investigation, the district concluded that all fatal crashes were due to driver error, including crossing over the double yellow line and speeding.

As such, the district proposed to 1) develop sign installation order for G69 (CA), W1-3, W13-1P AND W4-2 signs (See Figure 2-1); 2) revisit conceptual motorcycle safety sign (Figure 2-2); and 3) contact maintenance to repair or replace speed feedback sign (Figure 2-3).

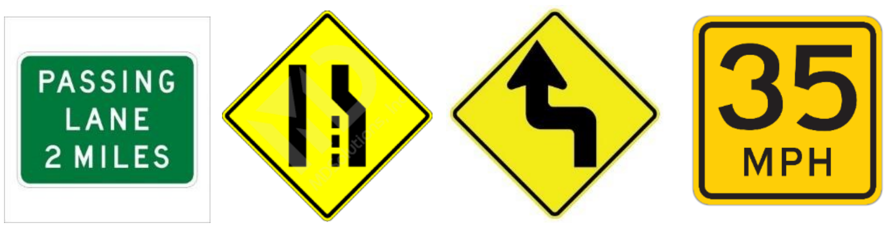


Figure 2-1 Signs to be installed (from left to right: G69 (CA), W4-2, W1-3, W13-1P

Figure 2-2 Speed feedback sign

Figure 2-3 Conceptual motorcycle safety sign

2.3.2.3 Before-after Analysis

A before-after analysis is conducted to evaluate the extent to which the safety improvement project proposed by the district will improve the Safe System alignment of the investigated location. The modified Safe System Matrix is applied to get the Safe System score of the investigated location before and after the implementation of the safety improvement project. When applying the Safe System Matrix, factors to be considered when evaluating each risk element (e.g., likelihood) of a specific crash type (e.g., run-off-road crash) are referred to the factor inventory (Table A2-1). And the score of each risk element is assigned according to a modified scoring system (Table A2-2).

2.4 Comparison with FHWA Safe System Project and Policy-Based Alignment Framework

The FHWA spreadsheet-based Safe System Alignment Frameworks allow practitioners to quantify alignment of projects and policies with Safe System principles and elements (Scurry et al., 2024). Table 2-5 lists the differences between the current effort in evaluating Caltrans's safety programs, and FHWA's framework in evaluating policies.

Table 2-5 Comparison with FHWA policy alignment framework (Federal Highway Safety Programs, 2024a)

<table>
<tr><th>Caltrans's program alignment method</th><th>FHWA's policy alignment framework</th></tr>
<tr><td>Evaluates Caltrans's crash programs, aimed at specific crash types, such as run-off-road, crossover, for alignment with Safe System.</td><td>Evaluates policies for alignment with Safe System.</td></tr>
<tr><td>Method evaluates each of the following:
targeted crash type,
location identification criteria,
location identification approach, and
countermeasures used.</td><td>Scoring assumes that alignment follows a five-level adoption process, as listed, with lower scores for earlier levels.
Initiation
Development
Execution
Evaluation
Integration</td></tr>
<tr><td>For each criterion, the method evaluates extent of alignment to relevant principles, as follows:
targeted crash type is selected based on the principle that death and serious injury is unacceptable
location identification criteria are selected based on the principle that death and serious injury is unacceptable
location identification approach is selected based on the principle that safety is proactive
countermeasures used are assessed to be effective and safe system aligned</td><td>For each Safe System principle (and equity), the policy is evaluated for alignment at one of the five levels listed in the above discussed comparison.</td></tr>
</table>

The FHWA method also includes a project-based alignment framework. Its differences with the methods proposed in this effort are listed in Table 2-6.

Table 2-6 Comparison with FHWA project alignment framework (Federal Highway Safety Programs, 2024b)

Caltrans's project alignment method	FHWA's project alignment framework
Evaluates exposure, likelihood, and severity for each of seven different crash types: run-off-road, head-on, intersection, other, pedestrian, cyclist, motorcyclist.	Evaluates exposure, likelihood, and severity for two broad categories of crashes, i) involving vulnerable road users and ii) motor vehicles.
The method is developed for the specific project evaluated.	Detailed framework lists different types of risk factors, roadway conditions, topographical risk, intersection geometry, speeds etc. for road segments and for intersections.

Compared to FHWA's project alignment framework, Caltrans's program alignment method is robust in evaluating its different crash programs. While it does not evaluate each Safe System principle explicitly as the FHWA framework does, it considers the principles applicable for the criterion being discussed. The FHWA framework is geared towards evaluating policies and performs well for that function.

For project alignment, the Caltrans evaluation method is worthwhile as it evaluates the roadway conditions and risk factors mentioned in the Traffic Investigation Report for seven different crash types. The FHWA framework uses the exposure, likelihood, and severity method for crashes with motorized vehicles and vulnerable road user only without further categorization. However, the FHWA methods lists all roadway conditions and risk factors in detail for intersections and for road segments. This list would be useful for Caltrans to include in its evaluation of locations for which the data is available.

2.5 Conclusion

This chapter proposes a method to evaluate the alignment of Caltrans's safety monitoring programs with the SSA. The method consists of two evaluation methods, one to evaluate the SSA alignment of a safety monitoring program and the other to evaluate the safety improvement projects proposed under the program on their safe system benefit. The program evaluation method measures the extent to which a program is aligned with the Safe System Approach in terms of targeted crash type, location identification criteria, location identification approach, and the list of countermeasures suggested by the program. The project evaluation method adopts a modified version of the Safe System Matrix from Austroads to quantify the magnitude of improvements of the investigated location under the safety improvement project. The two methods are then applied to the 2020 Cross Over (CO) Collision Monitoring program, and to one project location under the program as case study.

Based on the ***program evaluation***, we identified that the location identification criteria, location identification approach, and the list of countermeasures for the CO Collision Monitoring program could be improved to align more with SSA. To that end, Caltrans could take the following steps:

- Increase weight on *FSI* instead of equal weight on all crash types when developing the location identification criteria (e.g., select locations based solely on the number of FSIs it had in the past five years and on the probability of FSIs occurring at that location).
- Use robust estimates of crash risk with historical crash data (where available) when screening locations, to proactively include locations with high crash risk on the list.
- Promote Safe System countermeasures, that is, countermeasures that are effective in preventing or reducing the impact of FSIs (e.g., median barrier, rumble strips, double yellow median striping, etc.) when suggesting types of improvements.

The program is well aligned with the first criterion of selecting crash types that cause the most FSIs.

The program evaluation method is beneficial to Caltrans in several ways:

- It helps identify the areas of improvement to increase the Safe System alignment of a safety monitoring program.
- It can be used to track the progress towards SSA alignment of a safety monitoring program. As the alignment score goes up, the program becomes more capable of addressing safety concerns related to FSI crashes by proactively identifying and recommending countermeasures for locations with high FSI risk.
- The evaluation score produced by the method could also be used as a metric to compare the Safe System benefits of different monitoring programs. A program with a high SSA alignment score has greater potential in eliminating FSI in the system and can be prioritized when allocating budgets.

The proposed ***project evaluation*** method, on the other hand, could inform Caltrans whether or not the safety improvement projects proposed by the districts would benefit the investigated location from a Safe System perspective. A safety improvement project with a high MoI suggests the project will make the investigated location more aligned with the Safe System objective and thus is worth implementing, whereas an investigation project with a low MoI suggests the Safe System benefit of the project is marginal and thus needs further consideration.

2.5.1 Limitations

The project evaluation method has some limitations. First, when evaluating the exposures for vulnerable road users, information on the volumes of pedestrians, cyclists, and motorcyclist is usually not available. As such, assumptions on the exposure of vulnerable road users need to be made during evaluation, which might not reflect the actual count. Second, the likelihood evaluation—how likely a crash type is under current infrastructure and traffic operation and how much a countermeasure can lower that likelihood—is subjective. Future methods could incorporate crash reduction factor to help determine the impact of countermeasures in reducing crash likelihood in a more objective manner. Lastly, the crash severity evaluation brings in some objectivity by incorporating the risk curve, yet the score assignment is sensitive to the evaluator's assumptions about drivers' behaviors. For example, in the after-analysis of the case study, we assume the installation of a speed feedback sign or advisory speed sign can reduce the driver's operation speed by notifying them of the advisory speed or speed limit and providing speed feedback. However, it is difficult to determine, by how much, if any, the travel speed will decrease with the signs present. Practitioners could acknowledge that the score assigned based on the assumption on driver’s conformity might exaggerate the actual safety benefit of the countermeasures.

3 Evaluate the Application of Cable-Barriers as Safety Countermeasures by Caltrans

The objective of this chapter is to identify opportunities for expanding the use of cable barriers by examining successful installations by other transportation agencies. A summary of our findings obtained by a review of the available literature and interviews of Caltrans engineers is provided.

In 2022, Caltrans's first Director's Policy on Road Safety (DP-36) adopted the Safe System Approach (SSA) as the framework for eliminating fatalities and serious injuries (FSIs) in California. SSA focuses on making roadway infrastructure more forgiving and keeping the impact to humans in crashes at a tolerable level (USDOT, 2022). As highlighted in the Strategic Highway Safety Plan (SHSP), lane departure crashes are the topmost safety challenge in California. California has used safety barriers to protect errant vehicles from crashes with roadside hazards and with oncoming traffic. In comparison to other types of barriers, cable barriers are known to be more effective in absorbing kinetic energy in crashes (FHWA Highway Safety Programs, n.d.). This can reduce the impact of crashes on vehicle occupants.

As cable barriers do not obstruct sight, they are safer and more aesthetically pleasing. They allow water to flow through, small animals to pass through, and emergency vehicles to easily access the opposite traffic by just removing a few poles. The barriers are double-sided, i.e. take impacts from both sides, and are far less expensive than concrete barriers and even metal beam barriers, depending on pole spacing.

However, there are concerns about the use of cable barriers as a Safe-System-aligned safety countermeasure:

1. The deflection of cable barriers, as currently specified for Caltrans, could cause vehicles to cross over the median into the opposing stream of traffic.
2. Maintenance of the barrier is needed following an impact, whereas concrete barriers require no post-crash maintenance. Cable barriers require inspection of the posts and wire tension after every impact, and possibly inspection for temperature changes, depending on manufacturer's specifications. Repairing cable barriers on narrow two-way two lane (TWTL) roads amounts to closing the road and blocking access for all road users including for emergency vehicles. Even for roads with multiple lanes, repairing barriers in narrow medians necessitates closing some lanes. The additional maintenance requirements increase the exposure of maintenance personnel to high-speed traffic and necessitate the use of mobile barriers and truck attenuators to mitigate that.
3. It needs to be determined whether cable barriers are as safe for motorcyclists as the other barriers or the lack of any barrier.

To address these issues for medians, Caltrans's Traffic Safety Systems Guidance (TSSG) suggested a minimum width of 46 feet or, for medians with no plantings, 36 feet after consulting with HQ

Traffic Safety Systems branch for installing cable barriers (Caltrans, 2019). All installations required approval by the Deputy District Director of Traffic Maintenance and, until recently, also by the Deputy District Director of Traffic Operations. The TSSG is currently under revision.

Cable barriers deflect minimally at low crash angles. This is the case with narrow medians, given the small offset from the travel lane, especially for roads with fewer lanes as in the TWTL roads. Manufacturers could offer specifications for the deflection to be contained within the width of the narrow median. Safe System specialists recommend high-tension cable barriers in place of clear zones since they absorb crash energy and prevent possible rollover crashes. Many successful deployments nationally and internationally support the claim that these offer an inexpensive way of reducing FSI crashes on the many miles of the State Highway System (SHS) that do not have any barriers. It is important to assess maintenance needs and recommend installations on a case-by-case basis, depending on the availability of alternative routes to traffic and emergency vehicles. Studies on whether cable barriers are more dangerous for motorcyclists compared to other barriers, or to absence of a barrier, have been inconclusive.

We recommend that Caltrans work with the manufacturers of Manual for Assessing Safety Hardware (MASH)–approved barriers to create specifications with appropriate post spacing and cable tension to keep the deflection within the median width for the impact angle and speed combinations of the specific road. We propose that Caltrans also work with the manufacturer to create specifications that improve safety for motorcyclists. Several states have installed cable barriers in narrower medians, including in snowbound conditions. Caltrans could create guidelines for safe inspection and repair of cable barriers based on their examples. Finally, Caltrans could convert TWTL roads to 2+1 roads where right of way permits, to enable maintenance personnel to repair the barrier without closing the road completely.

A summary of our findings from case studies, manuals, and interviews with Caltrans engineers is presented here. Seven interviews were conducted. The respondents included lead engineers from the Division of Safety Programs (Office of Safety Systems and Devices) and the Safe System Leads or their representatives from five Districts. In the interviews, Caltrans engineers explained the countermeasure selection process, discussed advantages and limitations of cable barriers, and possible challenges to wider application of cable barriers in California. Some discussed projects in which they have proposed cable barriers. Their input informs the section on countermeasure selection and the strengths, weaknesses, opportunities, and threats (SWOT) analysis.

3.1 Background

Cable barriers are flexible barriers made from steel cables mounted on semi-rigid steel posts. In the event of a crash, these absorb energy from the crash capturing or redirecting the vehicle and thereby direct less energy towards the vehicle occupants (FHWA Highway Safety Programs, n.d.). High-tension cable barriers prevent serious injuries and fatalities on the road system as observed in the United States and abroad. Based on interviews with the California Department of Transportation (Caltrans) engineers and studies conducted on this countermeasure, this chapter outlines the suitability of implementing these on a wider scale in Caltrans business practices and operations.

Following Caltrans' Director's Policy 36 (DP-36) and the National Roadway Safety Strategy, Caltrans is committed to adopting the Safe System Approach (SSA), which focuses on eliminating fatalities and serious injuries (FSIs), even if that amounts to an increase in minor crashes. Additionally, the revised federal guidelines for Highway Safety Improvement Program also focus on the SSA. Cable barriers are among Safe System countermeasures that have been installed on the State Highway System (SHS) in California, including freeways and expressways, at locations in which the available median width is greater than 46 feet, and greater than 36 feet for medians with no plantings. The aim of this study is to explore opportunities for installing cable barriers in narrower medians.

3.1.1 Terminology

In this chapter, Thrie-Beam and W-Beam barriers are collectively referred to as metal beam barriers. These differ from the existing railing or barrier type 'metal beam barrier' referred to in the Traffic Safety Systems Guidance or TSSG (Caltrans, 2019) and barriers on the shoulder/right-side, referred to as roadside barriers. What TSSG refers to as guardrails is referred to in this chapter as roadside barriers (Caltrans, 2019). Along with 'guiderails' (Dobrovolny et al., 2021), FHWA uses the term 'guard-rail' to refer to metal beam barriers such as Thrie-Beam.

While our study is on high-tension cable barriers (HTCBs), the term "cable barriers" can also refer to low-tension cable barriers in some of the older studies. Low-tension cable barriers have not been used in California since the adoption of NCHRP Report 350 standards, but we have retained some case studies of their use in reducing FSIs. Cable barriers are also referred to as wire rope barriers and wire rope safety barriers in different literature. Median applications are sometimes referred to as cable median barriers.

In the next section, we discuss Caltrans' countermeasure selection process and how the process influences the possible selection of cable barriers. The information presented in this section is based on interviews with Caltrans engineers and from the TSSG currently under revision (Caltrans, 2019).

3.2 Current process for recommending cable barriers

For Caltrans, a complete site investigation precedes the recommendation of any safety countermeasure. Site investigations include a study of the following:

- crash history;
- roadway alignment, specifically isolated or sharp curves;
- number and width of lanes, shoulder widths, side slopes;
- the profile of the road: whether it is in a cut, fill, and the shape of the roadway prism;
- whether the right of way is owned by Caltrans and whether a clear recovery zone is present;
- operating conditions namely volume, speed of traffic, merge and weave areas; and
- climate conditions.

Caltrans follows a collision study warrant and a freeway traffic volume/width study warrant for installing median barriers. The freeway traffic volume/width study warrant is also applicable to expressways and multilane highways. The crash criterion is also the foremost criterion for two or three lane highways as per the TSSG (Caltrans, 2019).

Installing median or roadside barriers is a part of the safety monitoring programs, specifically the run-off-road and cross over (CO) crash monitoring programs, which are categorized under the Reactive Safety Programs. Reactive programs are necessary, but Caltrans may consider going beyond reactive and pursue proactive safety to be aligned with the Safe System Approach. Additionally, the CO crash monitoring program does not include adding passing lanes. However, passing is a major cause of CO crashes in TWTL highways and adding alternating passing lanes with cable barriers to these highways is an effective countermeasure.

3.2.1 Guidelines for selecting cable-barriers

Following site investigations, incremental improvements are first installed before considering barriers. The incremental improvements include striping, rumble strips, shoulder widening, and including buffer zones, surface mounted channelizers, and other appropriate devices and applications. After the incremental improvements, median and roadside barriers are considered for inclusion as countermeasures. Among barriers, proposing cable-barriers requires obtaining additional approvals from the Deputy District Directors of Traffic Operations & Maintenance. At the time of writing this chapter, these responsibilities have been re-assigned, and the Deputy District Director of Traffic Operations no longer approves cable barriers.

The TSSG 2019 refers to the Highway Safety Improvement Program guidelines, Chapter 4, and Deputy Directive 50 to provide guidance on study warrants and median barrier policy for two and three lane facilities, respectively. For two or three lane highways, Deputy Directive 50 suggests installing median barriers only in the locations where “normal long-term improvement such as adding lanes” is not a possibility among other criteria. This guidance may result in wide medians that are eligible for cable barrier installation being narrowed in the long-term to convert them to multilane highways.

The TSSG 2019 also refers to the Highway Safety Improvement Program guidelines, Chapter 4, Section 4.1.2.2, titled “Two- and Three-Lane Cross Centerline Collision” for guidance on study warrants and median barrier policy for two and three lane facilities respectively. The Highway Safety Improvement Program mentions funding allocations for projects that result from the Multilane Cross Median Collision (Freeways, Expressways, and Conventional Highways), and Two and Three-Lane Cross-Centerline Collision (Expressways and Conventional Highways) among other programs.

3.2.1.1 Guidelines for application in medians

The TSSG (Caltrans, 2019) recommends the minimum median width for cable barriers to be no less than 46 ft., which equates to a minimum offset of 23 ft. between the edge of the travel way and the cable barrier, as shown in Figure 3-1 and Table 3-1. This requirement exceeds the known deflection values. While containing the deflection so that the errant vehicle does not reach the opposite traffic stream, the large median width might create conditions for the errant vehicles to impact the cable barrier at angles greater than the impact angles in design and test conditions, leading to larger deflections than may have occurred at smaller impact angles in narrower medians.

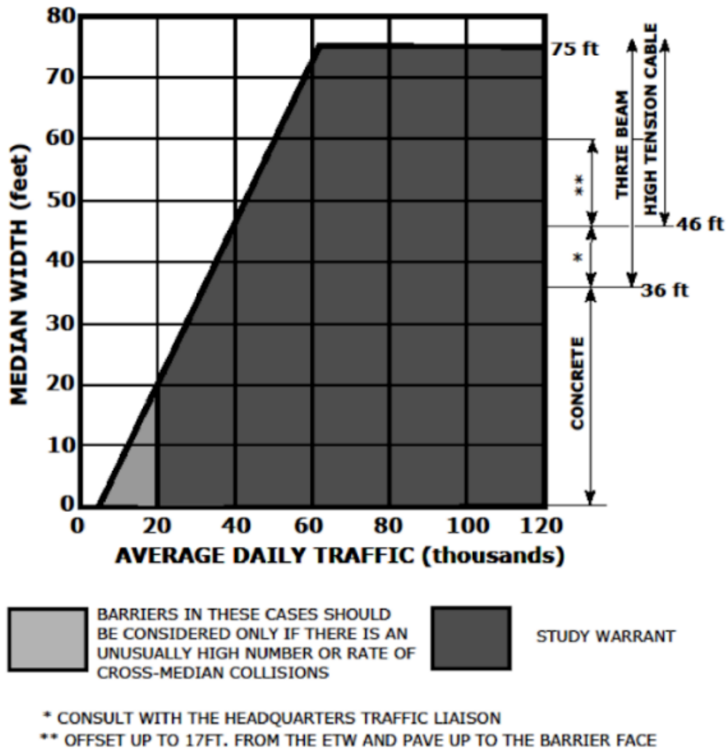


Figure 3-1 Freeway median barrier study warrant (Source: TSSG)

Table 3-1 Guidelines for using cable barriers as median barriers (Source: TSSG 2019)

		Median Width			
		Equal to or less than 36 feet (ft)	Greater than 36 ft to less than 46 ft	Equal to 46 ft to less than 60 ft	Equal to or greater than 60 ft
No plantings	Barrier Type	Type 60M concrete	Consult HQ Traffic Safety Systems Branch	Type 60m concrete, Thrie beam or cable	Thrie beam or cable
	Placement	On centerline pave up to face of barrier except when offset for barrier openings	Consult HQ Traffic Safety Systems Branch	Offset up to 17 ft and pave up to it, or on centerline (no paving)	On centerline
Plantings	Barrier Type	Type 60M concrete	Type 60M concrete or Thrie beam	Thrie beam	Thrie beam
	Placement	On each side of planting, pave up to the barrier	Consult HQ Traffic Safety Systems Branch	On each side of plantings, minimum offset 17 ft	On each side of plantings, minimum offset 17 ft

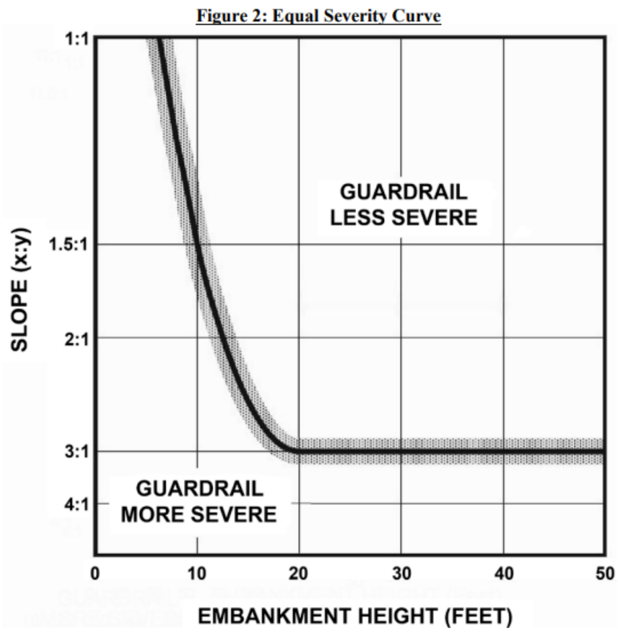
Footnote for Table 3-1: *"For median width equal to or less than 36 ft obtain approval from the District Maintenance Engineer for using thrie beam barrier. Cable barrier requires approval by the Deputy District Directors of Traffic Operations and Maintenance"*

As shown in Table 3-1, concrete barriers were the default option for narrow medians (less than 36 ft.) followed by thrie-beam barriers for medians of width between 36 and 46 ft. This guideline restricted the consideration of this CO crash safety countermeasure primarily to freeways with wide medians, or with adequate existing right-of-way to accommodate a wide median. It precluded consideration of cable barriers for many low-volume, high-speed rural highways, with medians less than 36 ft, that also experience a high number of FSIs related to CO crashes. Installing cable barriers would necessitate right-of-way acquisition which in turn could drive up the overall cost as well as the environmental mitigation risks for such projects.

Lower deflection values present an opportunity to update the TSSG minimum median width for installing cable barriers. Since deflection values could be adjusted with post spacing and rope tension (see Table A4-1, Appendix A4), manufacturers could provide specifications to meet lower deflection values, especially for smaller impact angles in TWTL or 2+1 roads.

3.2.1.2 Guidelines for application on shoulders

Cable barriers are equally applicable to shoulders that have an insufficient clear recovery zone. They are a low-cost option with costs comparable to that of metal-beam barriers. Additionally, the barriers provide more visibility and are aesthetically pleasing. Figure 3-2 displays the TSSG guidelines for installing cable barriers on shoulders.



Excerpts from TSSG 2019:

"Cable Guardrail is a high-tension three or four-strand flexible barrier. It may be recommended by the District Traffic Safety Systems Coordinator for locations that can accommodate cable deflections up to 9.5 feet.

Cable Guardrail must be approved by the Deputy District Directors for Traffic Operations and Maintenance. Documentation of the approval must be placed in the project files."

Figure 3-2 Guidelines for using cable barriers as roadside barriers (Source: TSSG) approval considerations

The Caltrans Highway Safety Features New Products Committee reviews MASH approved products for installation on the State Highway System. Of the various MASH approved cable barrier systems produced by manufacturers such as Brifen, WRSF, CASS-Trinity, Gibraltar, Nucor Marion, and Safence, only Brifen's O-post Wire Rope Safety Fence is approved by Caltrans as it has a MASH approved anchoring system, the Brifen MASH Gaiting Terminal. Having a greater number of approved manufacturers and products for the cable barrier system will possibly enhance wider use of the product.

3.3 Use of cable barriers in the median

Median barriers are longitudinal barriers that separate opposing traffic on divided highways, including freeways and expressways, and are designed to redirect vehicles striking either side of the barrier. Median barriers such as cable, metal-beam, and concrete barriers significantly reduce the number of cross over (CO) crashes, which are attributed to the relatively high speeds that are typical on divided highways. (FHWA Highway Safety Programs, n.d.).

The features of the high-tension cable barrier (HTCB) and the speed and width profile of the location both influence the performance of the barrier during a crash. Post spacing, end anchor design, the length of the barrier, and ambient temperature influence the extent of deflection that a vehicle undergoes on hitting the cable barrier (Brifen USA, n.d., NASEM, 2012). The number of strands (usually three or four) and height of the posts and of the cables influence the possibility of override or underride of vehicles. The design of anchors, the foundations, terrain geometry, and the soil conditions may contribute to the extent of damage the system undergoes on impact.

The speed, angle of crash, and the weight of the vehicle in the crash determine the force with which the barrier is hit and the extent of deflection it undergoes. While the approved manufacturer would provide the exact deflection values, some values are listed here. Brifen reports 8 ft. deflection for post spacing of 7 ft. and 11.9 ft. deflection for post spacing of 21 ft. (Brifen USA, 2020). Washington state assumes a deflection of 6 to 10 ft. (WSDOT, 2017). The deflection of high-tension cable barriers is reduced to 6.6 ft to 9.2 ft depending on the system, the post spacing, and the length of the barrier tested (Roadside Design Guide, 2011). More deflection values obtained from published studies are listed in Appendix 1.

HTCB may be placed in the median to reduce the probability of a head-on crash by catching the errant vehicle and reducing the speed to eventually bring the vehicle to a stop. When installed in locations in which the gap between the line of barrier and the opposing traffic lane is less than the design deflection of the HTCB, the vehicle might deflect into the traffic in the opposite direction.

When installed in locations where the gap between the line of barrier and the opposing traffic lane is less than the design deflection of the cable barrier, such as some narrow median locations, this may allow the vehicle or part of the barrier to encroach into the opposing roadway. Nationally and internationally, median widths ranging from 20 to 30 feet are considered normal design domain for many locations (Cooner et.al., 2009, Pappe, 2012), as we will discuss in subsequent examples.

3.3.1 Case studies

The first installation of the Brifen WRSF was in Oklahoma in 2000 and successfully prevented cross over crashes on a busy (110,000 vehicles per day) freeway that was earlier separated by a grass median. Subsequent installation on I-35 successfully prevented a 77,000 lb. semi-truck from crossing into oncoming traffic; there were no injuries ("Preventing 350 crossover accidents", n.d.). Cable barriers have since been applied in North Carolina, Oregon, Washington, Utah, Texas, and multiple other states. In a survey distributed to the American Association of State Highway and Transportation Officials Subcommittee of Design (AASHTO SCOD) on March 29, 2016, to which 10 states responded on the question of median barrier type and placement, high-tension cable barriers were found to be installed in medians with widths of 15 to 40 feet. One state reported to ensure that the median is wide enough to accommodate barrier deflection plus 50%. Table 3-2 shows the various median width requirements used for installing cable barriers in the United States.

Table 3-2 Median width guidelines for installing cable barriers in different states

State	Guidelines and/or examples	Source
Texas	The minimum recommended median width is 25 ft. Cable barriers are recommended for use on medians only and not on the roadside.	Roadway Design Manual, effective December 2022, (Ramthun, 2022)
Oregon	Cable barrier use can be considered on Interstate Highways and designated Freight Routes with a median width of 30 ft. without an increase in the post spacing. Cable barrier installations in median widths less than 30 ft. require consultation with the Senior Roadside Design Engineer.”	ODOT Traffic Roadway Section: Highway Design Manual, 2023.
Washington	In general, cable barriers are recommended with medians that are 30 ft. or wider. However, cable barriers may be appropriate for narrower medians if adequate deflection distance exists.	WSDOT Design Manual M 22-01.21, 2022
Colorado	10 ft. from edge of left travel lane on medians and 10 ft. to any fixed hazard on side.	Colorado Department of Transportation, 2017

Table 3-3 lists the findings from case studies of cable barrier implementations on medians narrower than 36’ nationally and internationally. All studies show a marked reduction in fatalities and serious injuries following implementation, although some show an overall increase in the number of crashes due to frequent hits to the cable barrier.

The 1.5-mile installation on the Mount Hood Highway (US-26) safety corridor in Oregon, in August 2007, was then the only non-freeway application of a cable median barrier, as well as the only application in the United States on a median that is less than 8 feet wide, and less than 4 feet wide in certain locations. Analysis of data from 2001 through 2013 for both the section with cable barrier and a control section indicated that after installation section crash rates increased by 72%, because of the installation of a fixed object in the middle of the road; FSI crashes decreased by 29%; and the severity indicator decreased by 59%. The authors report that the barrier prevented more serious crashes such as head on collisions.

The Oregon study also discusses Utah DOT’s standard drawings created in 2012 for high tension cable median barriers that require medians for cable barrier application to be 15 ft wide only, while requiring a design that allows less lateral deflection than typical. Utah DOT installed a HTCB in a 12-14 ft wide median on US-189 in Provo Canyon, Utah. While the before and after period is unknown, as of September 2014, the median barrier was reported to have performed well with no crashes resulting in a head-on collision.

While MASH approved products provide superior safety, posts of different specifications were used in Utah and Oregon. The Oregon system met the NCHRP 350 TL-4 standards. Additionally, cable median barriers were not a standard specification in the Oregon Standard Specifications for Construction (OSSC) at that time.

A study of the installation of Brifen WRSF on the Lake Hefner freeway in Oklahoma found the benefit/cost ratio showed an increasing trend between 2001 to 2009 (Oklahoma Progress, n.d.; Wilkerson, 2010).

Table 3-3 also lists three international applications of cable median barriers on median widths of 2.6 ft, 4.9 ft., and 32.8 ft. In all of these FSI crashes were reduced by 29 to 100%. Some of these were installed between 2000 and 2010, whereas the barrier in Japan was installed in 2017.

Table 3-3 Summary of case studies of cable barrier implementations

	Country/City, time, study duration, type of intervention (Reference)	Height	Post spacing	No. of strands	Climate	Traffic	Speed	Vehicle composition	Median width/ Number of lanes	Crashes
1	Mount Hood Highway, US-26 Oregon, August 2007, (included in standard construction specification in 2008) (Burns & Bell, 2016)	Top cable (close to the top of the post) just over 3.17 ft.	6 ft.	3			Principal Rural Arterial		<4 ft. to <8 ft., paved/ 2+2	Fatal & injury crashes reduced by 29%, severity indicator for crashes reduced by 59%
2	Utah US-189 Provo Canyon, September 2014 (Burns & Bell, 2016)	Approximately 2.46 ft.	6.5 ft.	3					12-14 ft./ 2+2 (shape of post and post spacing allowed for lower deflection during crash tests)	No crashes resulting in head-on crash
3	Oklahoma, 2000-2004, i) Lake Hefner freeway connecting Kilpatrick turnpike with I-44 to the south (7 miles, earlier grass median), ii) I-35 through Norman (Oklahoma Progress, n.d., & Wilkerson, 2010)	Brifen WRSF	Brifen WRSF	4		Freeway connecting Kilpatrick with I-44 (110,000)			From photographs, the median appears to be at least 30' wide.	In 3 years prior to installation in location i) 4 median crossover accidents resulted in 7 injuries and 6 fatalities. Test section immediately prevented two crossover crashes.
4	New Zealand, Centennial Highway 2004, before installing cable barriers, that section of roadway did not have any barriers (Marsh & Pilgrim, 2010)		3.3 ft. (deflection 2.5 ft.)	3		21958-22382	50 mph	Both light and heavy	4.9 ft./TWTL	In 2004 there were 12 fatal, 4 serious injury crashes. Between 2004 to 2010, there were no fatal or serious injury crashes.

	Country/City, time, study duration, type of intervention (Reference)	Height	Post spacing	No. of strands	Climate	Traffic	Speed	Vehicle composit ion	Median width/ Number of lanes	Crashes
5	Victoria, Australia, barrier installed for the first time and lane widths reduced (Candappa et al., 2009)			4			62.1 – 68.4 mph		32.8 ft./2+2; 2+2 undivided; 1+1 undivided (Larsson et.al. 2003)	Targeted crash types reduced by 87 percent; all crash types reduced by 75 percent. Of the four possible cable barrier locations, left side of road, right side of road, left side of median, and right side of median, only one side of the road had cable barriers. As such, the effect of the barrier obtained as a result of this study is conservative. However, the crash statistics also did not differentiate between the crashes that hit the barrier and others that didn't.
6	Japan, installed in April 2017, studied crashes for one year before and after; earlier rubber poles were used as a barrier) (Xing et al., 2019)	3.4 ft.	13.1 ft.	5	Snow	2300-9700	50 - 62.1 mph	See differenc es in deflectio n due to different vehicle weights, traffic included 13% heavy duty vehicles	2.6 ft./TWTL	Crashes increased from 45 to 238. Lane departures decreased from 45 to 1. Fatalities reduced from 7 to 0. Injuries reduced from 6 to 4.

Table 3-4 lists the observations made from different states in studies for installation of cable barriers available in FHWA CMF Clearinghouse (Storm et al., 2022). All states experienced a reduction in FSIs.

Table 3-4 Experience with Cable Barriers in Other States

State (Reference)		Median width	Entering opposing lanes, PDO*, or injury	Fatalities & Serious Injuries	Installation
Missouri (Chandler, 2007)	2007		Caught 95% vehicles entering median and kept them from entering opposing lanes.	92% decrease in cross-median fatalities with installation of 179 miles of HTCMB, from 24 cross-median fatalities in 2002 to 2 cross-median fatalities in 2006.	Initial HTCMB on interstates. Began systemwide installations starting in 2002.
Indiana, Colorado, Illinois, Missouri, New York, Ohio, Oregon, Washington (Villwock et.al.,2010)	2009	30 feet and more	Low- & high-tension cable barriers eliminate over 90% of cross-over crashes, along with an 80% increase in single vehicle crashes with the cable barrier.	Low-tension cable barriers decreased the proportion of fatal & injury crashes by 8 percent. The effect of high-tension cable barriers on crash severity was negligible.	Rural interstates
Texas (Cooner et.al. 2009b)	2009	(20 – 72 feet)		Reduction of 18 cross-median fatalities and 26 serious injuries in the first full year.	Interstate systems
Utah (Olsen et.al., 2011)	2011		62% reduction in all cross median crashes.	44% reduction in severe crashes.	Freeway
Florida (Alluri et.al., 2012)	2012	30-50 ft wide, 60 ft, 70 ft	Prevented 97% of vehicles from traveling into opposing lanes of traffic.	42.2% reduction in fatal crash rates, 20.1% reduction in incapacitating injury crash rates, 11.6% reduction in non-incapacitating injury crash rates.	Limited and non-limited access roadways
Washington (Olson et.al., 2013)	2013	30 ft or wider	Reduced cross-median crashes by 58%. Reduced rollover crashes by 53%.	Reduced fatal crash rates by almost 50%.	
Wyoming (Coulter & Ksaibati, 2013)	2013	25-40 ft wide	79% reduction in critical cross median crashes with vehicles on the other road, 41% reduction in critical crashes in the median.		
Illinois, Kentucky (Srinivasan et.al., 2016)	2016		48.2% reduction in cross-median crashes.		
Missouri (Srinivasan et.al. 2016)	2016		88.1% reduction in cross median indicatory plus head on crashes.		Implemented cable barrier and inside shoulder rumble strip at the same time.

Michigan (Russo et.al. 2016)	2016	Narrow (26-50 ft) wide (50-94 ft)	Greater impacts on crashes across nearly all severity levels when used on medians of width 26 to 50 ft, compared with medians of width 50-94 ft.		317 miles of HTCB
Tennessee (Chimba et.al. 2017)	2017	Minimum 24 ft		94% reduction in median related fatal crashes. 92% reduction in serious injury crashes and 84% reduction in non-incapacitating crashes.	
Tennessee (Bryant et.al. 2018)	2018			96% reduction in median related fatal crashes. 91% reduction in serious injury crashes and 93% reduction in non-incapacitating injury crashes.	
Kansas (Galgamuwa & Dissanayake, 2017)	2017		50% reduction in all lane departure crashes	18% reduction in fatal and injury lane departure crashes	
Iowa (Savolainen et.al. 2018)	2017	34.6 ft min., 4 ft min for express ways	11.2% and 108.3% increase in C- and O-level crashes respectively.	Reduction in K-, A-, and B-level crashes by 61.6, 30.8, 25.8% respectively.	
Ohio (Eustace & Almothaffar, 2018)	2018			73.9% reduction in fatal crashes, 80.1% reduction in KAB crashes and 80.4 percent reduction in KABC crashes.	

*PDO, property damage only; HTCMB: high-tension wire rope safety barrier
KABCO measures injury severity with K = fatal, A = incapacitating, B = non-incapacitating, C = Not visible but complaint of pain, O = no apparent injury. The exact definition varies by state. For definitions for the relevant states in the table, see KABCO Injury Classification Scale and Definitions, highways.dot.gov/media/20141.

3.4 Use of cable barriers on shoulders

Cable barriers could be used to shield obstacles or abrupt changes in gradient in shoulders with insufficient clear zones. In Iowa, Missouri, and New York, cable barrier installation on shoulders includes a minimum deflection distance ranging from 8 to 12 ft., depending on the post spacing. Concerns have been raised about vehicles traveling under the right shoulder cables on a sloped shoulder (Caltrans DRISI, 2020). Colorado DOT recommends a slope of 4:1 or flatter for at least 10 ft. behind the cable barrier (CDOT, 2017).

Improved safety conditions and reduced costs were reported by Iowa, Missouri, and New York State DOTs that use high-tension cable barriers on the shoulders. New York State DOT reported that even when a HTCB system is impacted, the cables maintain a height that enables the system to engage an errant vehicle. These are useful to prevent or reduce the severity of run-off-road crashes (MnDOT, 2015; Caltrans DRISI, 2020).

3.5 Multimodal facility applications

Cable barriers are also used to create a safety barrier to separate road users in space. Brifen WRSF has been used in Oklahoma City, Oklahoma to separate bicycle facilities from vehicular traffic (Brifen USA, n.d.).

3.6 Considerations for motorcycles & heavy vehicles

In some countries the motorcycle user groups oppose the installation of cable barrier system due to possible risk of harm to errant motorcycle riders. A review of studies on the effect of cable barriers on motorcyclists has been inconclusive. Although the posts for cable barriers are more forgiving than those for metal beam barriers, striking the cables has led to decapitations and amputations. Dobrovolny et al. (2021) propose retrofits for each of the barrier type to make them safer for motorcycles. An FHWA study on barrier design for motorcyclist safety summarizes different effects of motorcycle riders striking different barriers and finds that other barrier types were also hazardous. Striking concrete barriers at high speed could cause the rider to get ejected over the barrier (Dobrovolny et al., 2021). Striking metal-beam barriers while sliding could lead to impact with discrete posts, and, while upright, could lead to lacerations, tears or snagging on the top of posts due to sliding on top rails.

Other studies on crash data could not establish cable barriers to be more hazardous to motorcycle riders than other barriers or than lack of a barrier (NASEM, 2019; RDN 06-02, 2016; "Record of investigation", 2008; Larsson et.al., 2003). A study of injury severity in motorcycle-to-barrier crashes in North Carolina, Texas, and New Jersey found concrete barriers to be the safest, especially if the rider was wearing a helmet, and metal-beam barriers and cable barriers to pose approximately equal risks of severe injury (Daniello & Gabler, 2011). Zou et.al. did not obtain statistically significant results for motorcyclists given the small sample (Zou et al., 2014).

Corben et al. (2003) found that "although flexible barriers were not designed specifically to restrain heavy vehicles, they appear to have performed well in heavy vehicle impacts and tests around the world; [one particular barrier make] designed specifically to contain a tensile force of two tons, has contained heavy vehicles imposing tensile forces of over 11 tons on the wire ropes." The crash reported in NCHRP Report 996 describes a tractor-semitrailer truck crossing a 60-foot-wide depressed median and overriding a HTCB adjacent to the left northbound shoulder (NASEM, 2022). Specification details of the HTCB will be instructive for our purposes. Since barriers perform better under smaller crash angles, as in the case of narrow medians, crash testing double runs (Zou et al., 2014, NASEM 2014), one on either side of the median for wider medians, would be useful for future practice.

3.7 Maintenance considerations

Cable barriers need ongoing maintenance as well as repair after crashes. The frequency of maintenance depends on the system and use. Cable barriers installed along high traffic roads tend to get hit frequently (NASEM, 2012). However, unlike rigid barriers, the cable barrier posts are designed to fail for better flexibility. Consequently, the frequency of maintenance visits related to repairs is higher compared to rigid barriers. More frequent repairs expose maintenance crew to the dangers of high-speed traffic and increase costs. This could be a major consideration in determining the viability of the cable barrier systems. Cooner et.al. (2009b) reports on maintenance frequency, time for repair etc. in Texas. NCHRP report 711 compiles experiences of states for design, performance evaluation, and maintenance with case examples from Rhode Island, West Virginia, Florida, Michigan, Colorado, and Washington State (NASEM, 2016).

Crash under-reporting is an issue. For reported crashes, the insurance of the driver at fault could pay for the repair, which is not possible for unreported crashes. However, non-reported crashes are also less severe and cause less damage. NCHRP Report 711 mentions that police reports are usually available for slightly more than half of the crashes (NASEM, 2012). Certain sources report not having much maintenance. After five years' experience and 350 impacts with a Brifen wire rope safety barriers on Hefner Parkway, the state of Oklahoma found that the average number of posts replaced per crash has been just over five. Repairs were usually completed in less than 30 minutes by a one or two-person crew. "A typical five-post repair is usually made in about 15 minutes by one person using only hand tools. Two people can do it even faster." Additionally, the system was found to return to its original alignment after minor hits and retain capacity to withstand additional impacts before repairs were made ("Preventing 350 crossover accidents", n.d.).

To minimize the number of traffic diversions, bridge inspections and overlay repairs could be coordinated and delineator post washing and other maintenance activities could be performed during low traffic volume conditions. Locations with snow bound conditions require specialized training for maintenance. Broadly snow, should be removed in the first 1.3 ft. of the median and edge lines should be visible (Larsson et al., 2003).

Safety concerns and maintenance difficulties are reported when cable barriers are installed without use of a "mow strip" (Texas Department of Transportation, 2008). Some of the concerns that were experienced with the cable barriers approved under NCHRP 350 are listed here.

3.7.1 Type of cable barrier posts and post foundations

- It is harder to replace the posts that are sheared off at ground level rather than bent over.
- Replacing posts that are placed in sockets embedded in concrete foundations is easier and cheaper than replacing those placed in driven sockets.
- Failure of the concrete barrier foundations is reported in some cases despite using materials that exceeded manufacturer's specifications (NASEM, 2012)

3.7.2 Climate and soil conditions

The challenge of extracting damaged posts can be exacerbated during subfreezing weather when posts freeze in their sockets. Barrier post foundations are also reported to move, especially after spring thaws, and cracks have been known to appear in foundations in such conditions. A few cases of barrier posts gradually leaning over because of repeated snowplow shoving and spacer blocks collapsing on snow loads have been reported (NASEM, 2012). Sometimes sockets have been observed to accumulate brine causing serious corrosion (Caltrans DRISI, 2020).

3.7.3 Implications for maintenance resources

The need for increased maintenance necessitates the availability of trained maintenance staff to regularly inspect and maintain the rope tension, integrity of the fittings, the condition of screw threads and other fittings, nicks, gouges, cracks, or corrosions on the components. Cost of repairs can vary depending on whether DOT personnel or private contractors do the repairs (NASEM, 2012).

3.7.4 Traffic operation, worker safety, and maintenance response times

Work zone area safety is a concern. Repair work has so far been conducted under a Truck Mounted Attenuator having the overtaking lane closed and providing only one lane for each direction of traffic. One serious incident occurred where a passenger car crashed into a road lane closure device at high speed. Other concerns are emergency blockages and emergency vehicle operations (Larsson et al., 2003).

Maintenance on rural TWTL highways with limited right of way might require road closures for the safety of highway workers, which might lead to extensive traffic delays, especially at locations that lack suitable alternative routes. Caltrans may consider quantifying the additional maintenance cost due to road closure delays and additional energy consumption due to traffic diversion using accurate rates of repair frequencies from the manufacturer and from applications in similar situations.

The maintenance response time for remote locations might be longer. Of the 33 states surveyed in the NCHRP Report 711, four reported a response time of less than 2 days, four reported less than 4 days, five reported 5 to 7 days, six reported 8 to 14 days, and three reported up to a month (NASEM, 2012).

3.7.5 Cost of repairs

Of the 33 states surveyed in the NCHRP Report 711, five states reported a typical cost per repair of less than $500, twelve reported less than $1,000, four reported from $1,000 to $2,000, two reported from $2,000 to $3,000, and two reported more than $3,000 (NASEM, 2012).

3.8 Findings from interviews with Caltrans engineers and from literature

The case studies indicate a marked reduction in fatalities and serious injuries when median cable barriers are used. The findings of this chapter are summarized as a SWOT (strengths, weaknesses, opportunities, and threats) analysis focusing mostly on the applicability of cable barriers in medians.

3.8.1 SWOT analysis of cable barriers

3.8.1.1 Strengths

- Contains errant vehicles and absorbs impact energy such that minimal forces are directed at the vehicle and its occupants (Caltrans DRISI, 2020, FHWA Highway Safety Programs, n.d.).
- Does not redirect vehicles back into traffic, reducing the frequency of secondary crashes (WDOT, 2017).
- Are double-sided, i.e. can withstand impact from both sides, like concrete barriers

- Depending on post spacing, its cost is comparable to Thrie-Beam barriers and is approximately one-fifth that of concrete barriers. The barriers are easy to install. Maintenance effort and materials are also much less than that of the W-beam system (WDOT, 2017).
- Both installations and repairs are usually convenient and quick (Caltrans DRISI, 2020).
- Least visually obstructive providing uninterrupted sight distance for safety of road users and preserving the beauty of scenic routes.
- It can be placed on existing facilities without extended environmental permitting and complex highway reconstruction that might be needed for other barrier systems (WDOT, 2017). Trees and other obstacles do not need to be removed for construction, if they are not within the 'working width' (deflection distance) of the flexible barrier, a positive aspect for the environment and landscape (Larsson et.al., 2003).
- It has minimal potential to create snowdrifts and as such are advantageous in areas of heavy snowfall (WDOT, 2017).
- Enables easy access to all lanes for emergency vehicles: Emergency personnel can remove posts from their sockets and lower the cables so vehicles can drive across the median. The posts could then be replaced without re-tensioning the cables. ("Preventing 350 crossover accidents", n.d.).
- Allows water to flow through during flooding, and small animals to cut across.

3.8.1.2 Weaknesses

- Could allow vehicles to deflect into opposite side traffic, causing potentially serious crashes for both the deflecting vehicle and those that it may encounter.
- Could potentially cause decapitations and amputations for motorcyclists hitting the cable barriers at high speeds but are not proven to be more dangerous than other barriers for these road users (NASEM, 2012).
- Maintenance could be an issue as most crashes require immediate service. This can be a major demand on limited maintenance staff and a safety issue for maintenance crews on TWTL highways with limited right of way. Maintenance of cable barriers installed on a highway with narrow median could even require a full road closure.
- The cable material is more susceptible to variability in performance due to extreme weather changes.

3.8.1.3 Opportunities

- Recent adoption of SSA, which, among other principles, focuses on eliminating FSI by limiting the transfer of kinetic energy to the humans involved in the crashes as opposed to the traditional focus on reducing the incidence of all vehicular crashes.
- Revised standard plan details for cable barriers are being developed by Caltrans. Their dissemination would enable wider adoption of this countermeasure. In addition to international sources, such as VicRoads, some state Departments of Transportation in the U.S., for example Utah and Washington, also have standard plans for cable barriers that could be a relevant reference for Caltrans. Lane markings and rumble strips may be placed adjacent to the cable barriers to increase the conspicuity of the barriers and to minimize the occurrence of nuisance hits to the barriers.

3.8.1.4 Opportunities for wider implementation in narrow medians, on and off-ramps, bicycle lanes

- With reduced post spacing, cable barriers can be designed to undergo less deflection. International case studies and those from some of the other states in the U.S. indicate that high-tension cable barriers reduce FSI in crashes for medians as narrow as 4 ft. and under. Medians 25 ft. wide are considered a normal design domain in some countries (VicRoads, 2018).
- Turnouts on two-lane highways and 2+1 roads in locations with adequate right of way to allow safe opportunities for vehicles to overtake (RDN 06-02, 2016: Appendix E: Stopping refuge bay layout).
- Swedish experts at the US Vision Zero Academy suggested the use of double runs of HTCB barriers for wider medians, one on each side of the median, for reducing deflection of striking vehicles (Zou et al., 2014, NASEM, 2014). The double runs would still be more cost-effective than a concrete barrier and absorb crash forces.

3.8.1.5 Additional considerations

- Limited applicability of cable barriers on narrow median roads: To ensure adequate offset from moving traffic, the TSSG recommended cable barriers to be installed in medians 46 ft. or wider. This requirement restricted consideration of these barriers as a safety countermeasure to a limited number of highways with very wide center medians. For roads with existing narrow medians, this necessitated land acquisition leading to higher costs and possibly higher environmental impacts.
- In the absence of standard plans for cable barriers, engineers rely on the manufacturers for detail drawings. For road sections that need specialized detail drawings, such as bridges, engineers tend to favor the other barrier types for which standard plans are available.

3.8.1.6 Discussion of different barrier types

Studies have shown that concrete and metal beam barriers could have problems too. Concrete barriers transfer a significant share of the crash forces to the vehicle occupants. Studies find possible occurrence of secondary crashes with concrete barriers (Gabauer, 2010), poor performance in energy dissipation, deflection levels, and peak forces experienced by the vehicle occupants, when compared with semi-rigid and flexible barriers (Duncan et.al., 2001). Other problems associated with concrete barriers include vehicle roll-overs, higher risk in the event of poorly designed end-treatments, and likelihood of rebounding off the barrier (Corben et.al.,1999). Although less severe than concrete barriers, steel-beam guardrails could still cause serious injury, having the potential to ‘spear a vehicle’ through poorly designed terminal treatments, and they have limited effectiveness with heavy vehicles.

For most vehicles, the cable barrier systems are most capable of directing and/or containing an errant vehicle without imposing excessive deceleration forces on the vehicle occupants (Larsson et.al, 2003). Zou et al. found large percent reductions in the odds of injury following installation of cable barriers and that a guardrail should be preferred over a concrete wall, and a cable barrier should be preferred over a guardrail when road and traffic conditions allow. Based on the results they recommended that installing median cable barriers on both sides of the median to reduce their lateral offset is beneficial for safety (Zou et.al. 2014). Hu and Donnell (2010) studied median barrier crash severity on North Carolina interstate highways between 2000 and 2004 and found crashes with cable barriers were less serious compared to crashes with other barriers.

California's approach to placing barriers has used the long-held philosophy of the 1967 Yellow Book (AASHO 1967), which suggested a barrier 'should only be used where the result of striking the object or leaving the roadway would be more severe than the consequences of striking the rail' (NASEM 2022). As cable barriers absorb much of the crash forces, there is minimal possibility of severe injury on striking the barrier and it reduces the possibility of the vehicle leaving the roadway. As such, cable barriers could be a preferred option to clear zones depending on location and are approved as a Safe System countermeasure by both FHWA and Caltrans.

3.9 Recommendations

All case studies indicate a marked reduction in FSI following installation of high-tension median barriers including on road segments with narrow medians. In addition to its potential in preventing FSI on roadways by reducing the impact of lane departure crashes, it is relatively low cost and easy to install. As such, we recommend the following:

Narrow medians

- Since Oregon DOT has close to two decades of experience with cable barriers on narrow medians, (US-26, Mount Hood Highway), Caltrans connects with them to learn about their effectiveness in FSI reduction and maintenance characteristics. Caltrans uses that discussion as an input in their feasibility analysis of installing cable barriers in 4' – 8' wide medians.
- If found to be feasible, Caltrans pilots the use of cable barriers on a narrow median, working with the manufacturer of MASH approved barriers to create specifications with appropriate post spacing and tension to keep the deflection within the median width for the speed profile and possible impact angles on the specific highway.
- Subsequently, Caltrans considers installing cable barriers on TWTL sections of highways. Where right of way permits, Caltrans converts TWTL roads to 2+1 roads to enable maintenance personnel to repair the barrier without closing the road completely.

Wider medians

- For wider medians, Caltrans studies application of double runs of cable barriers, one on each side of the median.

Right side of the road

- For the right side of the road, Caltrans weighs the cost of ensuring a sufficient width of clear recovery zones with that of installing cable barriers, where applicable, to reduce run-off-road crashes.

General recommendation

- Caltrans reconsiders keeping the number of lanes as a minimum criterion for adding barriers. To be Safe System aligned, low-volume high-speed rural highways, that need barriers to prevent crossover or run-off-road crashes, could be eligible for barrier irrespective of the number of lanes.

Bicyclist lanes & motorcyclist safety

- Caltrans considers using cable barriers for separating Class II bicycle lanes from vehicular traffic.
- Caltrans works with the cable barrier manufacturer to create specifications that improve safety for motorcyclists.

4 Evaluate the Application of Roundabouts as Safety Countermeasures by Caltrans

This research presents an assessment of the suitability of roundabouts as an intersection control option on California's State Highway System. A summary of our findings obtained by a review of the available literature and interviews of Caltrans engineers is provided.

4.1 Background

A **roundabout** is an intersection where traffic travels around a central island in a counterclockwise direction. Vehicles entering or exiting the roundabout must yield to circulating vehicles, bicyclists, and pedestrians (Caltrans, n.d.).

Installing a roundabout at an intersection reduces the number of conflict points, the angles of possible conflicts, and causes vehicles to slow down. For a typical four-legged intersection, the number of vehicle-to-vehicle conflict points is reduced from 32 to 8, and the number of vehicle-to-pedestrian conflict points is reduced from 24 to 8. Consequently, the number of FSI crashes decreases. By eliminating stops at the intersection and maintaining a continuous flow of traffic, the capacity of the intersection increases. FHWA found that roundabouts increase traffic capacity of the intersection by 30 to 50 percent compared with signalized intersections (Caltrans, 2017). Because of their role in improving traffic flow, roundabouts are built to accommodate local development. In Hanford (District 6), where a Costco store was built, a roundabout was installed because it was projected to be a better traffic regulator than the upgrade of an existing traffic signal, given the heavy volumes expected (Caltrans, 2017). By reducing idling at the intersections, roundabouts also reduce greenhouse gas emissions.

Modern roundabouts differ from the earlier rotaries or traffic circles that had large diameters, speeds greater than 30 mph, and access to the central island. They also differ from non-mountable traffic calming circles, that are small traffic circles with raised central islands. The non-mountable traffic calming circles are typically used on local streets for speed and volume control and are not designed to accommodate large vehicles.

Figure 4-1 shows a modern roundabout and its difference from the very similar traffic circle.

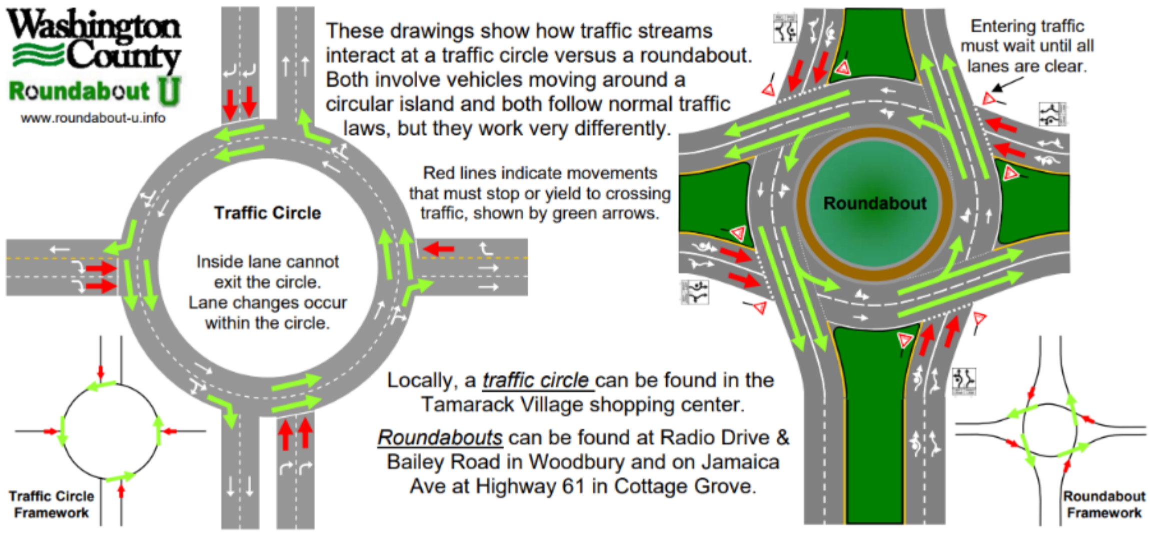


Figure 4-1 Traffic Circle and Modern Roundabout; Source: "How is a Traffic Circle Different from a Roundabout". Washington County. www.roundabout-u.info.

4.1.1 Considerations for Roundabouts at Intersections

In 2013, Caltrans adopted the Intersection Control Evaluation (ICE) process for selecting an optimal solution among intersection control alternatives. Several characteristics of the intersection, namely the number of legs, the traffic on each leg, the presence of pedestrian and bicycle traffic, and of larger vehicles such as semi-trucks influence whether roundabouts are the suitable treatment for the specific intersection.

The applicability of roundabouts in a location depends on several factors:

- *Traffic on the mainline and cross street:* At an intersection in which the traffic volume on the cross street is less than 25 percent of that of the mainline, installation of a roundabout causes delays to the vehicles on the primary road, since all lanes get equal priority at roundabouts. Specifically emergency routes should be assessed carefully for such delays.
- *Location:* Roundabouts are not a good countermeasure for commercial locations that might attract excessive parking or for locations in which the traffic from adjacent bottlenecks may spillover into the roundabout.
- *Traffic composition:* Larger vehicles, such as buses and semi-trucks, need a greater turning radius in roundabouts. Wider lanes and aprons, if provided, next to the central island and on the outer edges accommodate the turning radii of bigger vehicles (Shen et.al., 2000). Bicyclists and pedestrians also need design accommodations, namely properly positioned crosswalks, and sidewalks on the outer edge for pedestrians, and bicycle lanes, tracks, or share the road options for bicycles.

Depending on the diameter of the central island, roundabouts can be of different types: mini, small, medium, and large.

4.1.2 Design considerations

Research shows that visually impaired pedestrians face difficulties navigating the continuous flow of vehicles at roundabouts, despite the slow speed, and that older adults might face difficulties navigating the intersection both as drivers and as pedestrians. Safe crossing should be enabled for pedestrians to accommodate these users (Roundabouts, an Information Guide [RIG] Sun et al., 2019; Shen et al., 2000). Reducing the radius of the central island and the curvature at the junction of the approach legs and the roundabout help to reduce vehicle speeds. Pedestrian crossings located one to three car lengths away from the yield line of the roundabout allow cars to slow down sufficiently to see the pedestrians while exiting the roundabout. A central refuge island on each leg separating the entering and exiting vehicle traffic helps pedestrians focus on one direction of traffic at a time. Simple priority rules that consider typical road user behavior, such as drivers being less likely to yield at the exit legs, add to the safety and efficiency of these roundabouts.

Of all road user types, only bicyclists have reportedly had an increase in the number of crashes when an intersection is converted to a roundabout. Among studies conducted in Europe in the 1990s, only the roundabouts in Netherlands were found to be safe for bicyclists as a smaller radius of curvatures at the junction of the arm and the roundabout forced the other modes to slow down on entering the roundabout. Studies do not agree on whether it is safer to have bicycle lanes or tracks, or to allow bicyclists to share the road with motorized vehicles at a roundabout (Shen, 2000; Arnold, et al., 2010, FHWA, 2000). Bicycle bypass lanes have also been evaluated as a safety intervention for bicyclists at roundabouts (Dabbour, 2008). Small roundabouts and single-lane roundabouts have been found to be safer than large and multilane roundabouts (Shen et al., 2000). However, the Insurance Institute for Highway Safety reported that the 24 signalized intersections that were converted to roundabouts recorded a 10 percent reduction in bicycle crashes.

When the gradient of an approach is more than 4 percent, crashes due to loss of control at entry could occur. Sight distance might also be inadequate at such locations. Therefore, the design of a roundabout should ensure adequate sight distance in all directions and include countermeasures to control excessive speed (NASEM, 2010).

4.1.3 Barriers to Implementing Roundabouts

Resistance by local authorities is a major hurdle to installing roundabouts. Caltrans engineers report that local authorities often request traffic signals or other forms of control even for locations for which the Intersection Control Evaluation (ICE) process finds roundabouts to be the better option. The following is a list of common reasons for their opposition:

- Roundabouts usually have large footprints and often necessitate land acquisition. This is expensive, especially in urban areas. Depending on location, the land acquisition might involve environmental mitigation which adds to the cost. The cost of construction, compared with that of signalizing an intersection, depends on the number of legs and the size of the intersection. While building a large roundabout is expensive, signalizing an intersection could be more expensive if multiple signal heads are needed owing to the configuration of the intersection.
- Local communities object to installing roundabouts sometimes as these reduce vehicle speeds.

- While roundabouts reduce fatalities and serious injuries (FSI), sometimes they reportedly increase the number of property damage only and minor injury crashes, which may even increase the total number of crashes (Kansas Department of Transportation [KDOT]; Qi et al., 2018; Roundabout Maintenance Manual [RMM], 2015). The increase in total crashes is sometimes used as an argument against roundabouts, but the reduction in FSI crashes is what makes roundabouts serve as a Safe System countermeasure.
- Certain maintenance tasks, such as lane repairs or snow clearing, are more involved at roundabouts than at signalized or stop-controlled intersections.

While studies have reported negative public attitudes towards roundabouts before installation, they usually report positive attitudes after installation (FHWA, 2000). Various measures could be taken to address some of the public opposition before installation, as described in the next section.

4.1.4 Measures to alleviate the barriers to implementation

Involving the public at each stage of decision-making of a roundabout project helps build support for installing roundabouts. FHWA and some of the state DOTs, especially Wisconsin, have excellent resources to assist in explaining the functioning of roundabouts to the public and to help educate drivers. Disseminating case studies specific to the project location and context, testimonials, and national and state-specific statistics help in introducing roundabouts to a community. In addition, specific talking points or discussion bulletins could be distributed to local councilors to help them respond to user calls. Once roundabouts are installed, how-to videos and driver and vulnerable-user training materials are useful (Wisconsin Department of Transportation [WDOT], 2022). Other resources that have proven effective for local project outreach are as follows:

- Model vehicles at scale 1:87 or 1 inch equals 7.25 feet, available for purchase, and model roundabouts built at the same scale can be used in public outreach meetings to explain vehicle circulation and demonstrate operation of the system.
- Simulation of the expected operation of the roundabout and possibly a comparison of alternatives using renderings or visualizations.
- Project location brochure.

In addition to the outreach events, the material could be disseminated on the Caltrans website and in the Department of Motor Vehicles (DMV) offices.

It is essential to have a consensus among internal staff and stakeholders (local authorities) prior to conducting the first general public meeting. As such, it is imperative to consult all parties involved to know their opinions and address possible reasons for resistance ahead of public outreach.

As with material for outreach, FHWA and some states also have instruction manuals for maintenance. For example, Wisconsin DOT has a manual for repairing a lane in the roundabout without closing other lanes. Some states have instruction manuals for snow clearing at roundabouts. (Kansas Department of Transportation FAQs, Indiana LTAP Center, Qi et al., 2018,). Also, there are roundabouts in areas within California, such as Truckee, that experience significant snowfall during the winter. Maintenance personnel servicing these roundabouts are already experienced and could share their expertise in snow clearing at roundabouts.

Installing a first roundabout in an area requires greater outreach effort to educate the community and justify the need for the roundabout. The community might find it easier to adapt if the roundabout is small and easy to understand.

In the interviews, Caltrans engineers suggested ways to reduce the upfront cost of roundabouts. Quick-build projects with plastic and paint, as are being constructed in the City of San Diego, are a low-cost option to introduce a roundabout to a community at minimal cost (California Construction News, 2022). Additionally, to address the initial high cost of construction of roundabouts, a phased implementation could be considered. In the phased implementation, it might sometimes be necessary to approve interim improvements that are not necessarily consistent with the facility's long-term needs. For example, roundabouts could be constructed for shorter time horizons (e.g., 10 years instead of 20) and capacity accommodation made later for a future increase in traffic. Even though the cumulative cost of that approach may be higher, it reduces the initial cost.

4.1.5 Funding sources

Due to the high cost of building roundabouts, obtaining adequate funding is a challenge. The following potential funding options were recommended by Caltrans engineers:

- Combining with planned SHOPP work, such as rehabilitation;
- SHOPP safety funding if an existing safety deficiency has been identified;
- Congestion Mitigation and Air Quality Improvement (CMAQ) Program;
- Local Highway Safety Improvement Program;
- Active Transportation Program grant funding;
- Minor A or B funding;
- Regional Transportation Improvement Program;
- Developer fees or mitigation;
- Local transportation sales tax measures.

The District Traffic functional units, Asset Management, and Planning Division could be consulted to obtain information on the potential availability of such funding.

4.2 Multilane roundabouts

Multilane roundabouts have a higher number of conflict points and record higher crashes than single lane designs. Caltrans engineers reported that on State Route 1 and Simpson Lane in Fort Bragg, Mendocino County in Caltrans District 1, the number of crashes were found to double after converting the one-way stop-controlled intersection to a two-lane roundabout. One of the reasons cited for this was that after following slower semi-trucks for a long distance on the two-lane highway, drivers would use the additional approach lane of the roundabout to overtake the semis. The unsafe overtaking at the roundabouts led to more crashes, and as a remedy, the multi-lane roundabout was converted to a single-lane roundabout.

Additional engineering, signage, and education enable safe traffic movement in multi-lane roundabouts, especially for those with skewed approaches or more than four legs. Guidelines exist that address those less typical designs (FHWA, 2000; NASEM, 2010; WDOT, 2022). In addition, some countries have found roundabouts with differently shaped central islands, such as turbo roundabouts, as shown in Figure 4-2, to mitigate some of the conflicts commonly observed at multilane roundabouts. The special shape of the central island allows insertion of a second circulatory lane opposite to at least one entry lane, and the spiral alignment encourages smooth flow. Lane dividers discourage lane changing within the roundabout, and drivers are expected to select the proper lane before entering the roundabout, as is the case with signalized intersections. The diameter of the roundabout is kept small to encourage lower speeds through the roundabout and approach legs and entry are typically at right angles to the roundabout (Turbo Roundabouts, n.d.).

Figure 4-2 Turbo Roundabout, Delft. (Turbo Roundabout, n.d.)

4.3 Summary

The discussion in this chapter can be summarized in the form of a SWOT analysis as follows:

4.3.1 Strengths

- *Reduction in conflicts:* Roundabouts eliminate the possibility of head-on and broadside crashes and reduce the number of conflict points. Splitter or median islands provide refuge for pedestrians and allow them to cross one direction of traffic at a time.
- *Traffic calming:* Vehicle speeds can be reduced by increasing the deflection of vehicle trajectories.
- *Increase in traffic capacity:* They can accommodate greater traffic flow and reduce traffic delays. They have been used for economic development to accommodate increases in traffic.
- *Lower maintenance:* They need minimal maintenance, except for signs and striping.
- *Lower emissions:* They reduce greenhouse gas emissions by reducing vehicle idling time.

4.3.2 Weaknesses

- *Possible high cost:* Some roundabouts have large footprints necessitating land acquisition which leads to high costs.
- *Increased property damage only crashes:* While roundabouts practically eliminate fatal and serious injury (FSI) crashes, the merging and weaving actions might lead to higher property-damage-only crashes sometimes even resulting in higher number of crashes overall. This is especially true for multilane roundabouts.
- *Pedestrians and bicyclists:* All road users, including pedestrians and bicyclists, traverse a longer path through the roundabout. This may increase the exposure of pedestrians and bicycles to motorized traffic.
- *ADA:* Since the vehicles are constantly circulating, it is difficult for visually impaired pedestrians and older adults to find a gap to cross, especially since there are no audible cues (FHWA, 2000; Sun et al., 2000).

4.3.3 Opportunities

- Recent adoption of the SSA, which among other principles, focuses on eliminating fatalities and serious injuries by limiting the transfer of kinetic energy to the humans involved in the crashes as opposed to the traditional focus on reducing the incidence of all vehicular crashes.
- Materials for demonstrating the safety of roundabouts to the public have been created by FHWA and some state Departments of Transportation, such as Wisconsin DOT. These could be used at public meetings.
- Quick-build projects with plastic and paint can introduce a roundabout to an intersection at minimal cost when it does not require an increase in intersection footprint.
- Since designs for shorter time horizons can be less expensive, they could be considered to reduce the sticker shock of roundabouts.
- Pedestrian exposure to vehicles could be minimized with the provision of appropriately placed crosswalks, sidewalks, and splitter islands. Guidelines also exist that, when implemented, would enable visually impaired pedestrians to safely navigate roundabouts (NASEM, 2017). Bicyclist exposure can be reduced by adding separate bicycle lanes or tracks, designing sidewalks to accommodate bicycles, or even by adding bicycle bypass lanes at roundabouts.

4.3.4 Threats

- Designing for long time horizons might increase the initial cost of roundabouts due to the cost of possible additional land acquisition. Sometimes authorities have even preferred more expensive construction methods and materials in addition to the standard guidelines: for example, using concrete pavements for roundabouts not necessarily following any specific traffic mandate.
- Absence of a manual at Caltrans for addressing common maintenance concerns such as navigating a snowplow in a roundabout or repairing a lane without closing the intersection.

- Unfamiliarity: Because roundabouts are not common in the United States, many authorities and communities are unfamiliar with them and are apprehensive about using them for the first time.
- Property owners' resistance to giving up their property to provide the additional right-of-way.

4.4 Recommendations

A well-designed roundabout promotes safety for all road users, consistent with the Safe System Approach, by reducing the kinetic energy and conflict points and thus reducing fatalities and serious injuries. As such, we recommend wider use of roundabouts with special attention to the safety of bicyclists, pedestrians with visual impairment, and older adults. To achieve wider implementation of roundabouts, Caltrans could do the following:

- Leverage the Intersection Control Evaluation tool to evaluate intersections and identify suitable locations for roundabouts.
- Increase public awareness on roundabouts through dissemination of information to the public at DMVs and other avenues.
- Hold public meetings at all stages of implementing a roundabout and educate all road users about its appropriate use.
- Reach consensus among internal staff and external stakeholders before holding these meetings.
- Disseminate information for employees to respond to user calls.
- Educate maintenance staff on roundabout maintenance policies.
- Update guidelines to make it possible to build roundabouts at lower costs, for shorter time horizons.
- Design roundabouts to address the safety of visually impaired pedestrians, bicyclists, and seniors specifically at locations where there is a large population of that road user type.

5 Review of Training and Education Activities

This chapter summarizes the review of selected Caltrans basic trainings that are offered to Caltrans staff of various districts and divisions. In the spirit of making safety the default and including safety in all projects and programs of Caltrans, we reviewed some basic trainings from relevant divisions in addition to those on traffic safety. The aim was to identify ways to help Caltrans familiarize a diverse range of staff with the Safe System approach, and to make some of the basic trainings that are offered to most Caltrans employees better align with the Safe System approach.

Widely used trainings were compiled from different divisions. Some of these had already been reviewed by FHWA. Of the rest, the following were shortlisted for the current round of review:

- Basic Traffic Safety Investigator Training
- Complete Streets Training
- Traffic Safety Workshop
- Project Engineer Academy
- Project Engineer Fundamentals

A 90-minute training course on the Safe System Approach and a curriculum for a 6-hour training were also developed under this effort. The 90-minute course is assumed as a pre-requisite going forward for the other training reviewed.

5.1 90-minute training course and the 6-hour training curriculum

The objective of the 90-minute training course is to provide an introduction to Safe System, specifically to the Caltrans Safe System Framework, described in the rest of this section. It is intended for delivery at the beginning of most training programs to provide a basic concept of Safe System to all Caltrans staff, with the Caltrans Safe System Framework being an applicable reference material for Caltrans staff to use in their project decisions.

The 6-hour training curriculum was developed to provide more in-depth training of Safe System. Besides the Caltrans Safe System Framework, it also includes discussions on current theories and thinking relating to Safe System, focusing on aspects of a project that Caltrans has impact on.

5.1.1 The Caltrans Safe System Framework

At the time of review, the Safe System Pyramid (Ederer et al., 2023), prioritizing the order of interventions based on their effectiveness and the extent of individual effort required, had gained traction with the traffic safety community. FHWA's Safe System Roadway Design Hierarchy (FHWA, 2024) similarly prioritized countermeasures by function, i.e. whether it removed severe conflicts, reduced vehicle speeds, managed conflicts in time, and increased attentiveness and awareness. This literature, the concepts of movement & place from New South Wales, and the FHWA sponsored international scan of best practices there shaped the Safe System thinking. The review team compiled those concepts into one composite framework for use as reference by Caltrans engineers. Caltrans's Safe System Framework is a toolkit for systematically advancing safety based on the Safe System Approach. Different measures are outlined in the sequence of effectiveness and suggested implementation. While many of these approaches are for individual Caltrans divisions, some of them encourage collaboration across different departments and agencies. Table 5-1 shows the framework.

The first column of the framework lists the five elements of the Safe System Approach, along with the three components of kinetic energy risk, arranged in the order of effectiveness. The header row lists the movement and place context for Caltrans highways—namely local access, transition, and mobility—that correspond with a subset of applicable safety measures. The Design Information Bulletin 94 (DIB 94) offers a starting point for context identification before applying safety interventions and measures. 'Local access' broadly summarizes the city center, urban community, suburban community, and rural main street categories of DIB 94; 'transition' is the transitional area, and mobility refers to the rest of the highways, freeways, and the undeveloped rural area category of DIB94. The rural 'mobility' areas could further be categorized into the rural mountainous and the rural plains categories.

Table 5-1 Implementing Safe System at Caltrans

Safe System Foundation	**Context**		
	Local Access	**Transition**	**Mobility**
Step 1. Safe Road Users: Reduce Exposure	Demand Management	Demand Management	Demand Management
Step 2. Safe Speeds: Reduce Severity	Speed Management	Speed Management	Access Control and Conflict Management
Step 3. Safe Roads: Reduce Conflicts	Conflict Management	Conflict Management	
Step 4. Safe Vehicles and Post Crash Care	Technology, Policy, and Post Crash Care	Technology, Policy, and Post Crash Care	Technology, Policy, and Post Crash Care
Step 5. Ensure Redundancy	Increase attentiveness & alertness through signs	Increase attentiveness & alertness through signs	Increase attentiveness & alertness through signs

5.1.2 Context

5.1.2.1 Local Access

Local access refers to the urban and suburban areas, as well as to the rural main streets, as specified in the Design Information Bulletin 94 (DIB 94). These place types accommodate multiple road user types, motorized vehicles such as transit, private and shared cars, and motorized micromobility users, as well as bicycles, and pedestrians.

5.1.2.2 Transition

The transition areas are the sections of the highways and freeways passing through undeveloped areas in which the speeds transition from high to low on approaching settlements. Ideally these are marked by 'gateways' to signal the need to slow down and to share the road with non-motorized modes and with conflicting traffic movements.

5.1.2.3 Mobility

The mobility corridors refer to most rural highways and freeways that are meant for high-speed movement of goods and people. Ideally access-controlled, safety consideration for this type of road context mostly centers around access control, eliminating speed differentials, and providing good infrastructure for high-speed travel.

5.1.3 Safe System Foundation

5.1.3.1 Safe road users: reduce exposure through demand management

For all three contexts of the Caltrans State Highway System (SHS), demand management is the key first intervention to reduce exposure as a step towards achieving 'safe road users.' A system with safe road users must have a range of safe options and destinations available to them, regardless of their travel mode and socioeconomic status. Road users have less exposure to risk when they can avoid trips, take shorter trips, travel by safer modes such as transit, and/or encounter fewer potential conflicts with other road users (especially fewer encounters with high speed and high mass road users). Demand management addresses all these risk dimensions equitably across all road users. Demand could be managed through mitigation of vehicle miles traveled (VMT) by creating i) a better *balance between jobs and housing*, and by providing ii) *adequate affordable housing for all income levels*, which could culminate in shorter trips. Likewise, the exposure of the *unhoused population* could be reduced by supporting their needs. VMT could also be mitigated by iii) eliminating vehicle trips by *mixing land uses*. Development impact review is a key tool for Caltrans to enable demand management, and under SB 743 (Steinberg, 2013), impact assessment is now conducted using VMT instead of level of service. By connecting transportation and land use decisions, development impact review influences exposure. Demand could also be managed by iv) *shifting trips to safer modes, such as transit, paratransit, and shared ride modes* with reliable, comfortable experiences and first/last mile accessibility through transit-oriented development, and unbundled and priced parking. Transit-only lanes, transit-priority operations, first/last mile pedestrian and bicycle connectivity to transit, along with mixed uses and compact grids could all enable mode shifts to safer modes and reduce the need for impaired, distracted, or fatigued road users to have to drive, ride, or walk.

5.1.3.2 Safe speeds: reduce severity through speed management

Next, speed needs to be managed to reduce the likelihood and severity of crashes. Self-enforcing highway design could support safe speeds based on place types as suggested in DIB-94. First a context-appropriate target speed is decided upon, and then strategies are implemented to reduce speeds to the target speed. Use of Caltrans's proven safety countermeasures to reduce speeds is a major step in reducing fatalities and serious injuries. Other than the proven safety countermeasures, landscaping, on-street parking, and markings could be used to create 'friction' to reduce speeds. Arterial signal timing for speed management to target speeds (such as green waves, rest on red in off-peak, and smart signal technology) can also be effective and low cost. Speed management is especially critical while transitioning between settlements and high-speed rural highways. Gateway treatments of various forms of horizontal and vertical interventions could slow operating speeds to the target speeds of approaching settlements by delineating transitions from higher speed to lower speed environments.

5.1.3.3 Safe roads: reduce conflicts by separating users in space and time

Road users of different speed profiles, vulnerabilities, and directions may need to be separated in space and in time through the contextually appropriate use of countermeasures. Ensuring demand and speed management first enables practitioners to select lower cost countermeasures to manage conflicts. For example, Class II or III bicycle lanes are adequate for low-speed roads, and a rectangular rapid flashing beacon is sufficient to warn vehicles of approaching pedestrian crossings in the same context. These are countermeasures cost less than Class I or Class IV bike lanes or a pedestrian hybrid beacon to warn vehicles to reduce vehicle speeds to enable pedestrians to cross the road safely, devices that are required for efficacy in higher speed and volume contexts.

The appropriate level of separation should be based on the context, volume, mass, and speed of motor vehicles and the presence of vulnerable road users. DIB-89 and DIB-94 for separation of bicycle facilities and the FHWA STEP guide for pedestrian crosswalk design are key resources when vulnerable road users are present (which should be assumed in all but limited-access conditions).

Caltrans's proven safety countermeasures also lists design and operational elements for reducing conflicts in space and time. Along with the proven safety countermeasures, innovative design and operations could be piloted and adopted for this purpose. For example, concurrent protected signal phasing allows safe crossing for pedestrians and bicycles with the parallel through traffic, while being separated from turning traffic.

Access control also supports conflict management in the mobility-focused highway categories. This includes reducing or consolidating driveways or side streets, prohibiting (by physical separation) or protecting (by signals) movements at intersections, and adding median and roadside barriers.

The Intersection Safety and Operational Assessment Process (ISOAP) is a toolkit that both manages speeds and reduces conflicts at intersections. ISOAP offers a systematic assessment of conflict severity potential and recommends geometric and operational alternatives to reduce severe conflicts. In many cases, roundabouts may be preferable to signalized intersections to reduce the number and severity of conflicts.

Additional and updated design guidance will be needed for addressing bicycle facilities at intersections (DIB 94 focuses on midblock conditions), in particular to align Caltrans practice with the new American Association of Transportation Safety & Health Officials and National Association of City Transportation Officials Bicycle Design Guides.

5.1.3.4 Safe vehicles and post-crash care

Supporting the appropriate use of technology, policy, and post-crash care is a next step for Caltrans to ensure safe vehicle and post-crash care. Caltrans could support these objectives through critical partnerships with vehicle manufacturers and first responders, providing infrastructure for enhanced access to post-crash care as well as for future autonomous vehicles and connected infrastructure.

5.1.3.5 Ensure redundancy by increasing attentiveness and awareness through signage and enforcement

As a final step, redundancy could be ensured by increasing attentiveness and awareness. Installing signage, providing education in the form of stakeholder capacity building and decision maker culture shift support, and enforcement, specifically automated speed enforcement, in addition to the previous steps, help build redundancy.

Appendix A5 includes a case study of example of the framework in use for a rural highway safety corridor study.

5.2 Review briefs of the training

This section summarizes the training reviews. We recommend delivering a 90-minute Safe System training course including the framework, at the beginning of these training sessions.

Error! Reference source not found., showing the risk of fatality to pedestrian at different impact speeds, has been used in modules of multiple trainings. The numbers for impact vehicle speed and percent risk to pedestrian varies across literature. A study by the Insurance Institute of Highway Safety focuses on vehicle heights compounding the risk of exposure to high speeds for pedestrians. Table 5-2 shows that this study finds a lower risk of pedestrian fatality at the lower ranges of speeds, and a higher risk of pedestrian fatality at the higher ranges of speeds compared to the studies by Tefft, 2011, 2013, and compared to that for pickup trucks from the same study by Insurance Institute of Highway Safety. This is possibly because the current study is based on the outcome of impact by a ‘median-height car’ (Monfort & Mueller, 2024). The graphic used by the National Roadway Safety Strategy (USDOT, 2022) is the most conservative at the lower ranges of speed showing high risk at the lowest speeds.

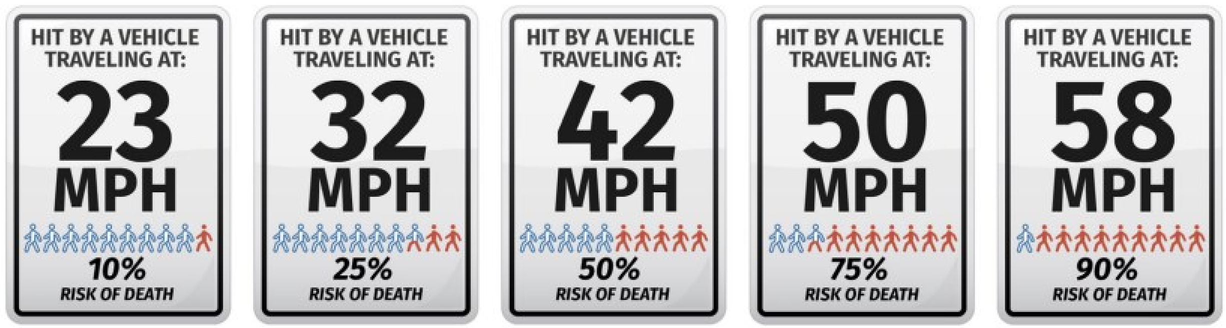


Figure 5-1 Fatality risk of struck pedestrian versus speed of striking vehicle used in Caltrans training modules

Table 5-2 Speeds at which various risks of pedestrian fatalities occur, according to various studies. All values expressed in miles per hour (MPH).

Risk of fatality (%)	NRSS based on Tefft (2011)	Tefft (2013)	Recent IIHS study (overall)	Recent IIHS study (US pickup)
10	23	24.1	31	25.5
25	32	32.5	36.8	31
50	42	40.6	42.3	37.6
75	50	48	48	42.25
90	58	54.6	53.4	48

*IIHS: Insurance Institute of Highway Safety

5.2.1 Basic Traffic Safety Investigator Training

Caltrans's Traffic Safety Investigation is a comprehensive process used to assess appropriate safety improvements at locations with a history of fatal and serious injury (FSI) crashes or other safety concerns commonly linked to FSIs. This process integrates multiple data sources and involves on-site investigations to identify contributing factors to crash frequency and severity.

To align Traffic Safety Investigation training more closely with the Safe System Approach, several enhancements are recommended. These include introducing site investigation training that examines root causes beyond crash reports, such as land use, socioeconomics, desire lines, and transportation choices, and providing case study examples focusing on areas with existing or potential high concentrations of FSIs, in line with Caltrans's updated focus.

The training should be preceded by the 90-minute Safe System module that introduces the Caltrans Safe System Framework. The Caltrans Safe System Framework guides treatment selection based on context (e.g., local access, transition areas, mobility corridors) and prioritizes safety measures by potential impact. Even when selecting low-cost interventions as incremental improvements, the sequence of the Framework should be followed, with site assessments factoring in varying weather and lighting conditions. Identifying and treating safety issues at a corridor, network, or systemic level is more proactive than treating them at the spot level.

Emphasis could move beyond warrant-based improvements, which focus on nominal safety as defined by existing practices, toward the installation or planning of all feasible measures that eliminate the risk of FSIs. Training could also include case studies from the local access context types in addition to mobility context types to address diverse road user needs. Proactive data such as vehicle speeds, near-misses, hard braking, and conflict points, along with feedback from road users (residents, businesses, commuters) could be explored in addition to the crash-based safety data used. Finally, materials from the Office of Transportation Equity and Community Engagement (OTECE) could be incorporated to ensure that equity, community engagement, and health considerations are embedded in every stage of the decision-making process.

A checklist for possible use by the Traffic Safety Investigator is included in the Appendix A.5. All trainings reviewed below are expected to follow after presentation of a 90-minute Safe System module.

5.2.2 Complete Streets Training

The Complete Streets Training is an extended course comprising modules on Complete Streets toolboxes, traffic calming, proven safety countermeasures, issues related to vulnerable road users, and the intersection of climate and safety. To strengthen its alignment with the Safe System Approach, the training could more explicitly reference how various safety strategies relate to the Caltrans Safe System Framework introduced in the earlier module.

Countermeasures could be organized according to the Caltrans Safe System Framework, which includes reducing exposure, reducing speeds, eliminating conflict, promoting safe vehicles and post-crash care, and ensuring redundancy. Additional examples demonstrating how road safety can be improved in different contexts could be included, particularly by applying DIB-94 in the Design Principles Training to show how countermeasures vary based on land use types. Lastly, the training would benefit from incorporating more examples of proactive versus reactive use of crash data to support decision-making.

5.2.3 Traffic Safety Workshop

Caltrans's Traffic Safety Workshop Training is a comprehensive, week-long course that addresses the policies, programs, engineering, and implementation aspects of safety projects. To better integrate the Safe System Approach, it is recommended that the training discuss the context and prioritization outlined in the Caltrans Safe System Framework where applicable. Emphasis could be placed on designing road facilities with safety as the top priority, and on applying the exposure, severity, and likelihood framework to assess interventions. The training could also encourage a context-sensitive approach to highway safety, including a discussion on the ineffectiveness of "StRoads" (street-road hybrids), and the use of DIB-94 to assess various land use types.

The Caltrans Safe System Framework can help prioritize effective safety solutions, expanding Caltrans's focus into addressing underlying land use and socioeconomic factors, such as homelessness and inadequate transit access, that influence safety outcomes. A root cause analysis based on the “w’s” (who, when, what, why, where) of upstream crash circumstances can guide proactive, targeted solutions. Addressing these socio-economic issues in collaboration with local agencies and stakeholders may reduce the need for costly engineering and countermeasures and/or have a greater population-scale impact.

5.2.4 PE Academy & PE Fundamentals

The Project Engineer Academy and Project Engineer Fundamentals trainings are well-structured and provide an in-depth understanding of Caltrans practices and processes relating to all stages of project development and delivery. Project Engineer Academy.pdf and Project Engineer Fundamentals Main Page.pdf list the sequence of training delivery over the week.

Many modules are similar across the Project Engineer Academy and the Project Engineer Fundamentals training. In our review, we recommend combining those so that both modules can be updated at the same time.

In Project Engineer Fundamentals, we suggest referring to the framework for the sequence of interventions and updating photographs and graphics in the SHS2022_Cordova031124.pptx and Phase1.pdf to show more examples of complete streets and highway corridors. In Project Engineer Academy, we suggest referring to the framework in the Design Principles (2-1), Project Engineer Academy Traffic Safety, and Highway Worker Safety Trainings, and including more examples of context when improving road safety using DIB-94 in the Design Principles Training. DIB-94 would be useful in discussing the applicability of different countermeasures in various land use types.

5.3 Future Research Needs

Based on our knowledge of Caltrans programs and projects, and review of Caltrans training, additional research needs and resources needed to achieve the Caltrans Vision Zero by 2050 are listed in Table 5-3. The sequence of research needs follows the sequencing of Caltrans Safe System Framework with the most effective research or resources needed being listed first. These are in order: identify/adjust context, set targets based on the context, select speed management tools, separate users in space and time, and enhance awareness.

Table 5-3 Proposed Caltrans Safe System implementation checklist for new projects and safety investigations

Step	Description	Kinetic Energy Aspect Addressed	Relevant Policy	Key Resources	Additional Research or Resources Needed
1. Safe Road Users: Identify/ adjust Context	Assess the existing and community-desired typology of the study location (i.e., through "movement" or local "place" context) Review local and regional plans and policies regarding transit, bicycle, freight, and other goals/needs for the study location. Implement demand management/VMT mitigation to shorten or eliminate trips and support mode shift.	Exposure	• Senate Bill 743 (SB 743): VMT • CalSTA Climate Action Plan for Transportation Infrastructure (CAPTI) • Climate Action Plan for Transportation Infrastructure (CAPTI) • Context sensitive Solutions: Director's Policy 22 • Road Safety: Director's Policy 36 • Complete Streets: Director's Policy 37 • Climate Change: Executive Order N-19-19 • Caltrans Director's Policy on Roadway Expansion • Complete Streets Action Plan: 2024-25 • Caltrans Mode Share Action Plan 2.0	• Smart Mobility Framework • Complete Streets Contextual Design Information Bulletin (DIB) 94 • Transportation Analysis Framework (TAF) • Transportation Analysis under CEQA (TAC) • Transportation Impact Study Guide (TISG) • VMT Mitigation Playbook • SB 743 Environmental Essentials in Project Development and Delivery • Caltrans Active Transportation Program (ATP)	Adjust context/ improve multi-modal access/ reduce exposure with VMT mitigation (i.e, mixed land uses, affordable housing, parking policies, curbside management, bus stop placement, crosswalk spacing, and grid development). **Research question:** What demand-side tools are most effective and how should Caltrans use them or partner to encourage/ influence them.
Safe Road Users: Set Targets based	Select target speed based on context Select other project goals based on related plans and policies (i.e., transit performance, multi-	Exposure, Likelihood, Severity	• Road Safety: Director's Policy 36 • Complete Streets: Director's Policy 37 • AB 43 (California Assembly Bill 43): Speed Limit Reductions • Zero Traffic Fatalities Task Force Recommendations	• Caltrans Safe System Approach to Speed Limit Setting • FHWA Speed Limit Setting Handbook	**Research questions:** How to select target speeds by context typology For "movement" typologies: how to allow for increased

Step	Description	Kinetic Energy Aspect Addressed	Relevant Policy	Key Resources	Additional Research or Resources Needed
on the Context	modal accessibility, evacuation)		• California Safe Roads: 2020-2024 Strategic Highway Safety Plan		target speeds with vehicle technology enhancements What policies or procedures need to change to allow for target speed determination/ design?
2. Safe Speeds: Select Speed Management Tools	• Select speed management tools for geometry and operations for the target speed • Select TSMO strategies to meet other project goals with “win-win” technologies and flex use	Likelihood, Severity	• Road Safety: Director's Policy 36 • Zero Traffic Fatalities Task Force Recommendations • California Safe Roads: 2020-2024 Strategic Highway Safety Plan	• Caltrans Traffic Safety Investigations Guidelines • FHWA Safe System Speed Management • Complete Streets Contextual Design Information Bulletin (DIB) 94 • Caltrans Traffic Calming Guidance • Main Street, California: A Guide for Improving Community and Transportation Vitality • Caltrans Proven Safety Countermeasures • FHWA Proven Safety Countermeasures	**Research questions:** What are the preferred and effective speed management tools for each typology? What additional flexibility should be provided for Safe System speed limit setting (especially in tandem with speed safety cameras)? How effective are the California speed safety camera pilots and when/how can they be expanded statewide? What vehicle technology could support this (i.e., ISA)? How could this be incentivized in CA?

Step	Description	Kinetic Energy Aspect Addressed	Relevant Policy	Key Resources	Additional Research or Resources Needed
					What are the preferred and effective TSMO strategies for win-win solutions (i.e., transit reliability, evacuation flex use)
3. Safe Roads: Separate Users in Space and Time	Review crash history for conflict locations that have been associated with FSIs. Proactively identify other severe conflict potentials using big data and AI analysis of existing or similar study locations Based on the target speed, select countermeasures to separate users in space and time to reduce conflicts, prioritizing those with more severe consequences based on mass, speed, and vulnerable users	Exposure, Likelihood, Severity	• Road Safety: Director's Policy 36 • Complete Streets: Director's Policy 37 • AB 1145 directs Caltrans to conduct a comprehensive safety study, addressing issues like semi-truck traffic and hazardous conditions.	Caltrans ISOAP Complete Streets Contextual Design Information Bulletin (DIB) 94 Cross-Section Reallocation Guide: NCHRP 1036 Class IV Bikeway Guidance Complete Streets Elements Toolbox 2.0 FHWA STEP Guide for Uncontrolled Crosswalks NATCO Bike Guide AASHTO Bike Guide	**Research questions:** Which big data sources and AI tools should Caltrans use to assess conflicts and severity? Which countermeasures should be considered defaults (design floors) for each typology? What is the state of the art for maintaining road infrastructure such as flexible barriers while protecting highway workers?

Step	Description	Kinetic Energy Aspect Addressed	Relevant Policy	Key Resources	Additional Research or Resources Needed
4. Safe Vehicles & Post Crash Care: Build infrastructure to accommodate these	Faster adoption of safe vehicles by requiring vehicle technology such as intelligent speed assistance (ISA), pedestrian and bicycle detection, DUI ignition interlock, automatic braking, and lane departure avoidance, starting with Caltrans vehicle fleet and those requiring state permits to operate Require VMT-based or risk-based insurance fees Safe routing for trucks and shifting local deliveries to smaller vehicles and e-cargo bikes Deploying V2X ITS systems and other roadside support	Exposure, Likelihood, Severity	• Vehicle Code Division 12 • AB 471: California Vehicle Safety Inspection Program (CVSIP) • AB33: Bill prohibiting delivery of commercial goods by autonomous vehicles without a human operator on highways in California • Other legislation relating to intelligent vehicle features such as SB 1394, AB 2286 and those related to testing and public use of autonomous vehicles and reporting requirements for collisions involving their vehicles to the DMV • Vehicles for protection of highway workers: shadow, barrier, & advance warning • AB1945: extended definition of first responders to public safety dispatchers and telecommunicators • AB 1168: focuses on prehospital EMS services, potentially impacting emergency ambulance services within local EMS areas.	• SHSP • FHWA Saving Lives Together Toolkit • CEMSIS	Along with crash data, Caltrans could create access to big data such as near miss, hard braking, speed, and conflict severity risk scores. **Research questions:** Research and adoption of weight-based, graduated registration, parking, and road user fees to reduce exposure to heavy vehicles (like SUVs) in high vulnerable road user (VRU) areas Introducing future proactive kinetic energy risk assessment along with present crash data analysis. What vehicle technology could support this (i.e., automatic braking, alcohol interlock, ped/bike detection)? How could this be incentivized in CA?

Step	Description	Kinetic Energy Aspect Addressed	Relevant Policy	Key Resources	Additional Research or Resources Needed
	elements for smart city technology and autonomous vehicle readiness Improving access for post-crash care by signal preemption for emergency vehicle access				
5. Ensure Redundancy: Enhance Awareness	Select signs, education, and enforcement countermeasures for system redundancy Monitor outcomes after interventions versus targets	Likelihood, Severity.	• Road Safety: Director's Policy 36 • Complete Streets: Director's Policy 37 • California Safe Roads: 2020-2024 Strategic Highway Safety Plan	• FHWA STEP Guide for Uncontrolled Crosswalks • NATCO Bike Guide • AASHTO Bike Guide • ITE Applications of Big Data in Safety Analysis • AAA Leading Your Community to Action Guide	**Research questions:** What capacity building and culture shift campaigns would best support Safe System institutionalization in California? Which interventions have been most successful in reducing kinetic energy risk (exposure, likelihood, and severity)?

NACTO, National Association of City Transportation Officials; AASHTO, American Association of State Highway and Transportation Officials

5.4 Conclusions

The review of Caltrans training and education activities underscores the importance of embedding the Safe System Approach across all levels of professional development. Aligning foundational training such as the Basic Traffic Safety Investigator, Traffic Safety Workshop, Complete Streets, Project Engineer Fundamentals, and Project Engineer Academy modules with the Caltrans Safe System Framework prioritizes actions in safety thinking in the order of effectiveness. Emphasizing context-sensitive design, proactive use of data, and integrating tools like DIB-94 helps tailor solutions to real-world conditions while promoting equity, health, and collaboration. The 90-minute Safe System module serves as a common foundation for all reviewed trainings, reinforcing a shared understanding of safety principles and countermeasure selection. Together, these enhancements support Caltrans's vision of eliminating FSI crashes by 2050, through a systemic, proactive, and equitable approach to safety across the state highway system.

6 Models of Best Practices to Advance the Safe Systems Approach

Caltrans Director's Policy on Road Safety (DP-36) committed Caltrans to the goal of achieving zero deaths and serious injuries in the roadway system (Vision Zero) by 2050 and states that we will achieve this goal through implementation of the Safe System Approach (SSA) (Caltrans, 2022). The fundamental objective of the SSA, as modeled by FHWA, is to eliminate fatalities and serious injuries (FSI) for all road users by accommodating human mistakes and keeping impacts on the human body at tolerable levels. Because of the limited tolerance of the human body, the risk of fatality and serious injury increases as the kinetic energy sustained within a crash increases. It does not take a high level of crash kinetic energy to cause a serious injury or fatality (FHWA, n.d.). As such, keeping the kinetic energy transfer within the system to a survivable level plays a central role in the implementation of the Safe System Approach.

Under the principle of "responsibility is shared," system managers, vehicle manufacturers, law enforcement, post-crash personnel, and system users all have the responsibility to limit the kinetic energy within the system so that we can eliminate fatal and serious injury outcomes from crashes. Drivers can regulate their behaviors by operating the vehicles in conformance with the speed regulations. Vehicle manufacturers can design vehicle features to absorb part of the kinetic energy transferred to the occupants during a crash. System managers like Caltrans can design, operate, and maintain the roadway infrastructure in a way that the kinetic energy transfer within the system is limited to a level to accommodate safe mobility.

Thirty-six percent of statewide FSI crashes from 2008-2017 happened on the State Highway System (SHS) (Caltrans, 2016). Eliminating fatalities and serious injuries on the SHS is a major step for Caltrans to move towards the goal of Vision Zero. Caltrans Strategic Highway Safety Plan (SHSP) has identified intersection crashes as a top three challenge area for eliminating FSI crashes. Given the central role of kinetic energy management in achieving and maintaining zero fatalities and serious injuries, Caltrans needs to monitor and manage the kinetic energy both at intersections and along the roadways within the SHS to ensure that the design, operations, and maintenance of the current system is consistent with the Safe System Approach (SSA).

This report provides a review on currently available kinetic energy management models for intersections developed within and outside of the United States, discusses the advantages and disadvantages of these models, their applicability to the safety assessment of the SHS, and further proposes the best practice model (with possible modifications) for Caltrans to conduct kinetic energy management at intersections along the SHS. It further summarizes other known methods of assessing safety at intersections, as well as of screening networks.

6.1 Best Practice Review of Kinetic Energy Management Models

6.1.1 Kinetic Energy Management Model (KEMM)

The Kinetic Energy Management Model (KEMM) (Corben et al., 2004) is a conceptual model developed by the Monash University Accident Research Centre (MUARC) to explain the different protective ‘layers’ or physical situations that could be managed such that the levels of kinetic energy to which a road-user is exposed does not exceed the tolerance level of the human body. Humans should be protected from serious injury and death either by preventing the crash from happening or by managing the transfer and exchange of kinetic energy if a crash does occur. The five protective layers that surround humans as introduced by the model, are:

Layer 1 – Human biomechanical tolerance;

Layer 2 – Transfer of kinetic energy to human;

Layer 3 – Kinetic energy per crash;

Layer 4 – Crash risk per exposure; and

Layer 5 – Exposure.

Managing the two outermost protective layers (Layer 4 and 5) helps prevent possible crashes, while managing the inner three layers (Layer 1, 2, and 3) helps reduce crash severity when a crash occurs. The KEMM conceptual model is integrated with the principal four risk factors of the transportation system including the human, the vehicle, the road and roadside, and system operation to ensure the characteristics of each layer of protection are considered comprehensively and systematically.

6.1.2 Kinetic Energy Management Model for Intersections (KEMM-X)

To evaluate the probability of fatality and serious injury, P(FSI), for existing intersection designs and proposed safe system designs, a mathematical model called Kinetic Energy Management Model for Intersections (KEMM-X) was developed (Corben et al., 2010) to model the transfer of kinetic energy from Layer 3 to Layer 1 that is described in KEMM. As it is impractical to quantify the energy flows in actual crashes, the model approximates crash energy given exposure as travel speed, energy transferred to vehicle given crash as impact speed, energy transferred to occupant as change in speed (delta-v), and the energy absorbed by occupant as occupant outcome and uses a stepwise calculation approach to determine P(FSI) from pre-impact travel speed.

Specifically, ***Layer 3*** approximately determines the kinetic energy embodied in a collision. It calculates the impact speed of the two vehicles given their initial travel speeds. The model assumes both vehicles travelling at constant speed. Once the drivers decide to stop to avoid a collision, maximum braking is applied, and the vehicles decelerate at a constant rate. When the distance between the striking vehicle and the collision point d, is smaller than the travel speed v_i times perception-reaction time (PRT), the driver of the striking vehicle does not have enough time to react and brake, the impact speed v equals to the travel speed v_i. When the driver of the striking vehicle has detected the crash and begins to brake, the impact speed can be calculated as:

$$v = \sqrt{v_i^2 - 2\mu g(d - v_i * PRT)},$$

where μ is the friction coefficient, g is the gravitational acceleration. If there is enough distance for the driver of the striking vehicle to react and apply the brake till the vehicle stops, the impact speed $v = 0$.

Layer 2 approximately determines the amount of kinetic energy embodied in both vehicles at the point of impact that is transferred to occupants of the target vehicle. By applying conservation of momentum, the model determines the change in velocity (of the subject vehicle from the point of initial contact to the point two vehicles separate), $Delta - V$, given the impact speed and conflict angle.

Finally, given $Delta - V$, ***Layer 1*** calculates the probability of fatality and serious injury based on the empirical relationship between $P(FSI)$ and $Delta - V$. The probability model is estimated by Evans (1994) (Evans, 1994) with 22,272 weighted National Automotive Sampling System (NASS) data. Assuming the vehicle occupants are wearing seatbelts, the probability of serious injury or fatal outcome $P(FSI)$ given the change in velocity (Δv) of the vehicle during the crash event can be calculated as:

$$P(FSI) = \left(\frac{\Delta v}{\alpha}\right)^k \quad if\ \Delta v \leq \alpha$$

$$P(FSI) = 1 \qquad if\ \Delta v > \alpha$$

The risk model used in KEMM-X is calibrated such that the delta-V of a side impact crash at 50 km/h corresponds to a fatality risk of 10%. In the final model, the new coefficients for side impact are:

$\alpha = 60\ km/h$ and $k = 4.57$ for fatalities (belted)

$\alpha = 58.5\ km/h$ and $k = 2.62$ for serious injuries (belted)

As the definition of a Safe System intersection focuses on reducing FSI risk rather than crash risk, ***Layers 4 and 5***, which relate to the risk of crash occurrence, are not considered in the KEMM-X model.

Based on KEMM-X, to keep the fatality and serious injury risk of a vehicle-vehicle collision below a certain level (say 10%), given the impact angle, the maximum allowed impact speed can be derived, which can inform speed limit setting and other speed-related regulation design. Vice versa, given the speed limit, the maximum acceptable conflict angle can be calculated, which can inform traffic control (e.g., separate the traffic flow that results in a certain impact angle) and the configuration design of an intersection.

KEMM-X proposes a mathematical approach to approximate the kinetic energy transfer to human bodies during a crash and provides a practical tool for evaluating the safety outcome of an intersection given its operation and design. However, it suffers from several limitations:

1. The risk curve estimated by Evans (1994) does not distinguish the FSI risk between different crash types, such as head-on, broadside, etc., which can bias the risk estimation given the variations in crash severity across different crash types under the same impact speed.
2. The model is estimated based on crashes that happened between 1982 and 1991, which is not representative of the safety systems in the vehicles manufactured at present and thus has the potential to overestimate the risk of occupants incurring FSI when a crash occurs.
3. The FSI risk calculated in the model only considers the probability of FSI of struck vehicle occupants and omits the FSI risk for occupants in the striking vehicles, thus failing to

facilitate the FSI risk analysis at an aggregate level (i.e., conflict point level and intersection level).

4. KEMM-X only considers vehicle-vehicle collisions and cannot be applied to the analysis of collisions with fixed roadside objects and other road user types such as bicyclists and pedestrians.

6.1.3 Extended Kinetic Energy Management Model for Intersections (X-KEMM-X)

Based on KEMM-X, Jurewicz et al. (Jurewicz, 2016) developed an extended tool, called X-KEMM-X, which updated the calculation of change in speed during impact (delta-V) based on newer research, distinguished between the FSI risk across different intersection crash configurations, and included intersection conflict point analysis to extend the safety analysis to an aggregate level.

The method of estimating FSI for each conflict point is as follows. For ***Layer 3***, no driver reaction and braking are assumed, and the impact speed is based on the approach speeds under speed limits or other speed management solutions.

For ***Layer 2***, the delta-v is calculated based on its relationship with impact speed and impact angle derived by Tolouei et al. (2011) (Tolouei et al., 2013):

$$\Delta V = \frac{\sqrt{V_1^2 + V_2^2 - 2V_1V_2 cos\emptyset}}{2} \quad (3)$$

where ΔV is the vehicle change in speed due to the crash, V_1 and V_2 is the impact speed of two vehicles involved, and $\emptyset$ is the angle between the axis of travel of both vehicles. This equation assumes that the mass of the vehicles is identical, and the collision is inelastic. Under the assumption, ΔV is the same for both vehicles 1 and 2.

For ***Layer 1***, the fatality and serious injury risk curve for vehicle-vehicle conflict is replaced with the MAIS3+ risk curve by Bahouth et al. (2014) (Bahouth et al., 2014), *which differentiates between the FSI risk of different crash types (including head-on, nearside, far-side, and rear-end crashes*) and is *estimated with recent data (2002-2012) from NASS/CDS* (Crashworthiness Data System). In addition to collisions between vehicles, analysis on vehicle-pedestrian collisions is also included in the X-KEMM-X model. Given the bullet vehicle speed, pedestrian probabilities of MAIS3+ injury are determined based on Davis (2001) (Davis, G.A., 2001).

To elevate the safety analysis to an aggregate level, X-KEMM-X proposes a procedure that includes five steps to quantitatively determine the probability of FSI crash outcomes for a given intersection design:

1. A conflict point diagram should be drawn for the evaluated intersection.
2. For each conflict point, the conflict angle and the impact speed of the vehicles at the conflict point need to be assumed.
3. Based on the assumed conflict angle and impact speed, the change in speed, ΔV can be calculated.
4. For each vehicle, the probability of fatality and serious injury can be estimated based on ΔV and the risk curve. The bullet vehicle is always assumed to be impacted on the front. The target vehicle is assumed to be impacted from the front and the rear respectively for head-

on and rear-end crash. To consider the worst-case scenario, in any angle (side) crash, the target vehicle is assumed to be impacted from the side due to the higher FSI risk of side impact compared to front or rear impact.

5. The overall FSI probability at the given conflict point is calculated as the union of the FSI probability of the two parties involved:

$$P(FSI) = P(FSI_1) + P(FSI_2) - P(FSI_1) * P(FSI_2)$$

For each intersection, the number of conflict points and the aggregated FSI risk (e.g., average, max, min) across all the conflict points can be calculated, which can then be used to compare the safety performance across different intersection configurations and inform innovative intersection designs.

Compared to KEMM-X, X-KEMM-X updates the risk curve with a more recent and robust model (Bahouth et al., 2014, and Davis, 2001), considers the interaction between vehicle and pedestrians, and extends the analysis to an aggregated level. However, the model still has its own limitations and can be further improved.

1. When calculating the change in velocity given the impact speed, the model can relax the assumption of equal vehicle masses by considering traffic compositions of the target intersection.
2. For risk estimation, the model used can be further refined and validated using more recent and local crash data if available. The FSI risk for vehicle occupants besides those in the front seat can also be considered.
3. Some conflict points are more likely to have crashes due to the difficulty to maneuver through. Conflict points with high exposure (i.e., traffic volume) and higher complexity of movements are more likely to have a higher number of crashes. The evaluation of intersection design could be extended to accounting for crash likelihood and exposure risk at each conflict point.

6.1.4 Safe System for Intersection (SSI)

Safe System for Intersection (SSI) is a method developed by the Federal Highway Administration (FHWA) for planners and designers to apply the concepts of the Safe System Approach and kinetic energy management to intersection projects. It takes exposure, risk of fatality and serious injury, and movement complexity into consideration and has four main components:

1) conflict point identification and classification;

2) conflict point exposure;

3) conflict point severity; and

4) movement complexity.

The output of the method is the SSI score for a specific conflict point type at an intersection, and the SSI score for the whole intersection. The SSI score ranges from 0 to 100. The higher the score, the closer *the* intersection designs are to a Safe System objective of low fatality and serious injury risk.

Specifically, the method categorizes conflict points by the movement of the traffic streams, including ***crossing***, ***merging***, ***diverging***, and ***non-motorized***. For each conflict point, three metrics including ***exposure index***, ***conflict point severity*** and ***movement complexity*** are calculated.

For ***exposure index***, the SSI method adopts the definition from Hakkert & Mahalel (1978) (Hakkert & Mahalel, 1978), which takes the product of vehicle or non-motorized user daily volumes through that conflict point:

$$I_c = Q_{1,c} * Q_{2,c},$$

where I_c is the exposure index at conflict point c, $Q_{1,c}$ and $Q_{2,c}$ are the vehicle or non motorized user daily volumes passing through that conflict point. The value of $Q_{1,c}$ and $Q_{2,c}$ are determined using the daily volumes, turning movements, and intersection geometry.

In terms of ***conflict point severity***, for vehicle-vehicle conflict, the SSI method estimates P(FSI) based on Evans (Evans, 1994). The probability of fatal and serious injury for vehicle i at conflict point c is calculated as:

$$P_c(FSI_i) = \left(\frac{\Delta V_{i,c}}{\alpha}\right)^k$$

where $\Delta V_{i,c}$ is the change in the velocity for vehicle i at conflict point c. Given impact angle and impact speed, the change in velocity is calculated using the same equation as in X-KEMM-X (see Equation 3).

While Evans (1994) estimated different values for α and k for different combinations of occupant restraint use and crash severity, the SSI method calculated a weighted average of α and k to obtain a more general model that does not consider occupant restraint use and combine fatality and serious injury together. The weight is derived by creating distributions based on crash severity and restraint use with the 2014-2017 FIRST crash data. In the final equation, $\alpha = 67.29\ km/h$ and $k = 3.79$.

The probability of fatality and serious injury, P(FSI), at the conflict point c are calculated using the same equation as X-KEMM-X

$$P_c(FSI) = P_c(FSI_1) + P_c(FSI_2) - P_c(FSI_1) * P_c(FSI_2)$$

For vehicle-pedestrian conflicts, they calibrated the model developed by Tefft to account for MAIS scores of 3 and above as fatal and serious injuries using data from Tefft (Tefft, 2013) and Chidester & Isenberg (Chidester & Isenberg, 2001). The FSI risk for non-motorists at conflict point c is calculated as:

$$P_c(FSI) = \frac{1}{1 + e^{3.8432 - 0.1237V}}$$

To determine conflict point severity, vehicle speeds through each conflict point and the collision angle between vehicles at a vehicle-vehicle conflict need to be estimated. The SSI method assigns each vehicle movement at a conflict point to a speed category based on a combination of factors including the intersection type, traffic control type and movement. For collision angles, the SSI method divides collisions into five categories (crossing-broadside, crossing-left turn, crossing-roundabout, merging, diverging) and assigns each category with a typical collision angle range.

For ***movement complexity***, the SSI captures both the complexity added by the characteristics of conflicting traffic (with the moderating effect of traffic control type considered) and the complexity specific to non-motorized movements through the intersection.

The first ***conflicting traffic complexity factor*** L_1 applies to both vehicle-vehicle and non motorized conflict points. It accounts for 1) the reduction in complexity that resulted from a specific type of traffic control, 2) the number of lanes that carry conflicting traffic movements for a selected movement of interest, and 3) the speed of conflicting traffic for different movements through the intersection:

$$L_1 = \alpha_{traffic\ control} * \alpha_{conflicting\ lanes} * \alpha_{conflicting\ speed}$$

The calculations on each parameter are shown below. The traffic control parameter is calculated as

$$\alpha_{traffic\ control} = BTCAV + (1 - f) * (1 - BTCAV)$$

where *BTCAV* represents the base traffic control adjustment value and *f* represents a weight given to the use of traffic control devices, and user compliance to those traffic control devices. Potential values for BTCAV are informed by Crash Modification Factor (CMF) values for stop control, protected, and protected/permitted traffic signal control operations.

The conflicting lane parameter is calculated for vehicle and non-motorists separately:

$$\alpha_{conflicting\ lanes,veh} = Cross\ Score_{veh} + Merge\ Score_{veh}$$

$$\alpha_{conflicting\ lanes,nonmotorized} = Cross\ Score_{nonmotorized} + Total\ Turn\ Score_{nonmotorized}$$

where for vehicle-vehicle conflict, the *cross score* is the number of through lanes carrying conflicting traffic on the intersection approaches that a movement crosses without refuge during the movement; *merge score* is a function of the number of lanes on the intersection approach that the subject movement is merging with. For non-motorized movement, the *cross score* is the maximum number of through lanes that it must cross without refuge. The *total turn score* considers complexity added by checking for oncoming vehicles from approaches parallel to the movement. It is the sum of the individual approach non-motorized turn scores, which is a function of the number of through lanes on the subject approach parallel to the non-motorized movement in question.

Finally, the conflicting speed parameter is calculated as:

$$\alpha_{conflicting\ speed} = 1 - \frac{60 - V_c}{60} * \frac{0.10}{0.15}$$

where V_c is the conflicting vehicle speed. $\alpha_{conflicting\ speed}$ is applied when computing the conflicting traffic complexity factor for crossing, merging or non motorized conflict points.

The ***non-motorized complexity factor*** L_2 accounts for indirect and non intuitive movements at an intersection that may present additional complexity for pedestrians and cyclists.

$$L_2 = 1 + i_{indirect} + i_{nonintuitive}$$

where $i_{indirect}$ equals to 1 if the pedestrian or cyclist need to traverse a path other than their intended direction; $i_{nonintuitive}$ equals to 1 if the non motorized movements cross any non intuitive motor vehicle movements.

Based on the calculated exposure index, crash severity and movement complexity, one then can calculate the sum of the exposure-severity-complexity products for all conflict points of a given conflict type t:

$$E_t = \sum_{i=1}^{n_t} \left[I_{i,t} * P(FSI)_{i,t} * L_{1,i,t} * L_{2,i,t}\right]$$

where $I_{i,t}$ is the exposure index for conflict point i of type t; $P(FSI)_{i,t}$ is the probability of a fatality or serious injury occurring if a crash occurs at conflict point i of type t; $L_{1,i,t}$ and $L_{2,i,t}$is the conflicting traffic complexity factor and non-motorized movement complexity factor at conflict point i of type t.

The SSI score for a conflict type is then:

$$SSI_t = 100 * exp\,(-\frac{1}{z} * E_t)$$

where the $z = 1.37 * 10^7$ is the scaling factor that restrains the SSI score to fall between 0 and 100.

The SSI score for the intersection considers all the four conflict types and is calculated as:

$$SSI_{int} = 100 * exp\,(-\frac{1}{z} * (E_{crossing} + E_{merging} + E_{diverging} + E_{nonmotorized})/4]$$

Table 6-1 compares the three intersection kinetic energy assessment models (KEMM, KEMM-X, X-KEMM-X), SSI, and a network assessment model, the United States Road Assessment Program (usRAP).

Table 6-1 Comparison across intersection kinetic energy assessment models (KEMM, KEMM-X, X-KEMM-X), SSI, and a network safety assessment model usRAP.

	KEMM	KEMM-X	X-KEMM-X	SSI	usRAP
Layer 1	Human biomechanical tolerance	Evans (1994)	Bahouth et al. (2014) Davis (2001)	Evans (1994) Tefft (2013)	Risk factor given the operating speed (Power model)
Layer 2	Transfer of kinetic energy to human	Assume equal mass Conservation of momentum	Assume equal mass $\Delta V = \frac{\sqrt{V_1^2 + V_2^2 - 2V_1V_2cos\emptyset}}{2}$		
Layer 3	Kinetic energy per crash	Impact speed = f(distance to collision|travel speed)	Assumed impact speed = travel speed		Operating speed (= max(speed limit, 85^{th} percentile speed))
Layer 4	Crash risk per exposure			Movement complexity	Likelihood
Layer 5	Exposure			Exposure Index	External flow influence
Conflict type		Veh-veh	Veh-veh, veh-ped	Veh-veh, veh-ped	

Both X-KEMM-X and SSI can potentially be applied to help manage kinetic energy at intersections along the SHS. While the two models share the same calculation on the change in velocity and the probability of FSI at a conflict point for vehicle-vehicle collision, they are different in the following aspects:

1. For the conflict point severity analysis, the fatal and serious injury risk curves used in X-KEMM-X and SSI are different. For vehicle-vehicle conflict, the SSI method adopts Evans (1994) model, where a homogeneous relationship between delta-v and fatal and serious injury risk is assumed across all crash types; whereas X-KEMM-X adopts the risk curve developed by Bahouth et al. (2014) that distinguishes the relationship between change in velocity and P(FSI) for different crash types, which can lead to a more accurate estimate of crash severity. For vehicle/non-motorist conflicts, X-KEMM-X uses the model estimated by Davis (2001) with United Kingdom crash data collected more than 30 years ago; whereas the SSI adopts a more recent model developed by Tefft (2013) that is fitted with 1994-1998

U.S. crash data and adjusted with the distribution of vehicles that struck pedestrians in the U.S. in 2007-2009, which can reflect the medical care, vehicle design, and composition of the vehicle fleet in the US better.
2. The SSI report includes a predefined range of assumed speed given movement, intersection type, and traffic control type, and assumed impact angle for different collision types, which facilitate convenient application to a variety of intersections.
3. While X-KEMM-X only focuses on the analysis of conflict point severity, which represents an aggregation of Layers 3, 2, and 1 of the KEMM, the SSI extends the analysis to layer 4 and 5 by incorporating movement complexity and exposure index in the method, further taking crash likelihood into consideration.

The advantages and disadvantages of X-KEMM-X and SSI are listed in Table 6-2.

Table 6-2 Comparison of benefits of X-KEMM-X and SSI as tools for measuring kinetic energy at intersections

Model Benefit	X-KEMM-X	SSI
P(FSI) by delta-V based on recent research for V-V crashes	X	
P(FSI) by delta-V based on recent research for V-P crashes		X
Differentiation between head-on, nearside, far side, and rear-end crashes	X	
Based on crash data since 2000	X	
Accounts for percentage of unbelted vehicle occupants		X
Delta-V calculated based on conservation of momentum	X	X
Accounts for movement complexity, that affects probability of a crash		X
Considers exposure index		X
Accounts for both vehicle-vehicle and vehicle-pedestrian crashes	X	X

To facilitate kinetic energy management at intersections on the SHS of California, adaptations and modifications can be made based on the above two approaches as follows:

1. For the conflict point severity analysis, models estimated with more recent data (Wang, 2022) can be used to calculate the FSI risk under recent vehicle design, medical care, and the composition of vehicle fleets, given the crash type and the change in velocity.
2. If information regarding the composition of vehicle fleets through an intersection is available, when calculating the change in velocity (delta-V), there is a potential to consider the situation where the masses of the two vehicles involved in the collision are unequal such that a more accurate estimate on delta-V is obtained (Tolouei, 2013).
3. The speed assumptions made in SSI can be adjusted based on the speed management measures in California or available intersection speed data to reflect the traffic operation within a specific intersection configuration in California.

6.2 Intersection Assessment Processes/Tools

6.2.1 Intersection Safety and Operational Assessment Procedure (ISOAP)

Intersection Safety and Operational Assessment Process (ISOAP) is an update and renaming of Intersection Control Evaluation (ICE). It is a process used by Caltrans to evaluate proposed traffic control and design geometrics for intersections as well as other access improvements proposed on the SHS. With greater emphasis on road safety performance, consistent with the strategic direction of Caltrans, intersection geometry and traffic control need to be determined with a performance-based analysis that considers all users and supports the principles of the Safe System Approach (Caltrans & CalSTA, 2024). Specifically, at Stage 1, the screening and initial assessment stage, assessment of bicyclists, pedestrians, transit, and freight are included. At Stage 2, data collected during appropriate time periods should include pedestrians, bicyclists, transit, and freight movements and detailed analysis on quality of service for pedestrians, bicyclists, and transit users is to be considered. When making recommendations, the strategy with the highest performance supporting the principles of the Safe System Approach should be selected, even if it may not be the one with the highest benefit-cost ratio. Additionally, bicyclist and pedestrian accommodations and descriptions on how the Safe System Approach is supported should be documented (Liu et al., 2024).

6.2.2 Safety Performance for Intersection Control Evaluation (SPICE)

The Safety Performance for Intersection Control Evaluation (SPICE) Tool is an excel-based macro workbook developed by FHWA to assist practitioners in evaluating the anticipated safety performance of different control strategies. It uses the SPFs in Part C of the Highway Safety Manual to select high-quality crash modification factors (CMFs) from Part D of the HSM and CMF Clearinghouse to predict crash frequency and severity for a variety of intersection control strategies. Based on the basic input from users, SPICE selects the appropriate SPF or CMFs to apply automatically and generate the predicted crash frequency and crash severity for each selected control strategy. The analysis can be conducted for a single year or for the lifespan of a project depending on the practitioner's choice. The output of SPICE (i.e., predicted crash frequencies and severities for intersections) can serve as input into other comprehensive ICE tools (e.g., NCHRP Project 3-110 tool) to consider a broad range of performance measures like traffic operations and emissions as well as the associated monetary costs (USDOT, 2018). Both SPICE and SSI are alternatives for use in conducting initial safety assessments of ISOAP.

6.2.3 Site-Specific Evidence-based Safety Analysis (SESA)

The SESA process (USDOT, 2018) was developed for predicting crashes at a site or intersection level to understand the underlying injury crash risk at a site and the likely benefits of upgrade options in reducing injuries and FSI crashes. It is a process that can be used to develop robust crash risk estimates for complex intersection layouts and innovative upgrade options. The process (see Figure 6-1) consists of five steps: 1) establish safety base estimation using most appropriate prediction models for each option; 2) determine key safety related features for each option and which of these are not covered by models and factors; 3) modify safety estimate (injury prediction) for each option; 4) determine relative risk of severe crashes for each option; and 5) assess benefits of improvement options over existing location. Since safety judgements need to be made through the process, input from specialized road safety engineers with design and research experience is often required. To estimate the risk of FSI crashes, crash severity factors also need to be developed and applied during the process. Crash severity factors can be developed using the kinetic energy models like X-KEMM-X, as used in the Breen/Gardiners/Harewood Intersection Upgrade at Christchurch (Turner et al, 2020).

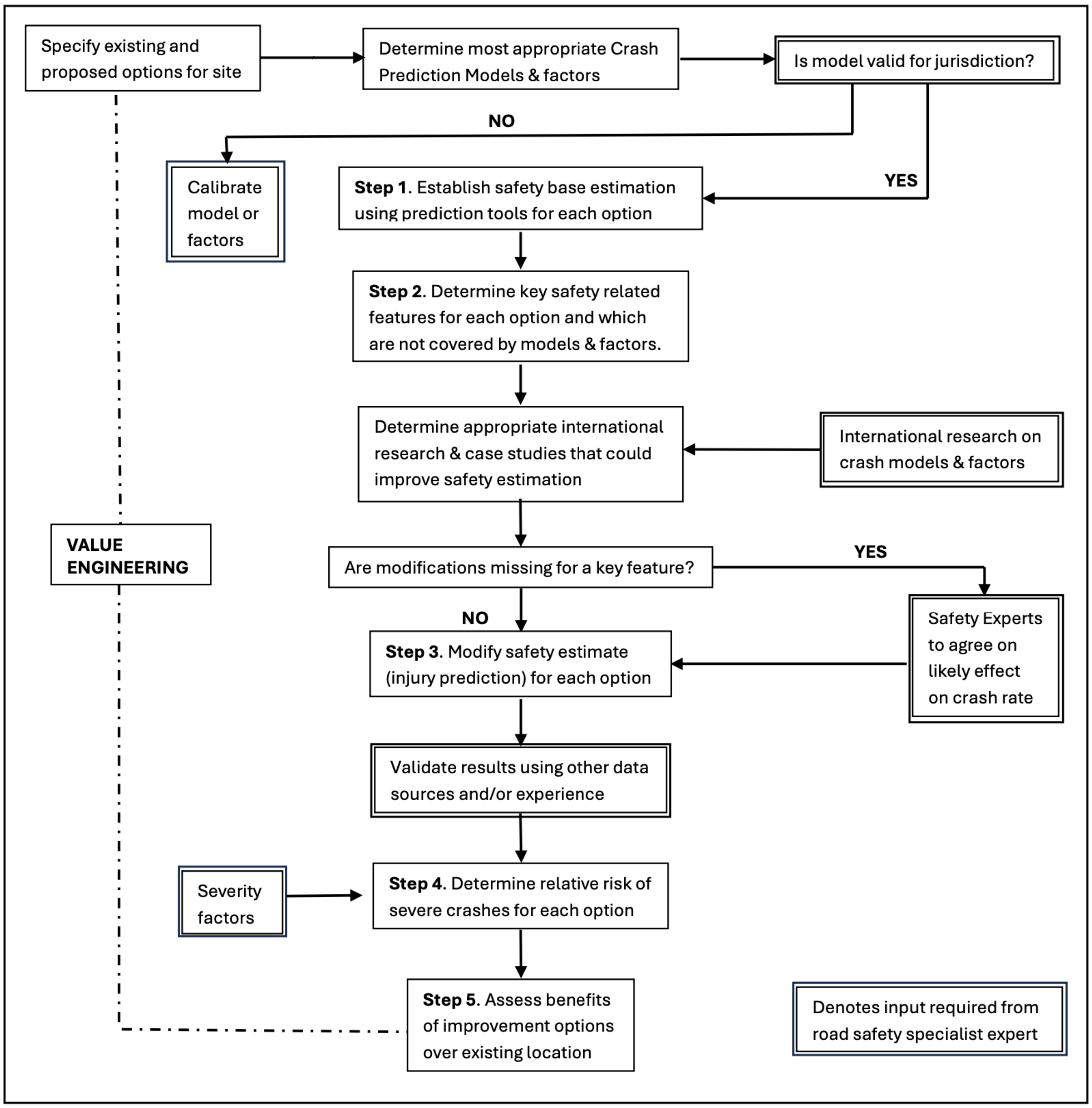


Figure 6-1 Flow chart of SESA process

6.3 Network-level Evaluation

6.3.1 United States Road Assessment Program (usRAP)

The United States Road Assessment Program (usRAP) is an innovative and proactive tool for analyzing the safety of a roadway and generating data-driven solutions for correcting hazards. The program uses the software called ViDA, which takes existing or newly collected video of a road network that is coded in 100-meter segments as inputs. It then outputs ***star ratings*** on a scale from 1 to 5 based on the presence or absence of the safety-related design and traffic control features within the roadway segments. A star rating of 1 indicates the fewest safety-related design and traffic control features while a star rating of 5 indicates many (United States Road Assessment Program, n.d.). As designs and features that affect crash frequencies vary across different road users, separate star ratings are assigned for vehicle occupants, motorcyclists, bicyclists, and pedestrians.

The star rating system of usRAP is based on the method developed by the International Road Assessment Program (iRAP). Specifically, the star rating is assigned based on the Star Rating Score (SRS) for a specific type of road user i, which is calculated as the sum of the scores for the crash types related to the road user:

$$SRS_i = \sum_{t=1}^{n_i} Crash\ type\ score_{i,t}$$

where SRS_i represents *the relative fatality and serious injury risk* for an individual of road user type i; n_i is the number of crash types related to road user type i.

The scores for crash type t of road user type i is calculated as

$$Crash\ type\ score = Likelihood * Severity * Operating\ speed * External\ flow\ influence * median\ traversability$$

The score for ***likelihood (severity)*** is calculated as the product of risk factors (or crash modification factors, CMF) of each road attribute considered to be associated with the crash likelihood (severity) of the crash type.

The score for ***operating speed*** equals to the relative fatality or serious injury risk of the road user type i involved in crash type t under the given speed, which is derived from a power model. The model calculates the FSI risk by multiplying together a likelihood factor (whereby the relationship between speed and the likelihood of crash is linear) and a severity factor (whereby the relationship between speed and the severity of a crash is generally square).

The ***external flow influence factor*** accounts for the way in which traffic flows can affect the type of crash an individual road user is involved in. Assuming a lane is saturated when the vehicle flow is above 18,000 vehicles per day, for vehicles and motorcycles, the factor reflects the relationship between lane saturation level, and the proportion of all crashes a certain crash type is accounting for. For pedestrians and bicyclists, this factor reflects the relationship between lane saturation level and the relative risk of fatality and serious injury.

Finally, the ***median traversability factor*** accounts for the potential that an errant vehicle will cross a median, which only applies to vehicles and motorcyclists run-off-road and head-on (loss-of-control) crashes. It equals 1 if the median is traversable and 0 if not.

6.3.2 Australian Road Assessment Program (AusRAP)

The AusRAP was developed to provide a consistent, independent safety rating system for highways in Australia. It consists of two protocols, ***risk mapping*** and ***star ratings*** to assess the safety of roads. The ***risk mapping*** is based on a road's history of crashes and traffic flow. It consists of two types of risk maps. One, referred to as the 'collective' risk map, plotted the annual average number of casualty crashes per kilometer on highway links and presents the 'crash density' on highways. The other, referred to as the 'individual' risk map, calculates the number of crashes per vehicle kilometer traveled for each road link and assigns the risk rating, from a low-risk rating (top 20%) to a high-risk rating (bottom 20%), based on the calculation. The ***star ratings***, on the other hand, provide a measure of the inherent safety of a road. The rating is based on an inspection of design elements that influence the *likelihood* of crashes occurring and the *severity* of those crashes if they occur, with a focus on the three most common and severe types of crashes on rural highways: run-off road, head-on, and intersection crashes. A road protection score (RPS) is calculated for each crash type based on design elements that influence it and weighted according to the relative impact of each element on the likelihood of the crash. The score is further adjusted according to the likely severity should it occur. Combining the RPS for the three crash types, the final RPS is obtained. And a star from 1 to 5 is assigned based on the star rating bands the RPS falls in, with 1-star being the worst and 5-star being the best. Homogeneous road sections are grouped together when assigning the RPS and the length of each can vary from 200 meters to 100 km depending on the frequency of alteration in road design (Smith et al., n.d.).

6.3.3 New Zealand Road Assessment Programme (KiwiRAP)

The New Zealand Road Assessment Programme, KiwiRAP was developed to help track road safety performance and assess potential improvements across New Zealand's highway network. KiwiRAP incorporates three protocols including ***risk mapping***, ***star rating***, and ***performance tracking***. ***Risk mapping*** rates the relative personal and collective risk of sections of the highway network with historical casualty crash and traffic volume data. ***Star rating***, based on the road protection score from AusRAP, rates each section of highway based on its physical features and their subsequent effect on the risk of three crash types: run-off road, head-on, and intersection crashes. A Road Protection Score (RPS) is assigned for every 100-meter section based on the evaluation of road's design elements that influence the targeted crash types. Road elements to be inspected can include road section type, lane width, sealed shoulder, horizontal alignment, terrain, delineation, overtaking provision, overtaking requirements, speed environment, offset, and severity of roadside hazards and traffic volume. Based on the RPS, a star rating from one to five is assigned. For example, a divided road with major deficiencies in some road features (e.g., poor median protection against head-on crashes) will score a 3-star (New Zealand Road Assessment Programme, n.d.). ***Performance tracking*** is used to measure the changes in the risk of roads over time to assess whether treatments aimed at improving safety have the desired effect.

6.3.4 Australian National Risk Assessment Model (ANRAM)

ANRAM is a risk-based severe crash assessment tool developed to support nationally consistent road assessment programs. ANRAM can help assess road networks and identify severe crash risk locations. It takes advantage of both the AusRAP protocols to identify injury risk based on roadway features and existing crash data to identify historical crash risk. The predicted and observed severe crashes are then combined to produce a severe crash estimate and the subsequent severe crash risk score (Austroads, 2018).

6.3.5 CycleRAP

CycleRAP is a safety assessment tool developed by iRAP to evaluate road features and bicycle infrastructure for the safety of bicyclists and other light mobility users. There is no need for crash data. The CycleRAP uses data about the features of a road, street, or path to calculate the crash risk for bicyclists and light mobility users for all types of crash (bicycle-bicycle, bicycle-pedestrian, vehicle-bicycle, and single bicycle) to identify high risk locations. The model evaluates a list of predefined features—such as facility type, facility access, and delineation—of a location and produces a risk score for each crash type. It then sums up all the four risk scores to produce the final CycleRAP score (iRAP, n.d.).

Table 6-3 compares the network safety assessment models.

Table 6-3 Comparison of the network safety assessment models

	usRAP	AusRAP	KiwiRAP	ANRAM	CycleRAP
Protocols	Risk Mapping, Star rating	Risk mapping, Star rating	Risk mapping, Star rating, Performance tracking	Risk-based severe crash assessment	CycleRAP score
Data	Safety-related design, traffic control features	Physical features	Physical features	Physical features, existing crash data	Road features, bicycle infrastructure
Crash types	Run-off-road, Head-on, Intersection, Property access	Run-off-road, head-on, intersection	Run-off-road, head-on, intersection	Run-off-road, Head-on, Intersection, Pedestrian, other	Bicycle-bicycle, Bicycle-pedestrian, Vehicle-bicycle, Single bicycle
Road users	Vehicle, pedestrian, cyclists, motorcyclists	Vehicle pedestrian, cyclists, motorcyclists	Vehicle	Vehicle, Pedestrian, Other	Cyclists

6.4 Risk-Based Road Network-Wide Screening (RB-RNWS)

A recent publication introduces the kinetic energy risk assessment framework—i.e. exposure, likelihood, and severity—into network screening (Bonera et al., 2024). Following data collection and data compliance with ISO 39001:2012 standard, the risk-based network-wide screening involves network segmentation, which is the process of partitioning the road into a set of homogenous road network units, similar to the highway segments in the Caltrans Transportation System Network (TSN) database. The Road Crash Risk Index is computed for each network unit as the product of the probability of a crash, the exposure factor, and the severity of the crash over the road network unit.

- The probability of crash over the road network is modeled using logistic regression, using road infrastructure, operational characteristics (such as percent heavy vehicles), environment (such as terrain, land use, urban, weather), and context (such as season, day of the week, etc.) as explanatory variables.
- For segments for which AADT data is not available, the road crash exposure is modeled as a function of road infrastructure, context, and operational conditions as before, as well as socio-demographics such as population density. For Caltrans, AADT is available for most TSN segments for vehicular traffic, and modeled outputs are available for pedestrian and bicycle traffic.
- Crash severity is modeled as a function of users involved, crash type, violation type, road infrastructure, percent heavy vehicles, environment, socio-demographics, and context conditions.

Speed is an important variable that influences both the probability of a crash as well as the severity of a crash that is not explicitly considered in this study.

6.5 Summary & recommendations

This literature review provides an overview of currently available models to monitor and manage kinetic energy at intersections and existing tools to conduct network-level evaluation on safety.

For the kinetic energy management model of intersections, we review the basic idea of the conceptual model, KEMM, and introduce three mathematical models—KEMM-X, X-KEMM-X, and SSI, which was developed based on the concept of KEMM. These three models enable the evaluation of safety outcomes for intersections according to their design and type of traffic control. Both KEMM-X and X-KEMM-X capture the inner three layers of KEMM and enable calculation of fatality and serious injury risk given travel speed and impact angle. SSI extends the analysis to layers 4 and 5 by incorporating movement complexity and exposure index in the model, evaluating intersections by crash likelihood in addition to crash severity. To monitor and manage kinetic energy at intersections on the SHS, Caltrans can adopt a combination of X-KEMM-X and SSI, including the updated $P(FSI)$ given delta-V by Bahouth et al (2014) for vehicle-vehicle crashes, and by Tefft (2013) for vehicle-pedestrian crashes. This model would include the exposure index and movement complexity considerations of SSI. Future work would include further updating the models with i) more recent data and ii) $P(FSI)$ in crashes between vehicles of different masses, or different vehicle types, such as car-truck, car-SUV etc., subject to availability of updated data. The updated models could be used at intersections based on the composition of vehicles that use the intersection.

For network-level evaluation, usRAP, AusRAP, KiwiRAP have the star rating protocol that could be used to rate the injury risk of a road based on its physical features. These tools are proactive in identifying road segments with high crash likelihood and severity. To monitor and manage the kinetic energy along roadways on the SHS, Caltrans can focus on analyzing the FSI risk for loss-of-control, head-on, and rear-end crashes, the three common and severe types of crashes on roadway segments (Caltrans, 2022a). Among readily available tools, ViDA, the iRAP online road safety software platform, provides estimates of FSI crashes for roadway segments based on a combination of road attribute data, flow data for each road user, and network-level crash data. This is a systemic tool that could help Caltrans identify segments with relatively high FSI risk for the targeted road user group and prioritize those for further improvement. Once an improvement project is granted, the estimates can be used to understand the safety implications of design solutions, and to facilitate comparison across different alternatives (iRAP, n.d.-a)

The risk-based road network-wide screening process (RB-RNWS) is the most aligned with the Safe System. Caltrans could develop the screening process on individual TSN segments, as the input data for the models are available. However, the network screening process does not consider the configurations of the many intersections in that segment. The tool needs to be further developed to include that, or safety of intersections needs to be assessed separately.

7 Intersection Kinetic Energy Assessment Model

This chapter addresses the need to assess and rate intersections based on the kinetic energy risk assessment metric consisting of exposure, likelihood, and severity. Following the literature review of the different kinetic energy models summarized in Chapter 6, FHWA's Safe System for Intersections (SSI) was selected to be a robust and comprehensive method for assessing kinetic energy. A spreadsheet-based model was created using FHWA's SSI method. Subsequently, when FHWA commenced work on their spreadsheet-based tool of this model, work on the spreadsheet-based model was suspended. This chapter includes a description of the beta version of FHWA's SSI tool.

7.1 Caltrans Preliminary Safe System for Intersections (SSI) model

FHWA's Safe Systems Intersections (SSI) method was developed to proactively evaluate intersections based on the kinetic energy management framework, i.e., the exposure, likelihood, severity (Porter et al., 2021). FHWA created this method to compare different intersection types and provide an objective quantitative value (SSI score from 0-100) to inform engineers and industry experts on the intersection configuration that would be the safest for the given conditions.

"FHWA released the SSI method in the 2021 report A Safe System-Based Framework and Analytical Method for Assessing Intersections. As described in the report, the SSI method constitutes a practical, research-based method for assessing how well various intersection alternatives align with the Safe System Approach, a holistic view of the transportation system that focuses on preventing fatalities and serious injuries.

The SSI method is designed to be used in the context of a Stage 1 Intersection Control Evaluation (ICE), which occurs at the scoping phase of project development to analyze alternatives with respect to whether they meet project needs. The method was developed to use typically available project data inputs, so that it could be readily usable by practitioners during alternatives screening." (FHWA, 2024)

The Caltrans Safe System for Intersections (SSI) preliminary model was developed to proactively rate the safety characteristics of an intersection. Two spreadsheet-based models were created: first, one for X-KEMM-X, and the other for the SSI.

The SSI model needs two sets of inputs, a core and a default set. These inputs are listed below.

7.1.1 Core Inputs

Core inputs are inputs that must be entered to determine the safety of each intersection. These inputs include:

- Design year AADT - major road
- Design year AADT - minor road
- Non-Motorized average daily traffic

- Number of through lanes - major road
- Number of through lanes - minor road
- Traffic control type
- Posted speed limit - major road
- Posted speed limit - minor road

7.1.2 Default Inputs

Default inputs are inputs that would normally be left untouched, as these inputs would not drastically differ with any reconstructed infrastructure in an intersection. However, these inputs may be changed with more drastic intersection improvements. These inputs include through and turning movement speeds, conflict angles, P(FSI) regression parameters, Base Traffic Control Adjustment Values (BTCAV), driver merging, and non-motorized turn score weights.

A basic T-junction was selected for the sample model as shown in Figure 7-1. Sample values were selected for each of the core and default inputs.

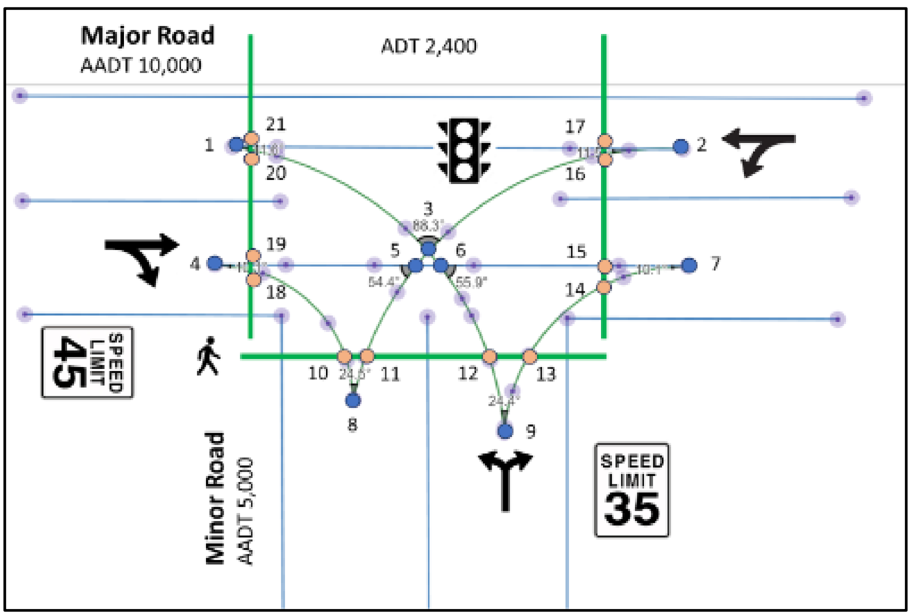


Figure 7-1 Details of the T-junction selected for the sample model

A screenshot from the spreadsheet model of the calculations of exposure, severity, and likelihood can be found in Figure 7-2. Descriptions of each are below:

Conflict points				Exposure Index			Conflict point severity						Conflicting Vehicle Complexity Factor											Nonmotorized Movement Complexity Factor			
Conflict Point Type	Conflict Point Name	Movement 1	Movement 2 (lower)	Q1	Q2	I	V1	V2	Angle	Delta-v	P(FSI)_veh	P(FSI)pts	BTCAV (base traffic control	f	a_traffic_control	Cross score		# merge lanes	Merge score	a_conflicting_lanes	V_c	a_conflicting_speed	L1	i_nondirect	i_nonintuitive	L2	Exposure-Severity-Complexity Product
Merging	1	WB-Thru	NB-Left turn	750	250	187500	45.0	20.0	45.0	17.0	0.0	0.0	1.00	0.5	1.0	1.0		1.0	1.0	2.0	45.0	0.8	1.7	--	--	1.0	3368.8
Diverging	2	WB-Thru	WB-Left turn	750	250	187500	45.0	20.0	10.0	12.8	0.0	0.0	0.75	0.5	0.9	1.0		1.0	1.0	2.0	45.0	0.8	1.5	--	--	1.0	1004.8
Crossing-Broadside	3	WB-Left turn	NB-Left turn	250	250	62500	20.0	20.0	90.0	14.1	0.0	0.0	1.00	0.5	1.0	1.0		1.0	1.0	2.0	45.0	0.8	1.7	--	--	1.0	563.2
Diverging	4	EB-Thru	EB-Right turn	750	250	187500	45.0	15.0	10.0	15.2	0.0	0.0	0.98	0.5	1.0	0.0		1.0	1.0	1.0	45.0	0.8	0.8	--	--	1.0	1090.7
Crossing	5	EB-Thru	WB-Left turn	750	250	187500	45.0	20.0	230.0	29.9	0.0	0.1	0.75	0.5	0.9	1.0		1.0	1.0	2.0	45.0	0.8	1.5	--	--	1.0	24770.6
Crossing	6	EB-Thru	NB-Left turn	750	250	187500	45.0	20.0	230.0	29.9	0.0	0.1	1.00	0.5	1.0	1.0		1.0	1.0	2.0	45.0	0.8	1.7	--	--	1.0	28309.2
Merging	7	EB-Thru	NB-Right turn	750	250	187500	45.0	15.0	45.0	18.0	0.0	0.0	0.98	0.5	1.0	0.0		1.0	1.0	1.0	45.0	0.8	0.8	--	--	1.0	2080.6
Merging	8	EB-Right turn	WB-Left turn	250	250	62500	15.0	20.0	45.0	7.1	0.0	0.0	0.75	0.5	0.9	1.0		1.0	1.0	2.0	45.0	0.8	1.5	--	--	1.0	35.9
Diverging	9	NB-Right turn	NB-Left turn	250	250	62500	15.0	20.0	10.0	2.9	0.0	0.0	1.00	0.5	1.0	1.0		1.0	1.0	2.0	45.0	0.8	1.7	--	--	1.0	1.4
																Cross score	Near-side	Far-side	Total turn	a_conflicting_lanes							
Nonmotorized	10	EB-Right turn	South Leg Nonmotorized	250	800	200000	15.0					0.1	0.98	0.5	1.0	0.0	1.0	1.0	2.0	2.0	15.0	0.5	1.0	0.0	0.0	1.0	23859.1
Nonmotorized	11	WB-Left turn	South Leg Nonmotorized	250	800	200000	20.0					0.2	0.75	0.5	0.9	0.0	1.0	1.0	2.0	2.0	20.0	0.6	1.0	0.0	0.0	1.0	39423.4
Nonmotorized	12	NB-Left turn	South Leg Nonmotorized	250	800	200000	20.0					0.2	1.00	0.5	1.0	0.0	1.0	1.0	2.0	2.0	20.0	0.6	1.1	0.0	0.0	1.0	45055.4
Nonmotorized	13	NB-Right turn	South Leg Nonmotorized	250	800	200000	15.0					0.1	0.98	0.5	1.0	0.0	1.0	1.0	2.0	2.0	15.0	0.5	1.0	0.0	0.0	1.0	23859.1
Nonmotorized	14	NB-Right turn	East Leg Nonmotorized	250	800	200000	15.0					0.1	0.98	0.5	1.0	1.0	0.0	0.0	0.0	1.0	15.0	0.5	0.5	0.0	0.0	1.0	11929.5
Nonmotorized	15	EB-Thru	East Leg Nonmotorized	750	800	600000	45.0					0.8	1.00	0.5	1.0	1.0	0.0	0.0	0.0	1.0	45.0	0.8	0.8	0.0	0.0	1.0	424276.7
Nonmotorized	16	WB-Left turn	East Leg Nonmotorized	250	800	200000	20.0					0.2	0.75	0.5	0.9	1.0	0.0	0.0	0.0	1.0	20.0	0.6	0.5	0.0	0.0	1.0	19711.7
Nonmotorized	17	WB-Thru	East Leg Nonmotorized	750	800	600000	45.0					0.8	1.00	0.5	1.0	1.0	0.0	0.0	0.0	1.0	45.0	0.8	0.8	0.0	0.0	1.0	424276.7
Nonmotorized	18	EB-Right turn	West Leg Nonmotorized	250	800	200000	15.0					0.1	0.98	0.5	1.0	1.0	0.0	0.0	0.0	1.0	15.0	0.5	0.5	0.0	0.0	1.0	11929.5
Nonmotorized	19	EB-Thru	West Leg Nonmotorized	750	800	600000	45.0					0.8	1.00	0.5	1.0	1.0	0.0	0.0	0.0	1.0	45.0	0.8	0.8	0.0	0.0	1.0	424276.7
Nonmotorized	20	NB-Left turn	West Leg Nonmotorized	250	800	200000	20.0					0.2	1.00	0.5	1.0	1.0	0.0	0.0	0.0	1.0	20.0	0.6	0.6	0.0	0.0	1.0	22527.7
Nonmotorized	21	WB-Thru	West Leg Nonmotorized	750	800	600000	45.0					0.8	1.00	0.5	1.0	1.0	0.0	0.0	0.0	1.0	45.0	0.8	0.8	0.0	0.0	1.0	424276.7

Figure 7-2 Screenshot of sample exposure, severity, and likelihood calculations

- **Exposure** is based on the traffic flow for each conflict point in an intersection. The product of the two traffic flows is determined to be the exposure for each conflict point.
- **Severity** is determined for each conflict point by looking at each conflicting movement speed and crash angle.
- **Likelihood** looks at a variety of factors such as the number of lanes a vehicle will have to merge into when making a turn, the number of lanes a pedestrian must cross, and whether the intersection is controlled/uncontrolled.

Each of these is calculated following the guidelines of the FHWA's methodology.

The product of exposure, likelihood, and complexity gives an index of the safety of a conflict point. The lower the product the safer the conflict point. These products at each conflict point are summed for each of the four types of conflict points, namely merging, diverging, crossing, and non-motorized. Each of these sums are converted to an SSI score as an index from 0 to 100, with the safety rating increasing from 0 to 100. The SSI score of the intersection is a composite of the scores of each of the four types of conflict points calculated. Figure 7-3 shows the screenshot from the spreadsheet model of the final SSI scoring for the T-junction considered.

Conflict point type	Conflict point name	I	P(FSI)	L1	L2	Exposure-Severity-Complexity Product
Merging	1	187500	1.08E-02	1.67	1.0	3369
Merging	7	187500	1.35E-02	0.83	1.0	2081
Merging	8	62500	3.94E-04	1.46	1.0	36
					Sum:	**5485**
					SSI_merging	**99.95996943**

Conflict point type	Conflict point name	I	P(FSI)	L1	L2	Exposure-Severity-Complexity Product
Diverging	2	187500	3.67E-03	1.46	1.0	1005
Diverging	4	187500	7.05E-03	0.83	1.0	1091
Diverging	9	62500	1.37E-05	1.67	1.0	1
					Sum:	**2097**
					SSI_diverging	**99.98**

Conflict point type	Conflict point name	I	P(FSI)	L1	L2	Exposure-Severity-Complexity Product
Crossing-Broadside	3	62500	0.005	1.67	1.0	563
Crossing	5	187500	0.091	1.46	1.0	24771
Crossing	6	187500	0.091	1.67	1.0	28309
					Sum:	**53643**
					SSI_crossing	**99.61**

Conflict point type	Conflict point name	I	P(FSI)	L1	L2	Exposure-Severity-Complexity Product
Nonmotorized	10	200000	0.121	0.99	1.0	23859
Nonmotorized	11	200000	0.203	0.97	1.0	39423
Nonmotorized	12	200000	0.203	1.11	1.0	45055
Nonmotorized	13	200000	0.121	0.99	1.0	23859
Nonmotorized	14	200000	0.121	0.50	1.0	11930
Nonmotorized	15	600000	0.849	0.83	1.0	424277
Nonmotorized	16	200000	0.203	0.49	1.0	19712
Nonmotorized	17	600000	0.849	0.83	1.0	424277
Nonmotorized	18	200000	0.121	0.50	1.0	11930
Nonmotorized	19	600000	0.849	0.83	1.0	424277
Nonmotorized	20	200000	0.203	0.56	1.0	22528
Nonmotorized	21	600000	0.849	0.83	1.0	424277
					Sum:	**1895402**
					SSI_crossing	**87.08**

Intersection Type	Intersection SSI Score	Conflict Type SSI Scores			
		Nonmotorized	Crossing	Merging	Diverging
T-intersection	96.49	87.08	99.61	99.96	99.98

Figure 7-3 Screenshot of example SSI scoring

The current preliminary model is designed for the basic T-intersection and can be expanded to include other intersection designs in future iterations. While work on this model was suspended once FHWA commenced work on their tool, to avoid duplication, the current model can be expanded to include Crash Modification Factors (CMFs) for different intersection improvements such as signage changes, adding refuge islands, and different phasing of signals.

7.2 FHWA Safe System for Intersections (SSI) tool

The FHWA Safe System for Intersections (SSI) tool is the expanded version of the Caltrans Safe System for Intersections model, with the capability to compare up to 12 different intersections, which can be custom made by the user or through a template designed by the FHWA.

The required data inputs include:

- Intersection type for 3 or 4-leg intersection
- Number of through and turning lanes
- Posted speed limits
- Volumes (AADT) for all movements in the intersection

The required traffic volume inputs can come in four different forms. These forms include 24-hour turning movement counts (TMCs), Peak hour TMCs with K-factors, Peak hour TMCs with AADTs, or Roadway AADTs only. In addition to these, there are optional inputs that, if available, can improve the accuracy of the results. There are other optional inputs for the custom SSI analysis.

7.2.1 Template Inputs

Default template inputs are located in the "Default Values" tab. The values of these inputs can be updated. Some of these values include:

- Movement type speed (e.g., major left-turn speed)
- Conflict angles
- P(FSI) regression parameters
- Base Traffic Control Adjustment Values (BTCAV)
- Traffic control parameter weights
- Driver merger weights
- Non-motorized turning weights

7.2.2 Custom Inputs

In addition to default templates for various intersection types, the tool accepts custom inputs for a custom intersection type. For each conflict point, details could be added such as the type of conflict point, characteristics of the movement such as direction, volume (vehicles per day), speed (mph), conflict angle, traffic control type, movement priority if any. It further allows the option to include the number of through lanes crossed, merged with, and running parallel to, along with conflicting traffic speed (mph), indirect paths indicator, and non-intuitive motor vehicle movements indicator.

7.2.3 Available Templates

The beta version of the FHWA tool includes certain intersection templates that auto-populate with the SSI values once the intersection characteristics, i.e. AADT, speed, and number of legs are added. The template in the beta version includes the following types of intersections: traditional signalized (3- and 4-leg), traditional all-way stop control (3- and 4-leg), traditional minor road stop control (3- and 4-leg), 1x1 roundabout (3- and 4-leg), 2x1 roundabout (3- and 4-leg), 2x2 roundabout (3- and 4-leg), signalized restricted crossing U-turn (3- and 4-leg), unsignalized restricted crossing U-turn (3- and 4-leg), median U-turn (4-leg only), partial displaced left turn (3- and 4-leg), full displaced left turn (4-leg only), bowtie (4-leg only).

1.1.4 Possible future work

The following are intersection types that have not been included as templates in the SSI tool:

- jughandle (4-leg only)
- quadrant roadway (4-leg only)

The current SSI tool is intended for use during the ICE Phase 1 scoping process. This tool could be used for planning a new intersection as well as for proactive risk-based identification of intersections on the California SHS for safety improvements. In its current form, the SSI methodology does not allow for assessing the impact of safety improvements, such as adding signage, refuge islands, and changes to the signal-phasing. However, the methodology could be modified to include these in the future.

With an increase in the number of lanes, the number of conflict points would increase exponentially, making it challenging to calculate all SSI scores. For multilane intersections, the FHWA SSI tool is movement-based and not lane-based, representing increased exposure through AADT without increasing the number of conflict points. Further studies on this method and tool would assess the extent of error that this might introduce.

8 Conclusion

This report has outlined key advancements, challenges, and opportunities in aligning Caltrans programs, training, and countermeasure selection with the Safe System Approach (SSA).

To evaluate and strengthen SSA alignment of safety monitoring programs, this report proposed two evaluation methods: one at the program level and one at the project level. These tools help assess whether the safety efforts are effectively targeting fatal and serious injury (FSI) crashes, using appropriate location screening, and implementing high-impact countermeasures. Applying this method to the 2020 Cross Over Collision Monitoring program revealed areas for improvement, such as prioritizing FSI crashes, integrating proactive risk data, and recommending more Safe System aligned countermeasures. Compared with FHWA's policy alignment framework, Caltrans's program alignment method is robust in evaluating its different crash programs. Since the FHWA framework is geared towards policy evaluation, it evaluates each Safe System principle explicitly, while the Caltrans method considers the principles applicable for the criterion being discussed. The project-level evaluation method used the concept of magnitude of improvement (MoI), helping Caltrans quantify the Safe System benefit of proposed safety improvements. While promising, this method faces limitations around data availability and subjective assumptions, particularly regarding vulnerable road user exposure and crash severity reduction. Compared with the FHWA project evaluation method, the Caltrans method evaluates the roadway conditions and risk factors mentioned in the Traffic Investigation Report for seven different crash types. The FHWA method does not evaluate different crash categories separately. However, it lists all roadway conditions and risk factors in detail for intersections and for road segments.

Next, two Safe System aligned safety countermeasures, cable barriers and roundabouts, were explored for their applicability to the Caltrans SHS. The case studies and literature review reinforced the value of specific safety measures, such as high-tension median barriers, particularly on roads with narrow medians and higher crash risk. Recommendations for expanded cable barrier use, including for right-side run-off crashes and as a separation for Class II bike lanes, demonstrate how targeted infrastructure interventions can align with Safe System principles. Likewise, the broader adoption of roundabouts, when designed inclusively for bicycles and pedestrians, especially for older adults and those with visual impairments, can contribute significantly to kinetic energy management and crash severity reduction.

The chapter on training and education identified the need for foundational and recurring training to consistently reflect SSA principles. Embedding the Caltrans Safe System Framework, emphasizing proactive risk assessment, and reinforcing context-sensitive solutions across training programs like the Traffic Safety Investigator Training, Traffic Safety Workshop, Complete Streets, Project Engineer Fundamental, and Project Engineer Academy curricula will ensure that professionals across all roles and districts are aligned in their understanding of effective, equitable safety strategies. In addition, the reviews list updates and modifications needed for individual modules in the training to be aligned with Safe System.

To support intersection safety and network-level analysis, this report reviewed emerging models like KEMM-X, X-KEMM-X, and SSI. These models enable Caltrans to manage kinetic energy by accounting for crash type, impact angle, speed, and movement complexity. For broader roadway networks, tools such as ViDA and the Risk-Based Road Network-Wide Screening (RB-RNWS) process offer the potential to proactively identify and prioritize segments with the highest FSI risk, particularly for loss-of-control, head-on, and rear-end crashes.

A Safe System is more than the sum of its parts—it requires systematic, proactive, and equitable strategies that go beyond crash-response to crash-prevention. Building on the progress made in adopting SSA principles, further integration across Caltrans's internal functions and external partnerships will be critical to realizing the state's Vision Zero goals. Moving forward, Caltrans could continue to invest in data systems capable of capturing near-misses, hard-braking, and conflict severity, expand collaboration with local and regional agencies, and other stakeholders, and evaluate all investments through the lens of eliminating fatal and serious injuries. With these steps, Caltrans can lead a comprehensive transformation in roadway safety that places human life at the center of all transportation decisions.

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Appendix A.1 Risk curve, factor inventory, and Safe System Matrix Scoring System

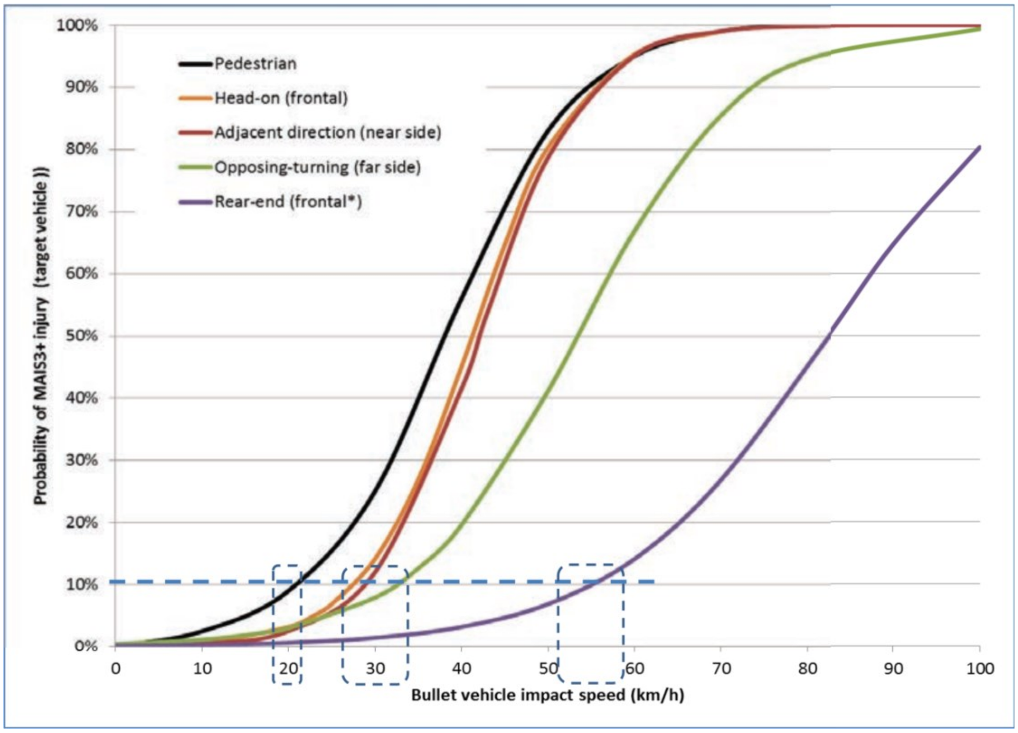


Figure A3-1 Risk curve (Jurewicz, 2016)

Table A3-1 Factor Inventory (Adapted from Turner et al. 2016)

	Run-off road	Head-on	Intersection	Other	Pedestrian	Cyclist	Motorcyclist
Exposure	AADT; length of road segment	AADT; length of road segment	AADT for each approach; intersection size	AADT; length of road segment	AADT; pedestrian numbers; crossing width; length of road segment	AADT; cyclist numbers; pedestrians	AADT; motorcycle numbers; length of road segment
Likelihood	Speed; geometry; shoulders; barriers; hazard offset; guidance and delineation	Geometry; separation; guidance and delineation; speed	Type of control; speed; design, visibility; conflict points	Speed; sight distance; number of lanes; surface friction	Design of facilities; separation; number of conflicting directions; speed	Design of facilities; separation; speed	Design of facilities; separation; speed
Severity	P(FSI)	P(FSI)	P(FSI)	P(FSI)	P(FSI)	P(FSI)	P(FSI)

Table A3-2 Safe System Matrix Scoring System (Adapted from Turner et al. 2016)

Road user exposure	Crash likelihood	Crash severity
0 = there is no exposure to a certain crash type. This might mean there is no side flow or intersecting roads, no cyclists, no pedestrians, no motorcyclists.	0 = there is only minimal change that a given crash type can occur for an individual road user given the infrastructure in place. Only extreme behavior or substantial vehicle failure could lead to a crash. This may mean, for example, that two traffic streams do not cross at grade, or that pedestrians do not cross the road.	0 = should a crash occur, there is only minimal change that it will result in a fatality or serious injury to the relevant road user involved. This might mean that kinetic energies transferred during the crash are low enough not to cause a fatal or serious injury (FSI), or that excessive kinetic energies are effectively redirected/dissipated before being transferred to the road user. P(FSI) < 0.1
1 = volumes of vehicles that may be involved in a particular crash type are particularly low, and therefore exposure is low. For run-off-road, head-on, intersection and 'other 'crash types, AADT is ,10000 per day. For cyclist, pedestrian, and motorcycle crash types, volumes are ,10 units per day.	1 = it is highly unlikely that a given crash type will occur	1 = should a crash occur; it is highly unlikely that it will result in a fatality or serious injury to any road user involved. Kinetic energies must be fairly low during a crash, or the majority is effectively dissipated before reaching the road user. 0.1<=P(FSI)<0.2
2= volumes of vehicles that may be involved in a particular crash type are moderate, and therefore exposure is moderate. For run-off-road, head-on, intersection, and 'other' crash types, AADT is between 1,000 and 5,000 per day. For cyclist, pedestrian, and motorcycle crash types, volumes are 10 – 50 units per day.	2= it is unlikely that a given crash type will occur.	2= should a crash occur, it is unlikely that it will result in a fatality or serious injury to any road user involved. Kinetic energies are moderate, and the majority of the time they are effectively dissipated before reaching the road user. 0.2<=P(FSI)<0.5
3= volumes of vehicles that may be involved in a particular crash type are high, and therefore exposure is high. For run-off-road, head-on, intersection and 'other' crash types, AADT is between 5000 and 10000 per day. For cyclist, pedestrian and motorcycle crash types, volumes are 50 – 100 units per day.	3=it is unlikely that a given crash type will occur.	3 = should a crash occur, it is likely that it will result in a fatality or serious injury to any road user involved. Kinetic energies are moderate but are not effectively dissipated and therefore may or may not result in an FSI. 0.2<=P(FSI)<0.5
4 = volumes of vehicles that may be involved in a particular crash type are very high, or the road is very long, and therefore exposure is very high. For run-off-road, head-on, intersection, and 'other' crash types, AADT is > 10 000 per day. For cyclist, pedestrian, and motorcycle crash types, volumes are >100 units per day.	4 = the likelihood of individual road user errors leading to a crash is high given the infrastructure in place (e.g. high approach speed to a sharp curve, priority movement control, filtering right turn across several opposing lanes, high speed.)	4 = should a crash occur, it is highly unlikely that it will result in a fatality or serious injury to any road user involved. Kinetic energies are high enough to cause an FSI crash, and it is unlileky that the forces will be dissipated before reaching the road user. P(FSI) >= 0.8

Appendix A.2 Deflections values, reduction of KA (fatality and incapacitating) outcomes, and CMFs

Table A4-1 lists deflections on vehicles based on vehicle weight, wire rope tension, and crash angle obtained from a study (Xing et.al. 2019). For fatigue related crashes, the vehicles typically leave the lanes at an angle of 7-8 degrees and graze the barriers. In crashes where the vehicles drift across three or four lanes, the angles are often bigger than 25 degrees, and the deflection of the vehicle is much greater. Since in wider medians too, the vehicle drifts across a longer distance, it is likely that the cable barrier undergoes larger deflections.

Table A4-1 Vehicle deflections based on wire rope tension, crash angle, and vehicle weight

Wire rope tension (lb. force)	Dynamic deflection (ft.)	Crash speed (mph)	Crash angle	Test vehicle weight (lbs.)
1,124	1.08	33.86	6.2	44,445
2,248	1.44	32.87	6	44,357

Source: Xing et al., 2019

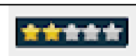
Table A4-2 KA (Fatality and incapacitating) outcome reduction - cable median barriers (KA CO crash/mi/yr.)

Bi-Direction AADT (veh/day)	Traversable Median Width (ft)										
	25	30	35	40	45	50	60	70	80	90	100
25,000	0.0003										
30,000	0.0009	0.0005									
35,000	0.0015	0.0010	0.0003								
40,000	0.0022	0.0017	0.0009	0.0004							
45,000	0.0030	0.0023	0.0015	0.0009	0.0002						
50,000	0.0039	0.0032	0.0022	0.0016	0.0008	0.0003					
55,000	0.0048	0.0040	0.0030	0.0023	0.0014	0.0008					
60,000	0.0060	0.0051	0.0039	0.0031	0.0021	0.0014	0.0003				
65,000	0.0072	0.0062	0.0048	0.0039	0.0028	0.0021	0.0009	0.0001			
70,000	0.0086	0.0074	0.0060	0.0050	0.0037	0.0028	0.0014	0.0006	0.0000		
75,000	0.0099	0.0087	0.0071	0.0059	0.0046	0.0036	0.0021	0.0011	0.0005	0.0002	0.0001
80,000	0.0114	0.0100	0.0082	0.0070	0.0055	0.0045	0.0027	0.0016	0.0009	0.0006	0.0004
85,000	0.0121	0.0107	0.0089	0.0076	0.0060	0.0049	0.0031	0.0019	0.0011	0.0008	0.0006
90,000	0.0121	0.0107	0.0089	0.0076	0.0060	0.0049	0.0031	0.0019	0.0011	0.0008	0.0006
>=95,000	0.0165	0.0147	0.0124	0.0108	0.0089	0.0075	0.0051	0.0035	0.0025	0.0019	0.0016

Source: NASEM 2022

Olsen et.al. obtained crash modification factors (CMFs) for cable median barriers in freeway medians, as shown below (Olsen et.al., 2011).

Table A4-3 CMFs for cable median barriers in freeway medians

CMF	CRF (%)	Quality	Crash type	Crash severity	Roadway type
0.38	62		Cross median	All	Principal arterial interstate
0.56	44		All	KA	Principal arterial interstate

Guideline for median barrier need determination and material selection

The need for the median barrier is determined by using Figure A4-1 and then performing the test level (TL) test using Table A4-4. Most areas in the figure give a clear indication of the type of barrier, or absence of any, that is appropriate. The area marked ‘consider cable if deflection into opposing lanes is acceptable to user agency’ is explained as ‘cable median barriers in these locations would reduce the risk of a fatal or serious injury crash compared with ***not*** having a median barrier, but median barriers in these areas may allow dynamic deflection of the barrier into the opposing lanes’ (NASEM, 2022). Next Table A4.4**.** is used to select the appropriate median barrier test level (TL) as a function of the percent trucks (PT) in the traffic in the design year. Based on this figure, cable barrier is considered safe for median widths of 16 ft for traffic ranging between 17000 to 47000 bi-directional AADT. For narrower medians, considering the dynamic deflection based on the TL is recommended (NASEM, 2022). International applications confirm that dynamic deflection is negligible for low impact angles, as in the case of a two lane or 2+1 lane road.

NASEM 2022 recommends guard-rails only for locations where a roadside object, or parallel feature such as water body, wall, or steep change in gradient need to be shielded, and provides details of designing barriers for different situations.

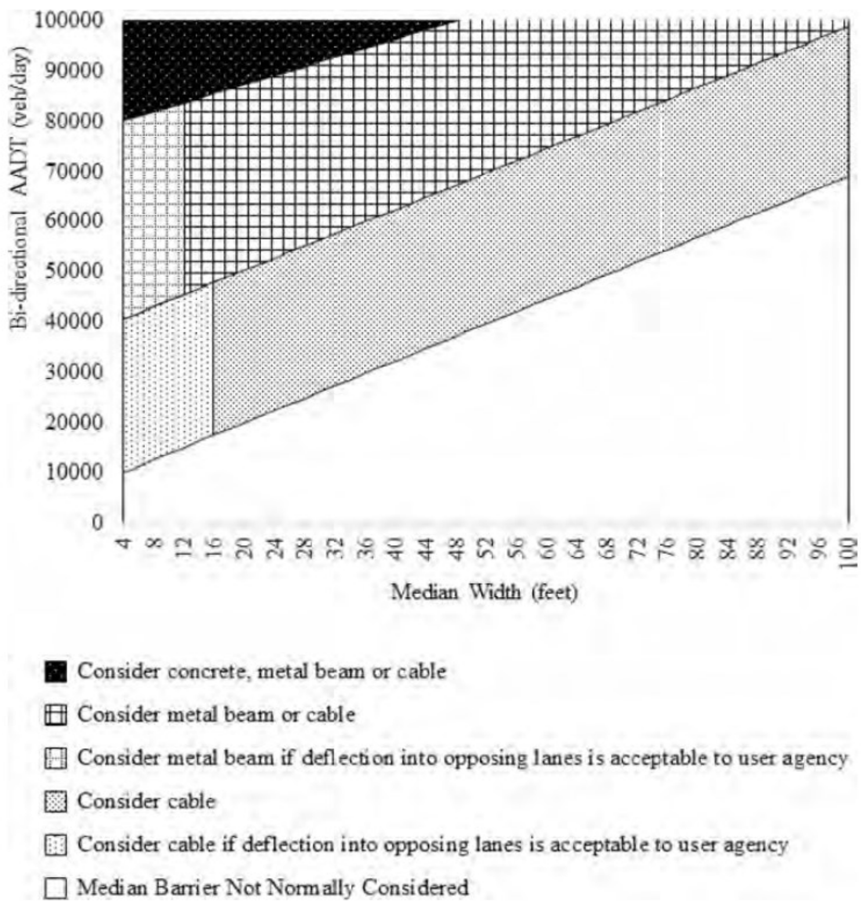


Figure A4-1 Guideline for median barrier need determination and material selection. (Source: NASEM, 2022)

Table A4-4 Guidelines for selection of longitudinal barrier test level (Source: NASEM, 2022)

MASH Test level	**Traffic conditions**
2 or higher	0 PT and posted speed ≤45 mph
3 or higher	0 < PT ≤10
4 or higher	10 < PT ≤ 15
5 or higher	>15 PT or a designated truck or hazardous material route

TxDOT Project 0-4254 recommended guidelines based on analysis of median-related crashes in Texas over a three-year period. The following table shows an economic comparison between high-tension cable and concrete median barrier performance based on the benefit/cost ratio of the expected benefits from reductions in crash rate and/or severity to the expected costs of installing, operating, and maintaining the project. Higher ratios represent increased favorability of installing the high-tension cable barrier over the concrete barrier, in terms of their mean benefit/cost ratios. Based on a deflection of 10 feet, the research team recommends installing cable barriers on medians wider than 20 feet only (Bligh et al., 2006).

Median Width (ft)	*AADT (in 1000s)*																									
	0	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**	**55**	**60**	**65**	**70**	**75**	**80**	**85**	**90**	**95**	**100**	**105**	**110**	**115**	**120**	**125**
0	0	2.0	1.8	1.7	1.6	1.5	1.4	1.3	1.3	1.2	1.2	1.1	1.1	1.0	1.0	1.0	0.9	0.9	0.9	0.8	0.8	0.8	0.8	0.8	0.7	0.7
5	0	2.0	1.9	1.7	1.6	1.6	1.5	1.4	1.3	1.3	1.2	1.2	1.1	1.1	1.1	1.0	1.0	1.0	0.9	0.9	0.9	0.9	0.8	0.8	0.8	0.8
10	0	2.1	1.9	1.8	1.7	1.6	1.5	1.5	1.4	1.3	1.3	1.2	1.2	1.2	1.1	1.1	1.0	1.0	1.0	1.0	0.9	0.9	0.9	0.9	0.8	0.8
15	0	2.1	2.0	1.9	1.8	1.7	1.6	1.5	1.5	1.4	1.4	1.3	1.3	1.2	1.2	1.1	1.1	1.1	1.0	1.0	1.0	1.0	0.9	0.9	0.9	0.9
20	0	2.2	2.0	1.9	1.8	1.7	1.7	1.6	1.5	1.5	1.4	1.4	1.3	1.3	1.2	1.2	1.2	1.1	1.1	1.1	1.1	1.0	1.0	1.0	1.0	0.9
25	0	2.1	2.0	1.9	1.8	1.7	1.7	1.6	1.5	1.5	1.4	1.4	1.4	1.3	1.3	1.2	1.2	1.2	1.1	1.1	1.1	1.1	1.0	1.0	1.0	1.0
30	0	2.0	1.9	1.8	1.8	1.7	1.6	1.6	1.5	1.5	1.5	1.4	1.4	1.3	1.3	1.3	1.2	1.2	1.2	1.2	1.1	1.1	1.1	1.1	1.0	1.0
35	0	2.0	1.9	1.8	1.7	1.7	1.6	1.6	1.5	1.5	1.5	1.4	1.4	1.4	1.3	1.3	1.3	1.2	1.2	1.2	1.2	1.1	1.1	1.1	1.1	1.1
40	0	1.9	1.8	1.8	1.7	1.7	1.6	1.6	1.5	1.5	1.5	1.4	1.4	1.4	1.3	1.3	1.3	1.3	1.2	1.2	1.2	1.2	1.2	1.1	1.1	1.1
45	0	1.9	1.8	1.8	1.7	1.7	1.6	1.6	1.5	1.5	1.5	1.5	1.4	1.4	1.4	1.3	1.3	1.3	1.3	1.2	1.2	1.2	1.2	1.2	1.2	1.1
50	0	1.8	1.8	1.7	1.7	1.7	1.6	1.6	1.6	1.5	1.5	1.5	1.4	1.4	1.4	1.4	1.3	1.3	1.3	1.3	1.3	1.2	1.2	1.2	1.2	1.2
55	0	1.8	1.8	1.7	1.7	1.6	1.6	1.6	1.6	1.5	1.5	1.5	1.4	1.4	1.4	1.4	1.4	1.3	1.3	1.3	1.3	1.3	1.3	1.2	1.2	1.2
60	0	1.8	1.7	1.7	1.7	1.6	1.6	1.6	1.6	1.5	1.5	1.5	1.5	1.4	1.4	1.4	1.4	1.4	1.3	1.3	1.3	1.3	1.3	1.3	1.2	1.2
65	0	1.8	1.7	1.7	1.7	1.6	1.6	1.6	1.6	1.5	1.5	1.5	1.5	1.4	1.4	1.4	1.4	1.4	1.4	1.3	1.3	1.3	1.3	1.3	1.3	1.3
70	0	1.7	1.7	1.7	1.6	1.6	1.6	1.6	1.6	1.5	1.5	1.5	1.5	1.5	1.4	1.4	1.4	1.4	1.4	1.4	1.3	1.3	1.3	1.3	1.3	1.3
75	0	1.7	1.7	1.7	1.6	1.6	1.6	1.6	1.6	1.5	1.5	1.5	1.5	1.5	1.5	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.3	1.3	1.3	1.3
80	0	1.7	1.7	1.7	1.6	1.6	1.6	1.6	1.6	1.5	1.5	1.5	1.5	1.5	1.5	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.3	1.3
85	0	1.7	1.7	1.6	1.6	1.6	1.6	1.6	1.6	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.3
90	0	1.7	1.7	1.6	1.6	1.6	1.6	1.6	1.6	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
95	0	1.7	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
100	0	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
105	0	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.4	1.4	1.4	1.4	1.4	1.4	1.4
110	0	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.4	1.4	1.4	1.4	1.4	1.4
115	0	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.4	1.4	1.4	1.4	1.4
120	0	1.6	1.6	1.6	1.6	1.6	1.6	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.4	1.4	1.4	1.4
125	0	1.6	1.6	1.6	1.6	1.6	1.6	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.4	1.4	1.4

*Based on a four-lane, 65 mph (88 km/hr) posted speed limit scenario

**Due to the deflection characteristic of cable barriers upon impact, installing on medians with a width less than 20 ft is usually not appropriate

Figure A4-2 Screenshot of table showing Benefit/Cost Ratios for installing HTCB over concrete barriers: Favorability (Source: Bligh et al., 2006)

Appendix A.3 Checklist for Traffic Safety Investigator & Case Study Example of the Framework in use

A.3.1 Safe System Alignment Prompts for Traffic Safety Investigations

- Context
  - What is the context of this study area: movement focused, access focused, or a transition zone?
  - What unique contextual considerations should be considered upfront (for example accommodating mass evacuation in case of an emergency)?
- Demand Management Ws
  - What mode options are available here and where do people access those modes?
  - Where are people typically traveling to and from?
  - Who is traveling in this area (in and through)?
  - When are they traveling?
  - What land uses are present here and why?
  - Which vulnerable populations are present here?
  - Was intoxication a factor in crashes here?
  - Was a party identified as unhoused in crashes here?
  - What physical or policy changes could support mode shift to transit, paratransit, and shared use vehicles?
- Speed Management Ws
  - What is the contextually appropriate target speed for this study location?
  - What is the current operating speed?
  - Was speed listed as a factor in crash reports or mentioned with community feedback?
  - When do higher speeds occur in this area (such as off peak or overnight)?
- Conflict Management Ws
  - Where are the conflicts occurring: at mid-block or at intersections?
  - Which conflicts could be severe based on speed and mass?
  - What conflicts were associated with reported crashes in this area?
  - Which conflicts were highlighted with community feedback and/or surrogate safety data?
  - What weather and lighting conditions could exacerbate conflicts?
- Redundancy and Partnership Ws
  - When did emergency services arrive and what challenges did they face?
  - What in-vehicle technology was missing or present?

A.3.2 Case Study Example of the Framework in Use

Rural Highway Safety Corridors Study

Overview: This study looks at six state highways in a rural, coastal and mountainous county. The highways traverse a variety of place types and serve local residential areas; small employment, retail and service clusters; through-freight trips; seasonal agricultural needs; and seasonal tourism.

Determine context: Clarify movement or place roles for each segment in the study area.

Segment the six rural highway corridors in the county into four place types:

- Rural main streets
- Transition zones
- Rural mobility corridors
    - Non-mountainous
    - Mountainous

The initial place type cshould be determined based on current land uses and context. Engage the community to determine if there are any desired shifts in place types that they would like to see with the project (like current transition zones that could become additional main streets).

Step 1 Safe Road Users: Consider opportunities for demand management to reduce overall exposure to risk on the corridors.

Through collision analysis, "big data" origin/destination assessment (via Replica data), and public engagement, determine unique travel patterns and needs that may be contributing to risk exposure. Which travelers in the corridors face limited options for origin/destination, route, mode, and/or time of day travel choice? Do any population segments face disproportionate exposure? Determine demand management strategies that could address the exposure risk. These could include:

- Formalizing or closing parking in informal parking areas that take direct access from high-speed roadways (trail heads, beach access points, etc.).
- Developing a parking reservation system for high demand tourist locations with limited parking capacity
- Providing shuttle service to tourist locations from off-site parking areas
- Enhancing transit frequency, reliability, and travel time to serve key origin/destination pairs
- Providing vanpool or other microtransit options to workers who need to live far from their place of work due to housing costs/availability (such as seasonal workers)
- Providing on-demand transit or ride hail vouchers for seniors or disabled travelers to reach key service areas
- Providing new school bus service and/or adding or relocating school bus stops

- Enhancing pedestrian and bicycle connectivity across the highways where the highway operates as a major or high stress barrier to connectivity of community activity transportation routes
- Providing pedestrian, bicycle, and on-street parking options to enable more main street and 'park-once' environments, as desired by the community (create more main street place types).
- Providing relocation and housing support for unhoused populations
- Ensuring VMT is used as an impact criteria under SB 743 to assess future infrastructure and land use projects in the study area

Step 2 Safe Speeds: Consider opportunities for speed management in transition and main street place types

Determine the contextually appropriate target operating speed in the transition and main street zones based on DIB 94. Complete a speed delta analysis to see where current operating speeds (from "big data" or collected in the field) are higher than the target speed. Additionally, review collision data to see where speed was listed as a collision factor. Recommend speed management interventions such as roundabouts, bulbouts, medians, on-street parking, and gateway treatments based on this proactive and reactive assessment to achieve the target speed.

Note the opportunity for speed camera deployment (and intelligent speed assistance), especially for cost efficiency on the rural mobility segments, when/if that technology is available for broader use.

Step 3 Safe Roads: Consider opportunities for access control and conflict management

For rural mobility corridors: analyze collision data to determine hotspot concerns and extrapolated systemic concerns for access and conflicts. Request public input regarding additional locations with near misses or unreported collisions (bring in "big data" to identify other locations at risk for severe near misses and hard braking when available). Develop safety profiles to summarize the key issues and focus areas. Conduct a Safety and Operational Assessment Process (ISOAP) to determine changes needed at signalized intersections in the focus areas. Assign proven safety countermeasures to the safety profiles for unsignalized and midblock/segments, removing conflicts when possible and separating users in space and time when conflict points remain. Enhance recommendations with additional, lower impact countermeasures that improve awareness (signs, education, enforcement, etc.).

For transition zones and rural main streets: analyze collision data to determine hot spot concerns and extrapolated systemic concerns for conflicts at intersections and along midblock segments. Request public input regarding locations with near misses or unreported collisions (bring in "big data" to identify other locations at risk for severe near misses and hard braking when available). Proactively conduct an ISOAP to determine changes needed at signalized intersections. Proactively assess pedestrian and bicycle facilities versus the design minimums for width and facility type in

DIB 94. Develop safety profiles to summarize the concerns assessed through this process. Assign proven safety countermeasures to the profiles, removing conflicts when possible and separating users in space and time when conflict points remain. Enhance recommendations with additional, lower impact countermeasures that improve awareness (signs, education, enforcement, etc.).

Step 4 Safe Vehicles and Post Crash Care: Consider partnership opportunities for Safe Vehicles and Post Crash Care

Collaborate with emergency response providers in the study area to develop recommendations for enhanced post-crash care (such as additional emergency call boxes in areas with limited cell phone reception). Collaborate with freight providers to consider needs for truck parking, in-vehicle technology, runaway truck ramps, or rest areas and designate truck bypass routes. Collaborate with local agencies and employers to recommend fleet vehicle safety standards for new purchases or retrofits.

Step 5 Ensure Redundancy: Signs, education, and enforcement

Enhance recommendations with additional, lower impact countermeasures that improve awareness (signs, education, enforcement, etc.). Create redundancy by adding signs, providing opportunities for stakeholder capacity building and decision-maker culture shift support, and for enforcement for speeding and impaired driving, including increased use of automated speed enforcement and alcohol ignition locks.

Prioritize and Implement: Select near, medium, and long-term projects

Develop a candidate list of projects based on the safety profiles and associated countermeasures identified in the previous steps. Prioritize implementation of the projects based on a scoring criteria of: 1) high injury network presence, 2) high risk network presence (developed based on kinetic energy risk factors of exposure, likelihood, and severity), and 3) public input “hot spots”. For projects selected for near term implementation through this prioritization, develop design and implementation plans. For those in lower priority tiers, seek overlapping implementation opportunities with maintenance, development, or capital projects planned for the corridor for accelerated deployment. Also consider systemic and/or quick build options to expedite project elements, focusing on speed management for greatest impact.