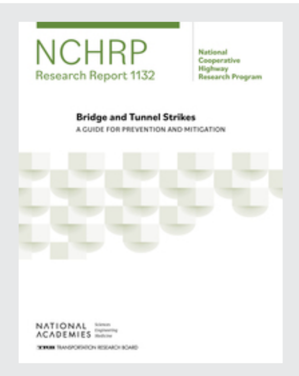

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NCHRP
Research Report 1132

National Cooperative Highway Research Program

Bridge and Tunnel Strikes
A GUIDE FOR PREVENTION AND MITIGATION

NATIONAL ACADEMIES Sciences Engineering Medicine

TRB TRANSPORTATION RESEARCH BOARD

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP RESEARCH REPORT 1132

Bridge and Tunnel Strikes

A GUIDE FOR PREVENTION AND MITIGATION

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TRB TRANSPORTATION RESEARCH BOARD

2025

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed, and implementable research is the most effective way to solve many problems facing state departments of transportation (DOTs) administrators and engineers. Often, highway problems are of local or regional interest and can best be studied by state DOTs individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation results in increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

Recognizing this need, the leadership of the American Association of State Highway and Transportation Officials (AASHTO) in 1962 initiated an objective national highway research program using modern scientific techniques—the National Cooperative Highway Research Program (NCHRP). NCHRP is supported on a continuing basis by funds from participating member states of AASHTO and receives the full cooperation and support of the Federal Highway Administration (FHWA), United States Department of Transportation, under Agreement No. 693JJ31950003.

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The needs for highway research are many, and NCHRP can make significant contributions to solving highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement, rather than to substitute for or duplicate, other highway research programs.

NCHRP RESEARCH REPORT 1132

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FOREWORD

By Ahmad Abu-Hawash
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NCHRP Research Report 1132: Bridge and Tunnel Strikes: A Guide for Prevention and Mitigation presents state-of-the-art information to assist state departments of transportation (DOTs) in the prevention and mitigation of bridge and tunnel strikes by overheight motor vehicles. The guide provides a risk-based approach that can help identify high-priority locations, diagnose factors contributing to the risk of bridge and tunnel strikes, select and prioritize countermeasures, and evaluate the effectiveness of mitigation measures. The guide also includes a roadmap for state DOTs and other transportation agencies to implement and maintain a national clearinghouse for data collection. The guide was developed based on an extensive review and study of the state of the practice. The research findings will be used by state DOTs and public safety agencies.

Bridge and tunnel strikes inflict serious damage to vehicles, highway bridges, and tunnels; cause injuries and fatalities; and impose detours and costly delays on highway users. Attempts by state DOTs and other bridge and tunnel owners to prevent bridge and tunnel strikes include signing, lighting, height detection systems, and actuated warning devices. However, these efforts have achieved limited success. Furthermore, the lack of comprehensive information on the number, location, and severity of bridge or tunnel strikes limits understanding of their frequency, impact, causation, and potential mitigation. Research was needed to inform state DOTs about the best practices for preventing and mitigating the risk of bridge and tunnel strikes by motor vehicles.

Under NCHRP Project 08-139, "Guide for Preventing and Mitigating the Risk of Bridge and Tunnel Strikes by Motor Vehicles," the University of Wisconsin-Milwaukee was asked to (1) develop a national data clearinghouse for collecting and analyzing data and communicating bridge and tunnel strike data and clearance information; (2) identify and evaluate implemented countermeasures used to prevent bridge and tunnel strikes; (3) develop a risk-based, data-driven approach to evaluate the risk of a bridge or tunnel strike; (4) develop prevention and mitigation strategies; (5) analyze the relationship between the vehicle-permitting processes and bridge and tunnel strikes; (6) develop training and outreach materials; and (7) develop a roadmap to implement and maintain the national clearinghouse. The research team developed a guide, training materials, and a web-based prototype national data clearinghouse for consideration by AASHTO.

In addition to the guide published as *NCHRP Research Report 1132*, the following materials are available on the National Academies Press website (nap.nationalacademies.org) by searching for *NCHRP Research Report 1132*: *Bridge and Tunnel Strikes: A Guide for Prevention and Mitigation.*

- *NCHRP Web-Only Document 411: Prevention and Mitigation of Bridge and Tunnel Strikes*, which is the research team's report documenting the entire research effort and the development of the guide.
- Counter Measure Selection Training Material.
- Information Sheet.
- Data Clearinghouse Roadmap.
- Implementation Plan.
- Industry Training Material: Know Your Height.
- Other Strategies Training Material.
- Executive Presentation.

CONTENTS

SUMMARY

Bridge and Tunnel Strikes: A Guide for Prevention and Mitigation

Bridge and tunnel strikes (BrTS) damage infrastructure, damage vehicles and cargo, create traffic delays, disrupt access to communities, and kill and injure people. For motor carriers, BrTS crashes have the potential to result in insurance increases, safety rating drops, operator termination, and direct responsibility to pay for the cost of repairs.

As highlighted in Figure S-1, there is an average of approximately 14,500 bridge crashes per year nationally, resulting in an average of 220 deaths and 4,700 injuries. Across several years of data, there were 11,000 to 18,000 crashes each year coded as collision with "Bridge Pier or Support, Bridge Rail (includes Parapet), or Bridge Overhead Structure." These crashes are among the most common causes of bridge failure and cost agencies millions of dollars in infrastructure repairs (Wardhana and Hadipriono 2003; FHWA, n.d.-e; Lee et al. 2013; Cook 2014). Examples include $4 million per year in Virginia and $7 million per year in Texas. Figure S-1 also illustrates three types of BrTS: on-bridge (or in tunnel) collision with superstructure, under-bridge (or entering tunnel) collision with superstructure, and under-bridge (or entering tunnel) collision with substructure.

Challenges Addressing the Issue

The following are three common historical challenges to addressing BrTS risk:

1. Challenges in identifying priority locations: BrTS crashes are underreported and tend to be spread across the network as opposed to clustered at specific locations. The small sample size and low crash density make it challenging to identify and prioritize locations for further diagnosis and potential treatment. There are also data quality issues, including the accuracy and completeness of location coding, contributing factors, and BrTS impact points. This makes it difficult to accurately assign a given crash to a specific bridge or tunnel and to diagnose the factors that contribute to a crash.
2. Challenges in diagnosing contributing factors: BrTS crashes are complex and may involve several diverse contributing factors such as roadway characteristics, bridge or tunnel characteristics, driver and human factors, and vehicle and load factors. Some of these factors are location-specific (e.g., roadway and bridge characteristics), while others could occur randomly (e.g., unsecured load) or propagate throughout the system (e.g., inattentive driver).
3. Challenges in implementing mitigation strategies and enforcing policies: Given the diversity in contributing factors, there is a need for similar diversity in mitigation measures that include engineering, operational, education, and enforcement initiatives. While there are numerous options available to mitigate BrTS risk, an individual strategy may not be sufficient. A combination of countermeasures is often more appropriate to provide redundancy in the system and address the multitude of critical events that can lead to a crash.

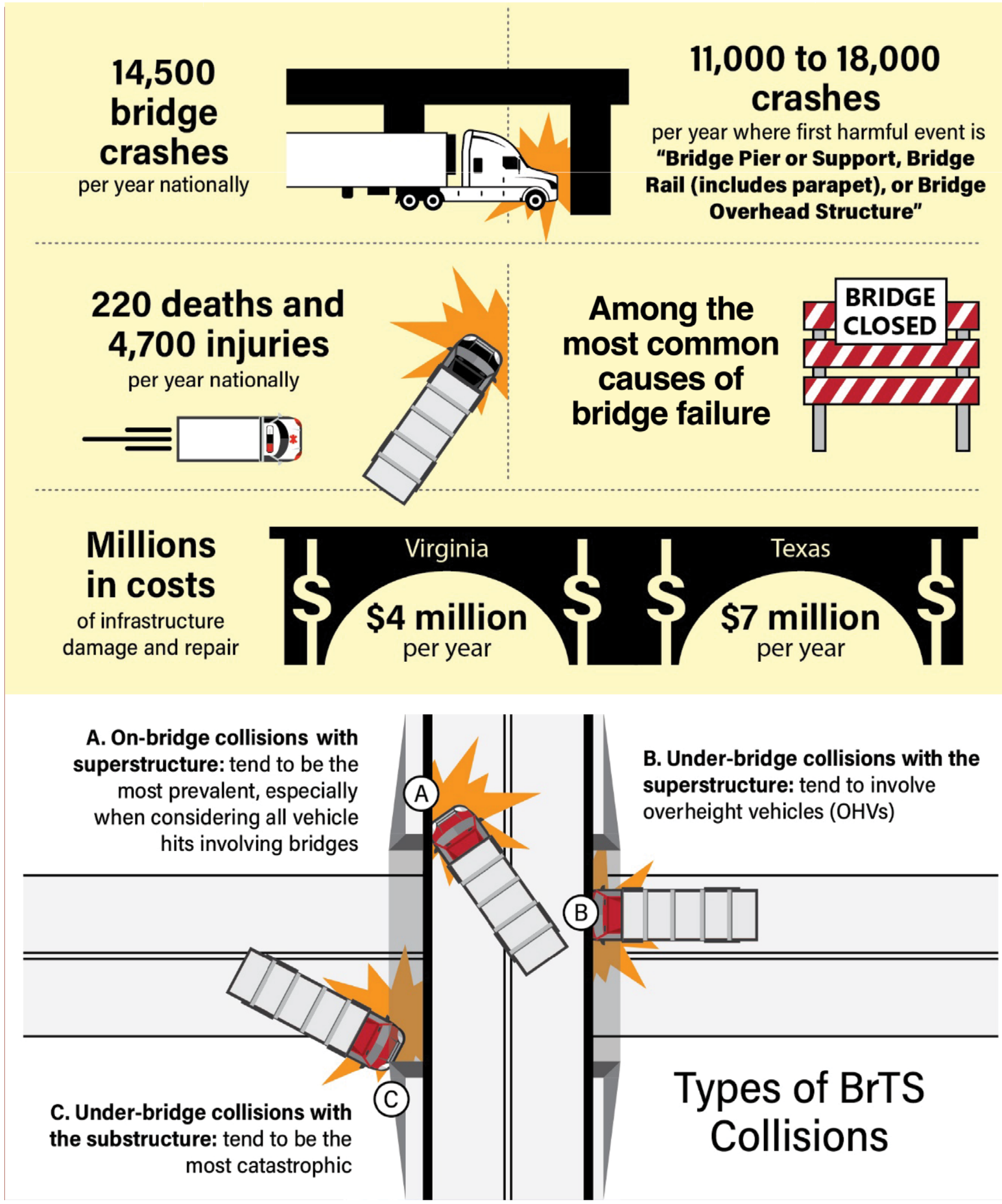

Figure S-1. Crash and cost statistics associated with BrTS.

Opportunities to Address the Issue

This guide provides methods and information to help agencies and analysts overcome the challenges in mitigating BrTS risk.

1. Identify high-priority locations: The first step to mitigating BrTS risk is to locate each crash to the respective bridge or tunnel. The guide describes various methods for locating crashes as well as the strengths and limitations of those methods. There are also various options for prioritizing bridges and tunnels, including crash-based and risk-based methods. The guide describes the challenges in using traditional crash-based methods and the value of using a risk-based approach to assess the vulnerability of the infrastructure to proactively mitigate BrTS risk.

2. Diagnose BrTS risk and crash contributing factors: Before an agency identifies countermeasures, it is important to understand the factors contributing to BrTS risk. This guide provides an overview of risk-based assessments and a list of common factors that increase BrTS risk. It also includes data collection and analysis procedures that agencies could use to identify jurisdiction-specific risk factors and assess BrTS risk based on state, regional, or local data.
3. Select countermeasures to mitigate BrTS risk: Once an agency identifies BrTS contributing factors, the next step is to identify appropriate countermeasures to target the underlying issue(s). This guide provides a list of common engineering, operational, education, and enforcement policies and strategies to address specific BrTS risk factors. The guide also includes detailed descriptions and information on the applicability, effectiveness, and cost of the various countermeasures. This will help practitioners identify appropriate options to address the issue at hand. The guide provides methods to pare down the initial list of options to the preferred alternative through a more detailed analysis of alternatives. This supports the development of agencywide strategies and procedures to mitigate BrTS risk.
4. Evaluate the effectiveness of investments: The final step is to evaluate projects and programs to understand their effectiveness and return on investment. This guide describes fundamental concepts for tracking and evaluating projects and programs, including measures of effectiveness, methods, and data needs. Agencies may then use the evaluation results to inform future funding and policy decisions. For instance, if new educational or enforcement programs are effective, then law enforcement agencies and motor carriers may choose to continue or expand those programs. Similarly, transportation agencies may choose to implement effective strategies at additional locations or incorporate them as standard practice for future projects.
5. Enhance BrTS data and analysis capabilities: Beyond the analysis of jurisdiction-specific issues, there is a need for agencies to provide accessible data and information for external users. This guide describes opportunities for agencies to contribute data to improve the completeness, accuracy, and accessibility of a comprehensive and up-to-date inventory of BrTS data through a BrTS Clearinghouse. This will support national efforts such as cross-jurisdiction truck routing, BrTS research, and BrTS tracking and reporting. Given complete and quality data, a national BrTS Clearinghouse can provide estimates of the risk (i.e., likelihood and consequences) of a BrTS crash based on bridge, tunnel, roadway, and operational characteristics. Transportation agencies can use this information to identify roadway, bridge, and tunnel locations for potential infrastructure improvement projects. Commercial motor vehicle enforcement officials can use this information to identify risk factors and potential locations for implementing enforcement strategies. Motor carriers can use this information to identify routes that are higher risk and instruct their drivers to avoid such routes. Researchers can use the BrTS Clearinghouse to advance the state of the practice for identifying and mitigating BrTS risk.

In summary, the objective of this guide is to assist transportation agencies, motor carriers, and practitioners in preventing and mitigating BrTS risk. This guide will help agencies and analysts identify high-priority locations, diagnose factors contributing to BrTS risk, select and prioritize countermeasures, and evaluate the effectiveness of projects and programs. By quantifying BrTS risk and considering safety alongside other factors, agencies will better understand the comprehensive costs and benefits of projects, which will lead to more informed decisions and impactful investments. The guide also supports the development and application of a national BrTS Clearinghouse that will support researchers in advancing the state of the practice and will support practitioners in implementing effective programs and policies for mitigating BrTS risk.

CHAPTER 1

Introduction

1.1 Defining a Bridge or Tunnel Strike

A bridge or tunnel strike (BrTS) is an incident in which a vehicle collides with a bridge or tunnel. More specifically, a BrTS can be defined by the type of bridge or tunnel (e.g., highway, railway, or pedestrian bridge) and the component of a bridge or tunnel struck by a motor vehicle (e.g., girder, truss, rail). Classifying BrTS by type and component is crucial for identifying the source of risks, evaluating the impacts, and identifying appropriate mitigation measures. Figure 1 illustrates three types of collisions: (A) on-bridge (or in tunnel) collisions with superstructure, (B) under-bridge (or entering tunnel) collisions with the superstructure, and (C) under-bridge (or entering tunnel) collisions with substructure. Type A, on-bridge collisions with the superstructure (e.g., railing), tends to be the most prevalent, especially when considering all vehicle hits involving bridges. Type B, under-bridge collisions with superstructure (e.g., girder, truss), tends to involve overheight vehicles (OHVs). Type C, under-bridge collisions with the substructure (e.g., supports), tends to be the most catastrophic. While tunnel crashes can be difficult to identify from crash datasets (see Section 1.3 for further discussion), most tunnel collisions are similar to Type B (under-bridge collisions with superstructure) or Type C (under-bridge collisions with substructure). This guide limits the discussion of tunnel collisions to the tunnel entrance and combines those entrance crashes with under-bridge collisions (Type B or C) as appropriate. This guide also focuses on BrTS involving heavy vehicles, especially OHVs, because of their significant impact on a bridge or tunnel. For this guide, OHVs are defined as vehicles and loads beyond legal size limitations or standard-size vehicles beyond a local height limitation of a specific bridge or tunnel.

1.2 Magnitude of the Issue

BrTS crashes damage infrastructure, damage vehicles and cargo, create traffic delays, disrupt access to communities, and kill and injure people. Nationally, the number of bridge crashes alone averages more than 14,500 per year (NHTSA 2022). Research has shown that crashes are among the most common causes of bridge failures (Wardhana and Hadipriono 2003; FHWA, n.d.-e; Lee et al. 2013; Cook 2014). As shown in Figure 2, the number of crashes where the first harmful event is coded as "Bridge Pier Or Support, Bridge Rail (includes Parapet) or Bridge Overhead Structure" (listed in the key as "crashes") ranged from approximately 11,000 to 18,000 crashes per year between 2012 and 2021. These collisions resulted in nearly 2,200 deaths and an estimated 47,000 injuries during the same time period.

Beyond the death and injury toll, BrTS result in millions of dollars of damage to the infrastructure. In Virginia alone, repair costs from BrTS are approximately $4 million per year (Bergal 2019), while in Texas, the repair costs from BrTS are nearly $7 million per year.

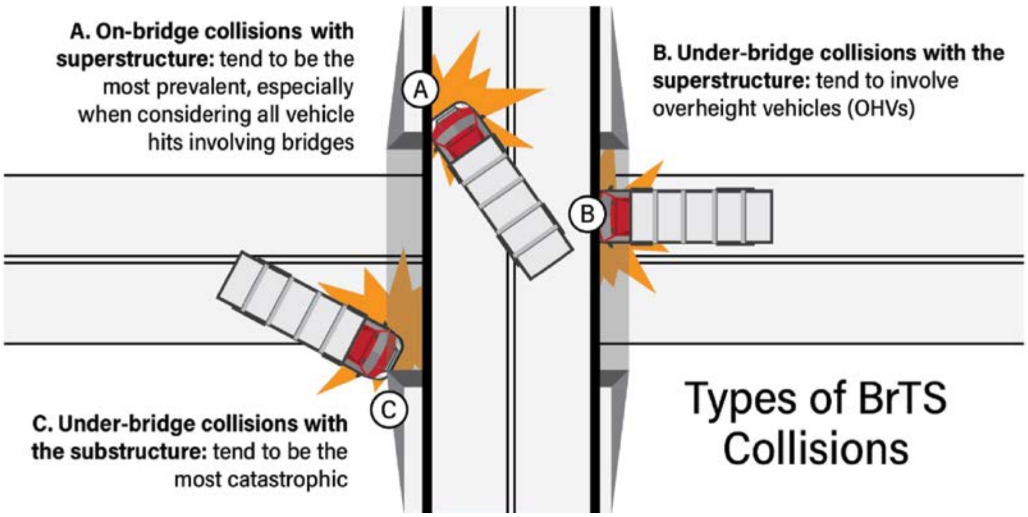

Figure 1. Types of bridge collisions.

It is in our national interest to sustain a dynamic and growing economy and transportation—especially heavy tractor-trailers carrying equipment and goods over the nation's roadways. As truck volumes increase, including oversize and overweight loads, the burden on our nation's transportation infrastructure grows. Further, if crash rates hold steady, the increase in heavy truck traffic will lead to an increased number of crashes. Yet even now, when transportation agencies have technologies ranging from unmanned vehicles to transportation automation and big data, they still seek better ways to prevent BrTS by motor vehicles and to mitigate outcomes when they occur.

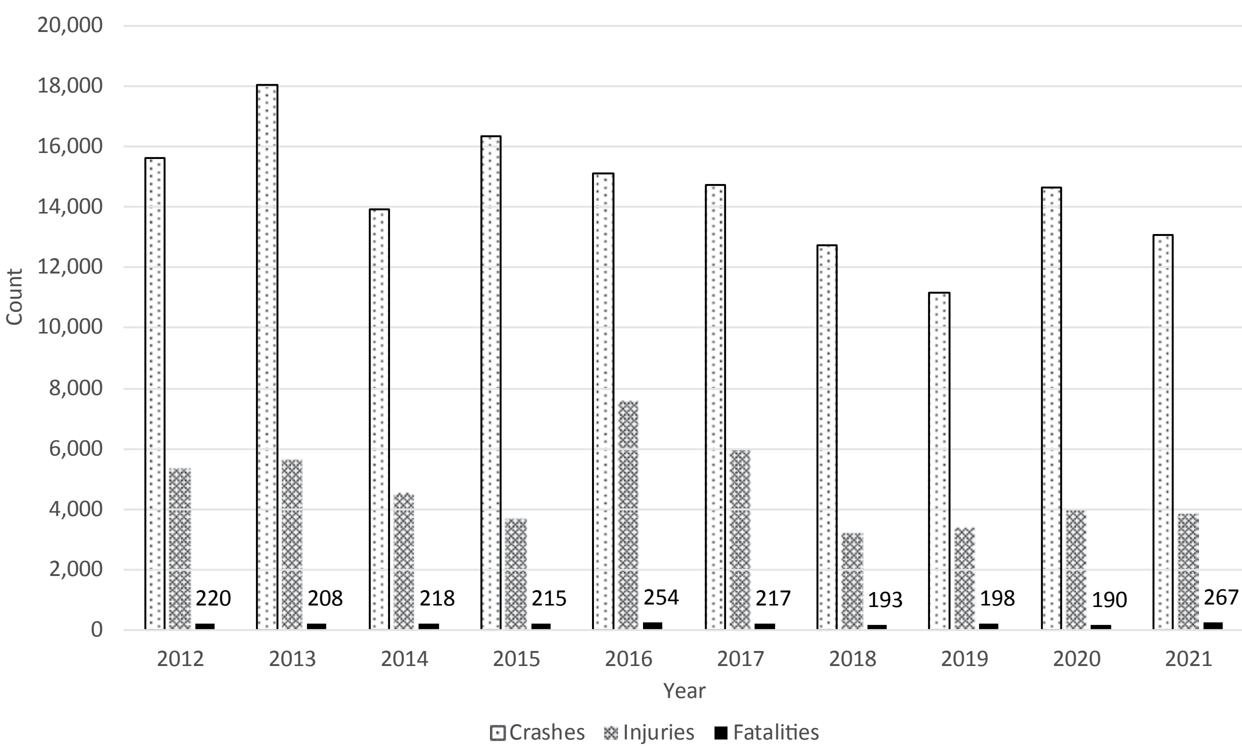

Figure 2. Number of collisions with a fixed bridge object per year.

Motor carriers also have a vested interest in BrTS mitigation. For motor carriers, a BrTS has the potential to result in insurance increases, safety rating drops (FMCSA, n.d.), operator termination, and direct responsibility to pay for the cost of repairs. BrTS can contribute significantly to insurance costs for motor carriers, especially if they result in damage to the truck, the load being carried, a bridge, or other vehicles involved. Insurance costs for motor carriers are influenced by various factors, including the frequency and severity of crashes, the safety record of the company, the type of cargo, driver history, and the specific insurance coverage. BrTS can lead to expensive claims for property damage and bodily injuries and fatalities, which may lead to increased insurance premiums for the trucking company. If a trucking company has a poor safety record (i.e., a history of crashes involving bridges and tunnels), insurance providers may consider them a higher risk, leading to further increases in insurance costs or even dropping the trucking company altogether. Although these costs to motor carriers are intuitively high, data are not currently available to quantify the magnitude of these costs.

1.3 Challenges Mitigating BrTS Risk

Transportation agencies and motor carriers are working hard to mitigate BrTS risk. Transportation agencies invest in operational, infrastructure, and technology strategies to reduce the likelihood and consequences of BrTS. Motor carriers invest in safety training for their drivers, implement technologies like global positioning systems (GPS) and collision avoidance systems, and maintain their vehicle fleet. Despite these efforts, there has been limited success in mitigating BrTS risk due to the following primary factors:

1. Challenges in identifying priority locations.
2. Challenges in diagnosing the contributing factors.
3. Challenges in implementing mitigation strategies and enforcing policies.

Challenges in identifying priority locations: There is a need to first identify priority locations. Traditionally, agencies have used crash history to prioritize bridge and tunnel locations for further investigation and potential treatment. The challenge with using crash history is that BrTS crashes may not cluster at a single location but are spread across the network. This can lead to issues related to small sample sizes when analyzing specific locations. To further compound the sample size issue, there is substantial underreporting of BrTS crashes (Nguyen and Brilakis 2016; Nguyen 2018; and Middleton et al. 2012). There are also data quality issues related to BrTS crash data, including the accuracy and completeness of location coding, contributing factors, and BrTS impact points (e.g., girder, abutment, railing). This makes it difficult to accurately assign a given crash to a specific bridge or tunnel and to diagnose the factors that contribute to a crash. While bridge-strike reporting is generally poor, tunnel-strike reporting is even worse, partially because tunnel strikes may not be identifiable from the crash data as tunnel strikes are categorized as "OTHER" fixed objects.

Challenges in diagnosing contributing factors: Once agencies have identified priority locations, analysts can diagnose the underlying crash contributing factors. The complexity of diagnosing BrTS crashes is related to the potential number and diversity of factors involved (e.g., roadway characteristics, bridge or tunnel characteristics, driver and human factors, and vehicle and load factors). Some of these factors are location-specific (e.g., roadway and bridge characteristics), while others could occur randomly (e.g., unsecured load) or propagate throughout the system (e.g., inattentive driver). One of the primary factors in BrTS is aging, "functionally obsolete" infrastructure that fails to satisfy current design standards and the increase in fleet size, weight, and height. The American Society of Civil Engineers (ASCE) *2017 Infrastructure Report Card* shows that among 614,387 bridges in the United States, 9.1% were structurally deficient and more than 1 in 8 (13.6%) were functionally obsolete (ASCE 2017). As early as 1973, Hilton (1973) investigated crashes involving highway bridges in Virginia and listed "inadequate vertical clearance" as one of the key contributing factors. In the 1980s, Shanafelt and Horn (1980, 1984) authored two NCHRP reports on damage evaluation and repair methods for prestressed concrete bridges and steel bridges, respectively. In the 1990s, some state DOTs started to develop procedures and methods to quantify the vulnerability of bridges to collision damage, including the Collision Vulnerability Assessment of the New York State DOT (NYSDOT 1995). Another major contributor to BrTS crashes is driver behavior and error. These include inattentiveness, failure to comply with truck routing regulations, insufficient understanding of low-bridge warning signs, load shifting in transport due to packing problems, inaccurate measurement of load height, and the use of passenger car GPS rather than commercial GPS units that offer information on roadway restrictions (FMCSA, n.d.). Confounding factors include the lack of alternative routes at low bridges, lack of route planning by haulers, and inadequate or outdated signing at and on the approach to low bridges (Agrawal, Xu, and Chen 2011).

Challenges in implementing mitigation strategies and enforcing policies: The state of the practice for mitigating a BrTS includes a multitude of engineering, operational, education, outreach, and enforcement initiatives. Engineering strategies, such as modifying bridge and tunnel dimensions, can be highly effective but are very costly and are not immediately feasible on a systemwide scale. Other engineering measures, such as signing and active warning devices, can be more economical but may not be as effective, particularly if the messaging is unnoticed or unclear to the truck drivers or too close to the structure to act. Passive signing is estimated to be 10% to 20% effective, and active warning systems are estimated to be 50% to 80% effective (Nguyen and Brilakis 2016). There are also several mitigation strategies to address the operation and routing of oversize loads, including policies and procedures related to the vehicle permitting process, oversize-vehicle routing systems, carrier equipment, pilot car/escort vehicle guidance, and technology. Challenges related to these operational strategies include noncompliance or improper use of existing procedures and guidance. Human-factor-specific practices, like training and education, or the use of predeparture checklists also address common root causes of BrTS crashes. While there are numerous options available to mitigate BrTS risk, any individual strategy is associated with strengths and limitations. A more reliable solution for reducing BrTS risk will rely on a variety of countermeasures, some relatively inexpensive and quickly implemented, others requiring substantial investment, planning, and an ongoing effort to operate and maintain. A combination of countermeasures can also provide redundancy and help to address the multitude of critical events that can lead to a crash.

1.4 Purpose of the Guide

The purpose of this guide is to assist transportation agencies, commercial motor vehicle safety agencies, motor carriers, and practitioners in preventing and mitigating BrTS risk. This guide will help agencies and analysts overcome the challenges in mitigating BrTS risk by providing methods and information in five areas:

1. Identify high-priority locations: This includes methods for locating crashes to specific bridges and tunnels as well as methods (both crash-based and risk-based) for prioritizing bridges and tunnels. The risk-based approach helps agencies to proactively assess the vulnerability of the infrastructure against collision impact.
2. Diagnose risk and crash contributing factors: This includes a list of common infrastructure, operational, and other factors that increase BrTS risk. This also includes methods to analyze and identify risk and crash contributing factors.
3. Select countermeasures to mitigate BrTS risk: This includes information on the applicability, effectiveness, cost, and consideration of various engineering, operational, education, and

enforcement policies and strategies. This provides a data-driven, decision-support system to inform the selection and prioritization of safety solutions. This also supports the development of agencywide strategies and procedures to mitigate BrTS risk.

4. Evaluate the effectiveness of investments: This includes fundamental concepts for tracking and evaluating projects and programs, including measures of effectiveness, methods, and data needs. This will allow agencies to better understand the return on investment and help inform future funding and policy decisions.
5. Enhance BrTS data and analysis capabilities: This includes opportunities to contribute data to a national BrTS Clearinghouse to improve the completeness, accuracy, and accessibility of a comprehensive and up-to-date inventory of BrTS data. These BrTS data can be used by practitioners to identify and address priority issues or by researchers to advance the state of the practice.

1.5 Target Audience

The target audience includes commercial motor vehicle permitting officials, transportation planners, traffic engineers, bridge and tunnel engineers, maintenance personnel, law enforcement officers, drivers, motor carriers, and industry organizations. While this is a diverse audience, there are many shared concerns with respect to BrTS risk. For instance, transportation agencies, industry organizations, and motor carriers likely share an interest in policy and operational measures as well as educational and outreach measures. All stakeholders are likely interested in crash contributing factors and factors that increase BrTS risk. In terms of countermeasures, transportation planners, bridge engineers, and traffic engineers may be more interested in infrastructure improvements, while law enforcement officers are likely more interested in behavioral measures. This guide includes information across all these areas to reach a diverse audience and address the array of BrTS contributing factors. The guide does not explicitly address incident response, which is critical to addressing the aftermath of BrTS, but it is not directly related to mitigating BrTS risk. Readers can refer to the following resources for further information on post-incident response:

- *Case Study: Response to Bridge Impacts – An Overview of State Practices* (Dunne and Thorkildsen 2020).
- *Post-crash Emergency Response Toolkit* (European Bank for Reconstruction and Development 2021).
- "Incident Management" (DHS, n.d.).
- *National Incident Management System: Intelligence/Investigations Function Guidance and Field Operations Guide* (DHS 2013).

1.6 Organization of the Guide

The remainder of this guide follows the general systemic approach to safety management, providing a framework for assessing risk (Chapter 2), identifying countermeasures (Chapter 3), selecting and prioritizing countermeasures (Chapter 4), and evaluating completed projects and programs (Chapter 5).

Chapter 2 focuses on BrTS risk assessment, beginning with an overview of risk-based assessments and common risk factors. It then describes data collection and analysis procedures that agencies could use to identify jurisdiction-specific risk factors and assess BrTS risk using state, regional, or local data. The chapter concludes with data collection and analysis procedures for updating a national BrTS Clearinghouse. Agencies can use the framework in this chapter to estimate the risk (i.e., likelihood and consequences) of a BrTS crash based on bridge, tunnel, roadway, and operational characteristics. This will help agencies prioritize locations for further investigation and potential treatment or to prioritize proposed projects within a larger program. Transportation agencies might use this information to identify roadway, bridge, and tunnel locations for potential infrastructure improvement projects. Commercial motor vehicle enforcement officials might use this chapter to identify risk factors and potential locations for implementing enforcement strategies. Motor carriers might use this chapter to identify routes that are higher risk and instruct their drivers to avoid such routes.

Chapter 3 focuses on countermeasure identification, beginning with a discussion of general considerations and a summary of common BrTS risk factors with applicable countermeasures. The remainder of the chapter provides detailed descriptions of individual countermeasures, including cost, effectiveness, service life, and other considerations. Once an agency identifies factors that contribute to BrTS, the next step is to identify appropriate countermeasures to target the underlying issue(s). If a transportation agency prioritizes a specific bridge that is at high risk of being struck and identifies the specific risk factors, then the agency might use this chapter to identify appropriate infrastructure or operational countermeasures to mitigate BrTS risk. Motor carriers might use this chapter to identify opportunities for policy, education, and technology strategies that could help reduce their risk of BrTS, which could lead to long-term benefits such as reduced costs (e.g., insurance, direct repairs) and reduced employee issues (e.g., pain and suffering).

Chapter 4 describes quantitative and qualitative measures for selecting and prioritizing countermeasures, focusing on an analysis of alternatives. While countermeasure selection starts with a larger list of options, this chapter will help agencies pare down the initial list to the preferred alternative through a more detailed analysis of the alternatives. This applies to infrastructure, operation, education, enforcement, and policy strategies.

Chapter 5 focuses on three levels of post-implementation evaluations: project, countermeasure, and program level. It describes project tracking and the fundamental concepts for evaluating projects, countermeasures, and programs, including measures of effectiveness, methods, and data to track before, during, and after implementation. Agencies can use this chapter to determine the effectiveness of a particular project, group of projects, or policy. Agencies might use the evaluation results to inform future funding and policy decisions. For instance, if evaluations show that certain educational or enforcement programs are consistently effective, then law enforcement agencies and motor carriers may choose to continue or expand those programs. If evaluations show that specific infrastructure or operational strategies are effective at reducing site-specific or systemwide risk, then transportation agencies may choose to implement similar strategies at additional locations or incorporate them as standards for future projects. On the other hand, if an evaluation shows that a project or program is not meeting expectations, then an agency may address the situation accordingly (e.g., install supplemental measures, discontinue or revamp the program).

CHAPTER 2

Bridge and Tunnel Strike Risk Assessment

It is critical to identify and understand factors that contribute to BrTS before selecting an appropriate countermeasure to target the underlying issue(s). This chapter focuses on BrTS risk assessment. It begins with an overview of risk-based assessments and common risk factors. It then describes data collection and analysis procedures that agencies could use to identify jurisdiction-specific risk factors and assess BrTS risk using state, regional, or local data. The chapter concludes with data collection and analysis procedures for updating a national clearinghouse.

In general, risk is defined by two components:

1. Likelihood: the chance of an event (e.g., BrTS) occurring and
2. Consequences: the impact(s) of an event, should one occur.

This chapter begins with a focus on the likelihood of a BrTS occurring. It is based on an approach that uses infrastructure characteristics related to the bridge, tunnel, and roadway to predict the likelihood of a BrTS, recognizing that many other factors related to the driver, vehicle, and operations can contribute to BrTS crashes. The chapter then incorporates the consequences of the outcome, which can help agencies prioritize locations for further investigation and potential treatment or prioritize proposed projects within a larger program.

2.1 Overview of Risk-Based Assessments

BrTS crashes may occur at seemingly random locations and may or may not cluster over time; however, the factors associated with BrTS crashes are strikingly consistent. As a result, it does not make sense to reactively address bridges and tunnels as they are struck. Instead, it is more appropriate to proactively identify locations with a high potential for a BrTS crash and then diagnose the underlying contributing factors for potential mitigation.

As an example, Figure 3 shows the locations of BrTS crashes in a region in Maine between 2017 and 2021. Some corridors have more crashes than others, but there are very few clusters. While geographic clustering is rare and crashes tend to occur in different locations from year to year, the factors that contribute to these crashes remain relatively consistent. Table 1 shows the proportion of crash contributing factors for these same crashes from year to year. Notice the consistency in the priority of issues from year to year: the three factors remain in the same relative priority order within each year with some minor variation.

There are often multiple factors that contribute to a BrTS crash, including human, vehicle, load, technology (GPS), and infrastructure factors. Consider the potential sequence of events involved in a BrTS crash—a truck with an oversize load is somewhere it should not be (this can occur when a permitted driver deviates from the designated route or when a driver does not get a permit), the truck is oversize relative to the infrastructure along the route, the driver is unfamiliar with

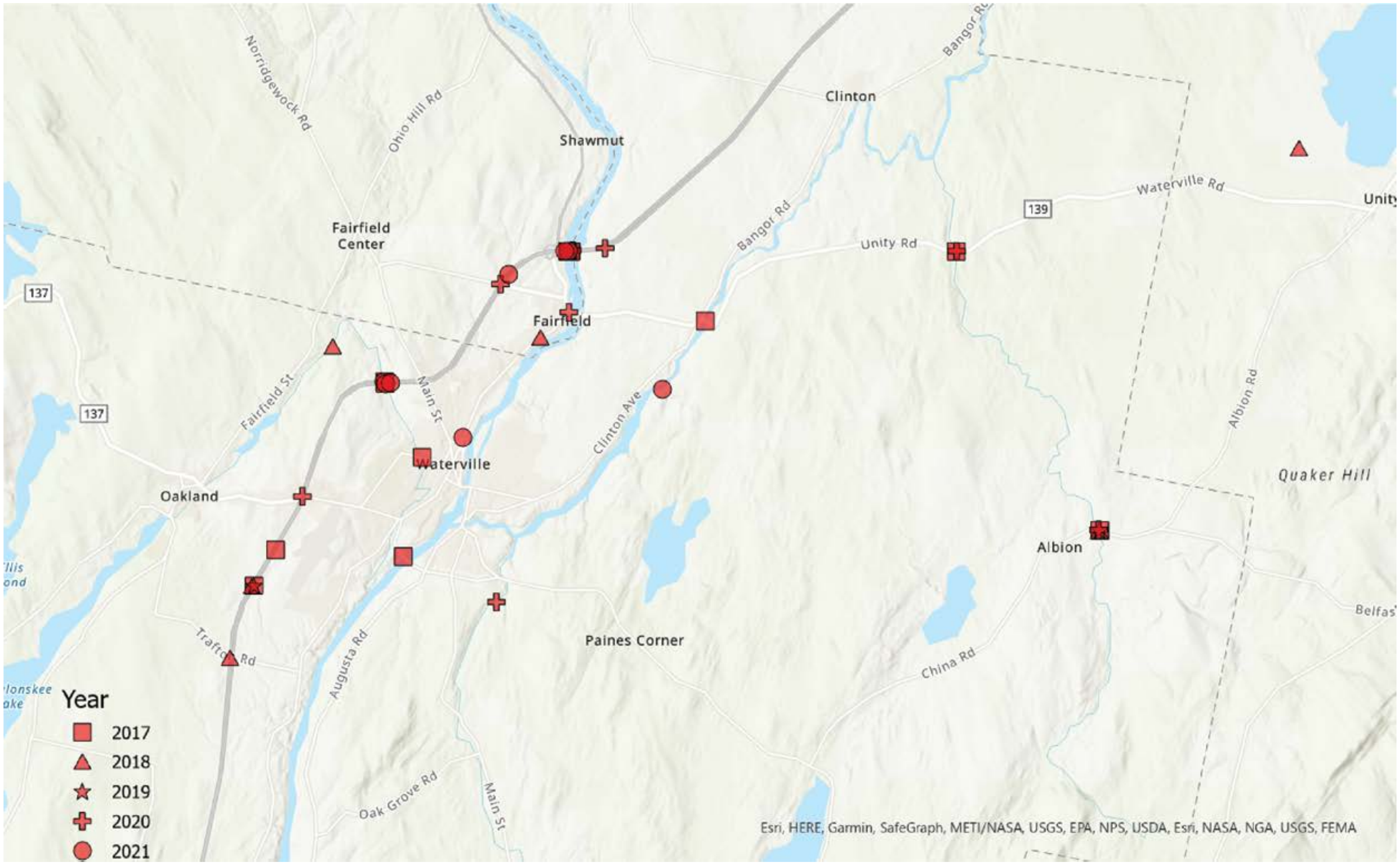

Figure 3. Temporal and spatial distribution of BrTS crashes in a region in Maine from 2017 to 2021.

Table 1. Crash contributing factors in BrTS crashes in a region in Maine from 2017 to 2021.

Crash Contributing Factor	2017	2018	2019	2020	2021
Traffic control – none	100%	83%	100%	63%	88%
Rural	83%	83%	100%	88%	88%
Road grade – level	75%	67%	100%	63%	75%

the route and looking to correct course, the driver takes the first exit to get back on course (and either misses the warning signs or there are no warning signs for maximum vehicle height). The result is a BrTS.

There is an opportunity to mitigate BrTS risk by eliminating one or more of the underlying factors from the scenario. For instance, if an unpermitted driver was permitted, then they would be more likely to understand the appropriate route for their given load. If the driver knew the size of their load, and appropriate warning signs were more conspicuous, then the driver may not have continued toward the bridge. In either of these cases, the BrTS crash may have been avoided if just one factor had been removed from the scenario. In other cases, the load could shift during transport, and even if the driver is permitted and observes the advance warning signs there are other factors (e.g., narrow offset to the structure) that could increase BrTS risk.

A proactive, risk-based approach can help agencies first identify factors that contribute to BrTS crashes and then develop measures to mitigate these events. In general, the following are the steps involved in deploying a risk-based approach.

1. Establish focus crash-type(s): Focus crash-types are typically those that represent the highest frequency of severe crashes or the highest potential of a severe crash on the system. In this case, the focus crash-type is BrTS crashes based on the scope of the research and guide, but these BrTS crashes could be further classified as specific subsets. It is useful to create specific subsets of focus crash-types if the risk factors and resulting treatments differ among the subsets of crashes. This research defined specific types of BrTS as focus crash-types:
   a. On-bridge strikes (e.g., truss, parapet, railing),
   b. Under-bridge strikes with overhead structure (e.g., girder),
   c. Under-bridge strikes with pier or support (e.g., bent, support, pier, abutment), and
   d. Tunnel strikes at entrance (which can be combined with under-bridge strikes with overhead structure or pier/support as appropriate).
2. Identify focus facility-type(s): Focus facility-types are those facilities where the focus crash-type is occurring. This can be identified based on prevalence or overrepresentation. As shown in Figure 4, a crash tree can be a useful tool to visualize the distribution of focus crashes and identify focus facility-types. In this guide, the focus facility-types include all facility types. It was difficult to determine overrepresented facility types because only a portion of BrTS crashes could be linked to corresponding bridges or tunnels. As BrTS crash and roadway data improve, agencies could consider the functional classification of the on-bridge or under-bridge roadways or designated truck routes to define the focus facility-type(s).
3. Identify risk factors: Risk factors are characteristics associated with an increased risk of the focus crash-type occurring on the focus facility-type. The term "risk" has a wide range of definitions, but in this guide, it serves as a measure of two components: (1) the likelihood of a BrTS crash, and (2) the consequences of a BrTS crash should one occur. Risk factors can range from site-specific characteristics (e.g., bridge and roadway features) to area-wide characteristics (e.g., driver population, vehicle fleet, state policies). Risk factors do not necessarily reflect causal relationships. Instead, risk factors are "associated with" an increased likelihood or consequence of BrTS crashes. In a risk-based assessment, agencies can use risk factors to prioritize locations for further investigation and potential improvements.

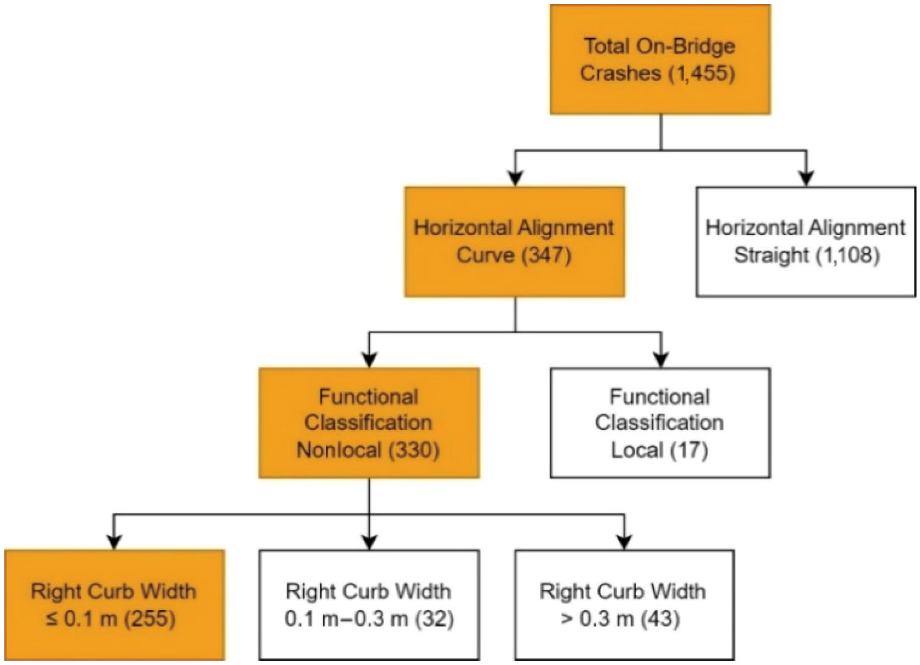

Figure 4. Example crash tree for BrTS crashes.

A risk-based approach has several benefits that include the following abilities:

- Identify high-risk locations that may or may not have a high-crash history: One of the primary benefits of the risk-based approach is that agencies do not have to wait for crashes to occur to address potential issues. The risk-based approach allows agencies to identify locations with a high risk of a BrTS based on network, corridor, and site characteristics. Agencies can then proactively implement strategies to address the risk factors rather than waiting for crashes to occur.
- Overcome data limitations: For less common crash types, including BrTS crashes, the risk-based approach is particularly well suited to overcome data limitations, such as small sample sizes and limited information on exposure measures. Related to sample size, there are often relatively few reported BrTS crashes at any given location. Related to exposure, there may be limited data on the number or proportion of trucks and oversize vehicles to help predict BrTS risk. The risk-based approach overcomes these limitations by incorporating other characteristics, such as bridge and tunnel characteristics, general roadway and operational characteristics, and land use and policy data to proactively assess risk in the absence of high numbers of crashes.
- Address regression-to-the-mean: Regression-to-the-mean is the seemingly random fluctuation in crashes from year to year. On average, a given location has a long-term average number of crashes, but the observed number of crashes in a given year will generally be higher or lower than that average. Regression-to-the-mean explains how a location with multiple crashes one year may, without any intervention, experience below- or above-average crashes in subsequent years. For instance, the average number of BrTS crashes at a specific bridge is usually zero but may vary over time. Despite this variability in observed crashes year to year, the risk of a crash occurring is still present, and this risk is higher at some locations based on site-specific characteristics. While historical crash data may not identify these locations as a high priority, the risk-based approach can help to identify sites with high risk.

The next section describes common BrTS risk factors and the scenarios in which the risk factors are most relevant.

2.2 Common BrTS Risk Factors

Agencies can use a wide range of data to identify risk factors. Categorically, risk factor data can include the following:

- Operational data: traffic volume, truck and bus volume, lane use, signing, and markings.
- Geographic and contextual data: State- and agency-level policies, adjacent land use, and trip generators (e.g., industrial parks, distribution centers, fabricating facilities, storage yards).
- Crash data: historical crash frequency from police crash reports or transportation agency–maintained BrTS reports.
- Roadway infrastructure data: geometric alignment, cross section, and proximity to ramps.
- Bridge infrastructure data: presence, location, dimension, and condition of bridges, tunnels, and barriers.

The project team generated a list of *potential* risk factors pertinent to on-bridge and under-bridge BrTS crashes. Table 2 shows the variables that were considered and assessed as potential risk factors. Note that Table 2 presents various types of potential risk factors: (1) binary (e.g., yes/no or present/not present indicator), (2) categorical (e.g., number of lanes, type of lighting, shoulder width), and (3) continuous (e.g., traffic volume, bridge age, bridge length). Additional analysis will identify which variables appear as risk factors for different types of BrTS crashes and, for categorical and continuous variables, which categories or ranges are associated with an increased risk. While other research studies have identified additional variables as potential risk factors in BrTS crashes, the variables below are those that are readily available for further analysis. Section 2.4 describes analysis procedures if agencies have more detailed information and are interested in assessing risk factors such as state- or jurisdiction-level operations data. For instance, the proximity of a bridge to the nearest access point on a controlled access facility (e.g., first bridge versus subsequent bridges) is likely a risk factor in BrTS; however, these data are not readily available in current datasets. There is an opportunity for future research to collect and analyze these types of additional risk factors for consideration in the identification of high-risk locations and potential mitigation.

Table 3 provides a summary of *confirmed* risk factors by focus crash-type. The research team developed statistical models, as described in Section 2.4, to assess and confirm the risk factors. As described previously, this guide does not include specific focus facility-types for BrTS crashes. The research team considered roadway functional classification to define focus facility-types but determined it was more appropriate to include functional classification as a risk factor due to data limitations. While these risk factors are largely infrastructure-based, agencies could assess and apply additional factors such as state- or jurisdiction-level operational and educational policies and practices. Further, it is important to note that these factors are associated with higher risk and should not be interpreted as causal factors. In some cases, the results may seem counterintuitive. For instance, a larger deck width is associated with a higher risk of on-bridge strikes, while one of the countermeasures in Chapter 3 is enhanced lateral clearance. The relationships shown in the table may be confounded by other variables in the model or by omitted variables. These factors are simply used to identify higher-risk locations. Agencies should refer to Chapter 3 for further details on the expected safety effectiveness of specific countermeasures.

2.3 Applying Risk Factors to Prioritize Locations

The objective of this step is to use the risk factors to prioritize locations for further investigation and potential safety improvement. As shown in Figure 5, the process includes identifying locations for screening, calculating a risk score for each location, and prioritizing the locations based on the total risk score.

Table 2. Potential risk factors for BrTS.

Bridge or Roadway Features	Description	On-Bridge	Under-Bridge or Tunnel Entrance
AADT	Annual average daily traffic	•	•
Approach rail (Y/N)	Presence of guardrail on approach	•	—
Approach rail end (Y/N)	Presence of guardrail end on approach	•	—
Approach roadway width	Width of usable roadway approaching bridge	•	—
Average shoulder width	Average shoulder width of roadway	•	•
Bridge age	Bridge age	•	•
Bridge length	Bridge length	•	•
Bridge serviceability and functional obsolescence	Bridge serviceability and functional obsolescence	•	•
Bypass, detour length	Bypass, detour length for roadway	•	•
Curb (Y/N)	Presence of curb on roadway	•	•
Curb width	Curb width	•	•
Curve (degree)	Degree of horizontal curve of roadway	•	•
Curve (k-value)	k-value of vertical curve of roadway	—	•
Curve length	Length of curve	•	•
Deck condition rating	Condition rating of bridge deck	•	•
Deck width	Deck width	•	•
Flare (Y/N)	Presence of flare (variable width of structure)	•	—
Functional classification	Functional classification of roadway	•	•
Horizontal clearance	Total horizontal clearance for roadway	•	•
Lateral clearance	Lateral clearance	•	•
Lighting	Type of lighting present on roadway	•	•
Maximum span	Length of maximum span of bridge	•	•
Median width	Width of median grass or sod	•	•
Narrow approach (Y/N)	Indicator for structure narrower than approach	•	—
National truck network	Indicator if roadway is part of national truck network	•	•
Number of lanes	Total number of lanes on roadway	•	•
Operation (1-way/2-way)	Direction of traffic (1-way/2-way) on roadway	•	•
Paved road (Y/N)	Presence of paved road	•	•
Railing (Y/N)	Presence of railings on bridge	•	—
Roadway width	Width of roadway	•	•
Rumble strip (Y/N)	Presence of longitudinal rumble strips	•	•
Shoulder type	Pavement type of shoulders on roadway	•	•
Speed limit	Speed limit of roadway	•	•
Surface type	Pavement type of lanes on bridge	•	•
Transition (Y/N)	Presence of transition rails	•	—
Truck AADT	Truck annual average daily traffic	•	•
Truck percentage	Percentage of truck traffic	•	•
Variable vertical clearance	Vertical clearance varies by lane	•	•
Vertical clearance	Vertical clearance over roadway	•	•

Note: — = Not a risk factor.

Table 3. Summary of confirmed risk factors for BrTS focus crash-types.

Category	Variable/Risk Factors	On-Bridge Strikes (e.g., truss, parapet, railing)	Under-Bridge Strikes with Overhead Structure (e.g., girder) or Tunnel Entrance	Under-Bridge Strikes with Pier or Support (e.g., bent, support, pier, abutment) or Tunnel Entrance
Exposure	One-way traffic/dual carriage	•	—	•
	Larger AADT	•	•	•
	Larger truck AADT	•	•	•
	More than two travel lanes	—	•	•
	Part of national truck network	—	—	•
	Rural arterial	•	—	—
	Rural local	—	—	•
	Rural major collector	•	—	—
	Rural minor collector	•	—	—
	Urban local	—	•	•
	Urban minor arterial	—	—	•
	Urban other principal arterial	—	—	•
Design	Concrete shoulder	—	—	•
	Concrete surface	—	—	•
	Curve (larger degree)	—	—	•
	Larger bridge roadway width	•	—	—
	Larger deck width	•	—	—
	Larger lateral clearance	—	•	—
	Longer bridge length	•	—	—
	Lower vertical clearance	—	•	—
	Approach road narrower than bridge	•	—	—
	No transition from road to bridge	•	—	—
	Presence of longitudinal rumble strip	—	—	•
	Presence of railing on bridge	•	—	—
	Presence of guardrail on approach	•	—	—
	Structure flared	•	—	•
	Unpaved road	•	—	—
Condition	Lower deck condition rating	•	—	—
	Older bridge	•	•	—

Note: — = Not a risk factor.

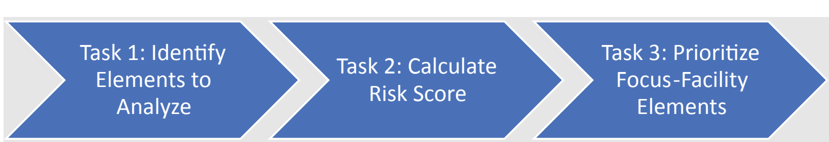

Figure 5. Process to screen and prioritize candidate locations.

Table 4. Example element table for bridges and on-bridge roadways.

Bridge Characteristics					On-Bridge Roadway Characteristics				
Bridge ID	Age (year)	Max. Span Length (m)	Serviceability/ Functional Obsolescence	Crash Count in 5 Years	Functional Classification	AADT	% Trucks	# Lanes	National Network for Truck
1830210	64	16.7	0	7	Urban – Principal Arterial – Interstate	43,750	16	3	Yes
1910363	11	35.9	29	4	Urban – Principal Arterial – Other Freeways or Expressways	13,500	12	2	No
1970057	5	10.3	17	4	Rural – Minor Collector	1,200	6	2	No
810221	56	16.4	22	3	Urban – Collector	2,100	7	2	No

The screening and prioritization process requires an integrated dataset, including the focus facility-types and the features associated with each location (e.g., bridge, tunnel, roadway, operational, and policy characteristics) to produce a risk score. The recommended practice for integrating and preparing the data for this step is to use spatial or tabular data tools, such as geographic information systems (GIS) or spreadsheets. The spatial data capabilities in GIS tools provide additional opportunities for agencies to integrate various sources of spatial and tabular data for risk-based scoring.

Task 1 – Identify Elements to Analyze

In this task, agencies identify the elements of interest (e.g., bridges, tunnels, roadways) from the focus facility-type. There are various options for this task. For instance, this could include all bridges and all tunnels on all facility types across the network. An agency may also choose to focus on a more select list, such as only bridges or only tunnels on one or more focus facility-types across the network depending on the intent of the analysis and potential funding program.

Table 4 is a sample of elements of interest for bridges and on-bridge roadways. Table 5 is a sample of elements of interest for bridges and under-bridge roadways. As shown in the tables,

Table 5. Example element table for bridges and under-bridge roadways.

Bridge Characteristics				Under-Bridge Roadway Characteristics					
Bridge ID	Age (year)	Max. Span Length (m)	Crash Count in 5-years	Functional Classification	AADT	% Trucks	# Lanes	Min. Vertical Clearance (m)	National Network for Truck
630280	42	20.4	12	Urban – Local	11,000	12	2	3.74	No
670265	59	19.8	2	Urban – Collector	38,500	12	4	4.49	Yes
510129	4	28.0	1	Urban – Principal Arterial – Other Freeways or Expressways	3,500	6	2	4.81	No

each location (row) should have the features associated with each risk factor (column). Agencies can use spreadsheets, GIS, and other tools to integrate data. Spreadsheets are useful for organizing the elements in tabular format and collecting relevant uniform data in each column. GIS offers more sophisticated analysis options to create and analyze elements, including the ability to incorporate spatial data such as state-level policies and regulations, jurisdiction-level operation practices, or proximity to carriers with low safety ratings.

Task 2 – Calculate Risk Score

This task involves calculating the risk score for each element (i.e., for each row in Tables 4 and 5). In this context, "risk score" is a quantitative measure based on the presence and weight of risk factors for the element. The risk score is ultimately used for prioritizing the elements.

There are two primary options for computing the risk score:

1. Binary risk factor score and
2. Regression-based risk factor score.

All agencies have access to the National Bridge Inventory (NBI) and National Tunnel Inventory (NTI); these are national datasets of bridge, traffic, and roadway characteristics that served as the basis for the regression-based risk factor modeling in this guide. As such, all agencies have the basic data required to compute risk scores using the regression-based risk factor method. If an agency would like to include additional risk factors in the scoring process (e.g., operational policies and practices), then the binary risk factor scoring method might be more applicable, especially for the additional factors.

Binary Risk Factor Score

One option is to assign a binary score (0 or 1), using 1 to indicate the presence or 0 to indicate the absence of each risk factor and prioritize locations based on the risk score. Using this approach, locations with the most risk factors would be ranked as the highest priority. Table 6 provides an example prioritization using this binary approach for functional classification, year built, minimum vertical clearance, and national truck network. In this example, the presence of a risk factor is simply flagged with a 1 and the absence of a risk factor with a 0 (shown in parentheses after the actual value for the variable). The risk factor scores are summed across each row to calculate the risk score for each site as shown in the final column.

Based on the example in Table 6, it is clear that one or more sites may receive the same risk score. This can create challenges when an agency is prioritizing a large number of sites. To overcome this issue, an agency can apply weights to one or more of the risk factors (e.g., 0.25, 0.5, 1.0, 2.0) depending on the relative importance of each factor. Analysts can use the overrepresentation charts to guide the weighting decisions where variables that appear to be more overrepresented

Table 6. Example prioritization table for bridges and tunnels on focus facility.

Bridge ID	Crash Count	AADT	Functional Classification	Year Built	Minimum Vertical Clearance	National Network for Truck	Total Risk Score
B400047	24	1,800	Urban Local (1)	1959 (1)	12’4’’ (1)	1 (1)	4
B400271	4	200	Urban Local (1)	1966 (1)	12’4’’ (1)	0 (0)	3
B640031	2	21,600	Rural Principal Arterial – Other (0)	1967 (1)	14’9’’ (0)	0 (0)	1
B050147	1	4,400	Urban Local (1)	1974 (0)	14’7’’ (0)	0 (0)	1
B400916	0	3,400	Urban Minor Arterial (0)	2016 (0)	20’11’’ (0)	0 (0)	0

could be weighted higher than variables that are only slightly overrepresented. This can introduce subjectivity into the process but provides flexibility in how an agency considers each factor in the prioritization process. The next section describes a more rigorous process for assigning variable weights.

Regression-Based Risk Factor Score

Another option is to use a statistical model to predict the likelihood of a crash and then use the model prediction as the risk score to prioritize locations. In this approach, an agency would use the statistical model to weight each factor; however, rather than using subjective weights, the coefficients estimated during the modeling process serve as weights for each risk factor.

The industry standard for predictive crash modeling is a negative binomial (NB) crash count model. Using these models, agencies can estimate the number of BrTS crashes at a given location based on the site-specific characteristics.

The following is the general formulation of the equation to predict BrTS crashes.

$$BrTS\ Crashes_i = n \times Structure\ Length \times AADT^{\alpha} \times e^{\beta_0 + \sum_{j=1}^{q} \beta_j x_{ij}}$$

where

- $BrTS\ Crashes_i$ = the estimated bridge strikes at bridge i;
- n = the number of years considered for the study (e.g., 5 years);
- *Structure Length* = the length of the structure defined as:
  - Length of bridge structure for on-bridge strikes (e.g., truss, parapet, railing),
  - Length of deck for both under-bridge strikes with overhead structure (e.g., girder) and under-bridge strikes with pier or support (e.g., bent, support, pier, abutment);
- *AADT* = the annual average daily traffic (based on the type of the estimated crash);
- x_{ij} = the quantitative measure of each explanatory variable j associated with bridge i;
- α and β_j = estimated model coefficients for the explanatory variable q; and
- β_0 = the estimated constant.

Task 3 – Prioritize Elements

The objective of this task is to prioritize the elements based on the risk scores and other potential factors as desired. The task begins with a simple ranking—rank the elements from the highest risk score to the lowest. Agencies can set thresholds for priority elements to help focus on a manageable number of bridges or tunnels. Agencies can create visualizations in addition to simple ranked lists. Figure 6 is an example of how an agency could visualize high-, medium-, and low-risk locations. Again, GIS tools are useful for visualizations and spatial analysis.

In some cases, an agency may want to prioritize a single list of elements that are scored using different risk factor criteria. For instance, one set of elements (e.g., bridges) may be scored from a total of nine risk factors, and another set of elements (e.g., tunnels) may be scored from a set of seven risk factors. In these cases, it is appropriate to normalize the risk scores to facilitate comparison across the different elements (e.g., bridges versus tunnels). To create normalized risk scores, agencies can divide the assigned risk score by the total potential risk score. The agency can then prioritize the various elements using the normalized risk score.

Table 7 shows an example with several elements that are first scored using three different sets of risk factor criteria and then normalized by the maximum possible risk score to prioritize across all elements in a single list. For example, Site 1 received an initial risk score of 6 out of a maximum possible risk score of 7. The normalized risk score for Site 1 is 0.86 (i.e., 6/7).

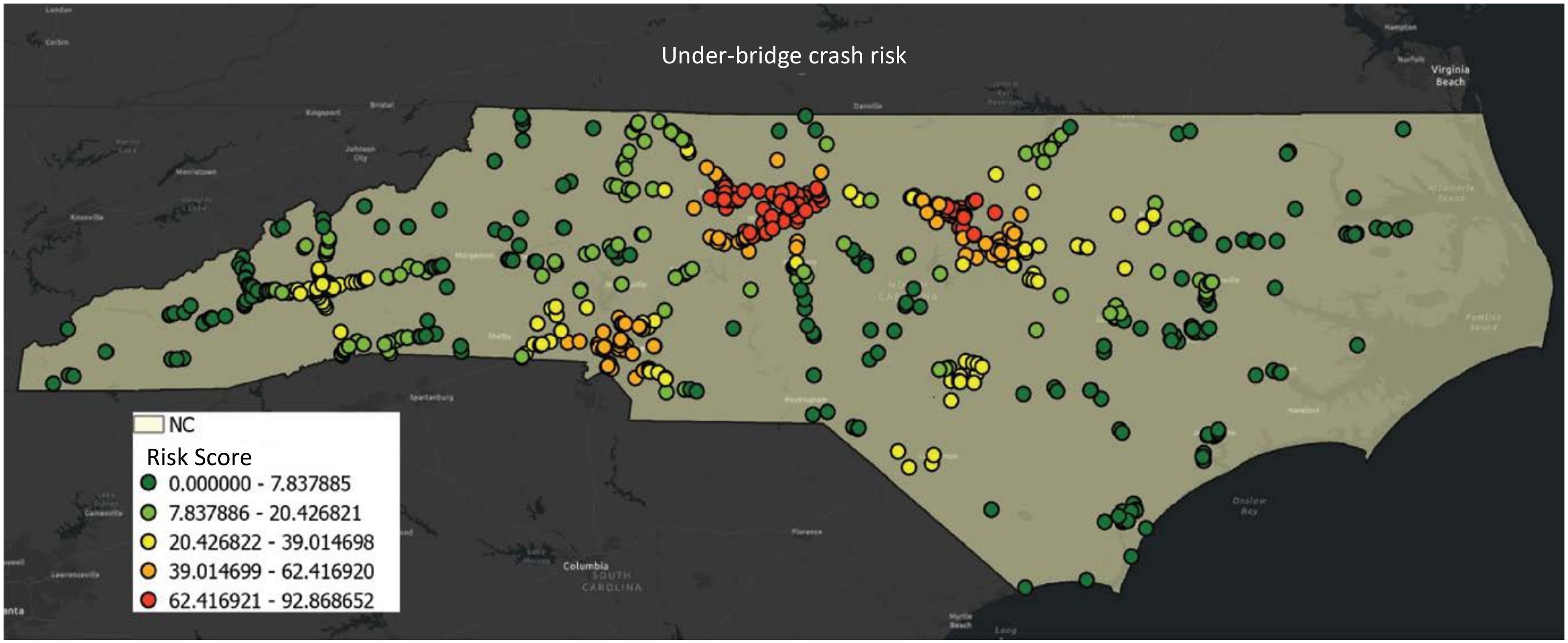

Figure 6. Example visualization of high-, medium-, and low-risk elements determined in North Carolina.

Table 7. Example risk scores with normalization.

Site ID	Risk Score	Maximum Possible Risk Score	Normalized Risk Score	Priority Rank
1	6	7	0.86	3
2	1	7	0.14	7
3	4	7	0.57	4
4	8	8	1.00	1
5	7	8	0.88	2
6	5	9	0.56	5
7	2	9	0.22	6

In other cases, an agency may want to include other factors to prioritize elements that represent substantial consequences should a crash occur. Substantial consequences could include conditions where a BrTS would close down a road that serves a hospital, emergency response (e.g., fire or police station), school, a high-traffic-volume roadway, or a roadway without an alternative route. At this stage, the consequences can further be applied to prioritize elements and serve as a tiebreaker for locations that have approximately the same likelihood of a crash occurring. For instance, if the following two locations have an equal risk score, which one would take priority?

1. Rural, two-lane road that serves 500 vehicles per day and a residential community with alternate access available.
2. Urban, six-lane arterial that serves 25,000 vehicles per day and a nearby hospital.

The BrTS crash at the second location would likely have more severe community and operational impacts if a crash occurred. As such, an agency may prioritize this location for further review and improvement.

2.4 Analyzing Data to Identify Risk Factors

This section focuses on data analysis to help practitioners and researchers replicate the results from this study with more focused local data if desired. The first subsection describes the data needs, and the second subsection describes the analysis procedures. Data limitations should not be viewed as an impediment to a proactive risk-based analysis. At a minimum, states should be able to use existing crash data and information from the NBI and NTI for analysis. For agencies with limited data capabilities, there is an opportunity to collect and organize the data in a standard format to support a future risk-based program (refer to Section 2.5, "Collecting and Integrating Risk Factor Data").

Data Needs

Data needs vary significantly based on the desired level of effort and analysis. At a minimum, agencies should have BrTS crash data. Ideally, these crashes are geolocated and integrated with infrastructure and traffic data, so an analyst can connect the existing infrastructure and traffic conditions to each crash.

The ideal dataset for this step includes the following data integrated at the crash- and site-level:

- Crash data, including crash type, vehicle type, truck classification, OS/OW hauling permit, severity, location, and contributing factors.

- Roadway data, including cross section, geometry, and grade for the on-bridge, under-bridge, and tunnel roadways.
- Bridge and/or tunnel data, including physical characteristics of the bridges and tunnels. Agencies can download bridge and tunnel data from the NBI and NTI, respectively.
- Traffic volume data, including traffic volume, truck volume (or percentage trucks), and number of oversize loads.
- Supplemental data, including state or local policies, land use data, warning signs and systems, and asset management inventories (e.g., sign inventories).

Refer to Section 2.5, "Collecting and Integrating Risk Factor Data," for further details on how to collect, process, and integrate these data. The section also provides sample templates to illustrate the appropriate data format.

Analysis Procedures

There are three general quantitative approaches to identifying and mitigating risk factors:

- Critical event analysis,
- Overrepresentation, and
- Statistical modeling.

Critical event analysis is a site-specific analysis approach that involves a detailed review of crashes and the context of the specific location to identify the plausible sequence of events leading up to a crash. Overrepresentation is a basic system-level analysis approach that offers an option for agencies with limited data or analysis capabilities. Statistical modeling is an advanced system-level analysis approach that requires a certain level of data and expertise to perform but can offer more insightful results.

Agencies can select the preferred approach based on the context of the analysis (site versus system), data capabilities, and resources available to perform the analysis. The following sections describe each approach with example applications.

Option 1: Critical Event Analysis—A Site-Specific Analysis Approach

Critical event analysis is a site-specific analysis approach agencies can use to identify risk factors. In this approach, agencies perform a detailed review of historical crashes (if applicable) and examine the context of the specific location (e.g., location of ramps, placement of signing, and availability of turnarounds and alternative routes) to identify the plausible sequence of events leading up to a crash. The idea is that there are generally multiple events (or contributing factors) that lead to a crash. Once an agency identifies and understands these events, it can mitigate crash risk by removing one or more of the events (factors). This is similar to the root cause analysis performed by the National Transportation Safety Board for major crashes or the failure mode and effects analysis (FMEA) performed by the National Aeronautics and Space Administration for major incidents. In the FMEA, "failure mode" is an event that increases the risk of an incident. "Event analysis" is an assessment of the consequence of a particular failure mode (e.g., what is the contribution of a specific factor to the overall risk of an incident).

For a more systematic approach, agencies could develop a checklist to assist bridge and tunnel engineers in identifying locations or factors that are at a higher risk of a BrTS. Similarly, industry organizations and motor carriers can develop checklists to assist drivers in identifying factors related to the load (e.g., height, width, and load securement) that increase the risk of a BrTS. Refer to Section 3.3 for further details on checklists.

Critical Event Analysis: Example Application

In this example, critical event analysis is used to postulate the sequence of events leading to a BrTS classified as an under-bridge collision with the superstructure. The analysis is based on one historical crash and the context of the specific bridge. The crash involved an OHV compared to the bridge height. The driver had a permit but deviated from the designated route. Based on the police officer's narrative, the driver was unfamiliar with the area and was looking to correct course. Based on the crash data, it was dark when the crash occurred. Based on a site review during the day, there were warning signs well in advance of the bridge to indicate the low-clearance height. Based on a site review at night, it became evident that the advance warning sign was worn and difficult to see. Figure 7 shows a potential sequence of events to better understand the contributing factors and opportunities to mitigate BrTS risk for this specific scenario.

There is an opportunity to mitigate BrTS risk at this location by eliminating one or more factors from the sequence of events. For instance, if the driver was familiar with the area, then they would have remained on the designated route. If the driver was transporting the load during the day or if the warning signs were more conspicuous, then the driver may have stopped before the bridge. If the bridge was designed to standard height clearance, then the load would not be considered overheight. The crash may have been avoided if just one factor had been removed from the scenario. Of course, some of the factors are more expensive to address than others, and addressing multiple factors adds redundancy.

Option 2: Overrepresentation—A Basic System-Level Approach

Overrepresentation is a basic system-level approach agencies can use to identify risk factors. In this approach, agencies compare the proportion of BrTS crashes at locations with given attributes to the proportion of an exposure measure, such as the number of sites or vehicles passing through those locations.

Overrepresentation: Example Application

In this example, overrepresentation analysis is used to assess five categories of percent trucks as BrTS risk factors within a defined geographic area (e.g., a region or state). Specifically, the analysis compares the percentage of BrTS associated with each category of percent trucks to the percentage of bridges associated with the same category. As shown in Figure 8, it is easy to identify those categories that stand out as risk factors. In this case, the proportion of BrTS crashes is greater than the proportion of bridges for the 5–10, 10–15, and 15+ categories. These overrepresented categories indicate that truck percentage greater than 5% is a risk factor for this example.

Option 3: Statistical Modeling—A More Rigorous System-Leven Approach

Statistical modeling is a more rigorous system-level approach agencies can use to identify risk factors. In this option, agencies use their own data to develop crash frequency or crash probability regression models for BrTS crashes on one or more focus facility-types. The regression model uncovers features that are statistically correlated with increased frequency or probability of BrTS crashes, depending on the model type. Each variable in the model can be considered a risk factor.

Figure 7. Sample critical event analysis.

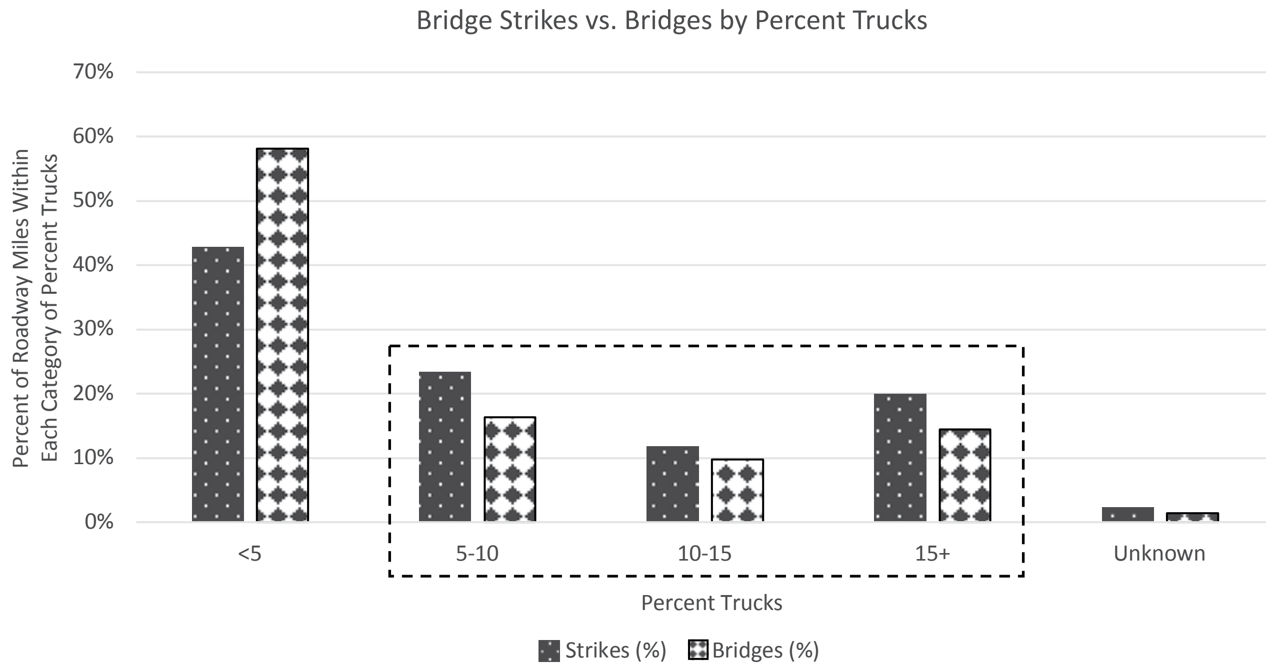

Figure 8. Sample overrepresentation graph to assess percent trucks as a BrTS risk factor.

Agencies can use the model results as described in the earlier Section, "Task 2 – Calculate Risk Score," to prioritize locations based on predicted risk.

Statistical Modeling: Example Application

In this example, an agency developed a statistical model to assess several variables as risk factors for under-bridge strikes with overhead structures. Table 8 summarizes the model results, which were estimated using NB regression. As shown in the table, each of the variables is associated with an increase in the likelihood of an under-bridge strike with an overhead structure. This is evident from the column, Estimates (i.e., all positive coefficients). As such, all of these variables could be identified as risk factors for under-bridge strikes with an overhead structure.

Table 8. Summary of regression model for under-bridge strikes with an overhead structure (e.g., girder).

Parameter	Estimate	Standard Error	Pr > z
(Intercept)	0.7622	−8.0140	—
Log of Under-Bridge Average Daily Traffic	0.0779	3.8390	0.00
Bridge Age	0.0048	3.2270	0.00
Functional Classification of Under-Bridge Roadway: Rural Interstate	0.3123	−3.3610	0.00
Functional Classification of Under-Bridge Roadway: Urban Interstate	0.2871	−1.6660	0.10
Functional Classification of Under-Bridge Roadway: Urban Other Principal Arterial	0.2528	2.6110	0.01
Functional Classification of Under-Bridge Roadway: Urban Local	0.2491	8.0790	0.00
Length of Maximum Span of the Bridge	0.0103	−4.7450	0.00
Average Daily Truck Traffic Percentage of Under-Bridge Roadway	0.0190	3.3110	0.00
Number of Lanes Under Bridge	0.0536	2.1680	0.03
Bridge Serviceability and Functional Obsolescence	0.0106	−1.7690	0.08

The standard error is used in combination with the estimate to determine the statistical significance of the variable, which is expressed in the final column of the table (Pr > z). A value less than 0.10 indicates the variable is statistically significant at the 90% confidence level; a value less than 0.05 indicates the variable is statistically significant at the 95% confidence level. In this example, all variables are statistically significant at the 90% confidence level or higher.

This example shows the wide range of features that can be considered as BrTS risk factors using statistical modeling. Agencies should consult previous studies and literature, including the results of this research, when identifying potential risk factors for a risk-based analysis.

2.5 Collecting and Integrating Risk Factor Data

This section focuses on data collection and integration procedures to support BrTS risk assessments, beginning with details on processing existing state-level data (state-maintained crash data) and national-level data (NBI and NTI). It describes two methods for linking crash data to specific bridges or tunnels, along with the challenges and opportunities to overcome those challenges. The section concludes with a discussion of how agencies can contribute to the BrTS Clearinghouse for collecting and analyzing BrTS data and communicating bridge and tunnel clearance information. By collecting and integrating additional data elements, agencies will be able to perform more robust and reliable risk assessments to mitigate BrTS risk. By updating the Clearinghouse with more complete and reliable data, agencies will support more advanced and automated risk-based screening and prioritization. The Clearinghouse will also serve as a means to communicate bridge and tunnel clearance information, which is one of the most important factors in mitigating BrTS risk.

Crash Data

Although a BrTS is defined as a collision between a motor vehicle and a bridge or tunnel, the actual query of such information is not straightforward since there are various ways to store and present the information. The relational crash database in Figure 9 illustrates the recommended method for querying a BrTS. As shown, events related to bridge strikes can be archived at the vehicle level or crash level. Vehicle-level data elements describe the characteristics of the vehicles involved, while the crash-level data elements describe the overall characteristics of the crash. In most states, only the "most harmful event" and sometimes the "first harmful event" are available at the crash level. ["Most harmful event" is one that results in the most severe injury or, if no injury, the greatest property damage involving the motor vehicle. A "first harmful event" is defined as the first injury- or damage-producing event that characterizes the crash type (NHTSA 2017).] For these states, querying the most harmful events for bridge-related collisions will leave out a substantial number of bridge hits that are neither the most harmful nor the first harmful event. Therefore, agencies should query BrTS from data fields such as first harmful event (crash level), most harmful event (crash level), or sequence of events (vehicle level) for attributes such as "Bridge Overhead Structure," "Bridge Pier or Support," "Bridge Rail," and "Other Fixed Object (wall, building, tunnel, etc.)" to compile a more complete dataset.

Ideally, the crash data should contain information to identify the specific bridge (based on a unique bridge ID) that can help specify which bridge parts were struck and distinguish bridge hits from tunnel hits. A few states do not distinguish by bridge part. For instance, the bridge-hit records from one state were all labeled as "Bridge Railing" crashes. In terms of tunnel strikes, very few states (e.g., Washington) assign dedicated attributes or fields to tunnels in the crash data. In general, the only way to identify tunnel hits from "Other Fixed Object (wall, building, tunnel, etc.)" or to identify a specific part of the bridge is to review the crash narrative. However, the

Crash Level

Crash ID	Most Harmful Event	First Harmful Event	...
Crash 1	Bridge Rail	Motor Vehicle in Transport	...
Crash 2	Bridge/Pier/Abut	Run Off Roadway Right	...
...	...	...	...
Crash N	Bridge Overhead Structure	Bridge Overhead Structure	...

Vehicle Level

Crash ID	Vehcle ID	Seq Event 1	Seq Event 2	Seq Event 3	Seq Event 4	...	Vehcle ID
Crash 1	Veh 1	Motor Vehicle in Transport	Cargo/Equipment Loss or Shift	Cross Centerline	Bridge Rail	...	Veh 1
Crash 1	Veh 2	Motor Vehicle in Transport	Cargo/Equipment Loss or Shift	Cross Centerline	Bridge Rail	...	Veh 2
Crash 2	Veh 1	Run Off Roadway Right	Reentering Roadway	Bridge/Pier/Abut		...	Veh 1
...	...	...	...	...	...	...	...
Crash N	Veh 1	Bridge Overhead Structure	Motor Vehicle in Transport			...	Veh 1

Person Level

Crash ID	Person #	Person Type	...	(Vehicle ID)
Crash 1	1	Driver	...	(Veh 1)
Crash 1	2	Passenger	...	(Veh 1)
Crash 1	3	Driver	...	(Veh 2)
Crash 2	1	Driver	...	(Veh 1)
...	...	...	...	
Crash N	1	Driver	...	(Veh 1)

Figure 9. Relational crash database with relevant information for BrTS.

crash narrative is one of the data items that is frequently not available through data requests, and there are challenges in consistently querying the narrative for relevant information.

As states move toward all electronic crash reporting and compliance with the suggested data fields in the Model Minimum Uniform Crash Criteria (MMUCC), there will be more uniformity and consistency for identifying BrTS from the crash data. There will also be an opportunity to capture more details for each BrTS if the structure of the electronic crash form asks questions in a sequential order with logic to trigger additional questions as appropriate. In the interim, agencies can convert or collapse state-specific data fields and attributes to better align with MMUCC data fields. Table 9 shows an example of converting and collapsing the state-specific sequence of events field to the corresponding MMUCC attributes.

Table 9. Example of data fields/attributes conversion (Wisconsin).

State Crash Data Field	MMUCC-Compliant Data Field
ANM DA – Domesticated Animal – Alive	Animal (live)
ANM NA – Non–Domesticated Animal (Alive)	Animal (live)
ANM DD – Domesticated Animal – Dead	—
ANM ND – Non–Domesticated Animal (Dead)	—
BRIDGE – Bridge Overhead Structure	Bridge Overhead Structure
BRPAR – Bridge Parapet End	—
BRRAIL – Bridge Rail	Bridge Rail
BRPIER – Bridge/Pier/Abut	Bridge Pier or Support
CABL B – Cable Barrier	Cable Barrier
CARGO – Cargo/Equipment Loss or Shift	Cargo/Equipment Loss or Shift
CONC B – Concrete Traffic Barrier	Concrete Traffic Barrier
CR CL – Cross Centerline	Cross Centerline
CR MED – Cross Median	Cross Median
CULVRT – Culvert	Culvert
CURB – Curb	Curb
DITCH – Ditch	Ditch
DOWN – Downhill Runaway	Downhill Runaway
EMBKMT – Embankment	Embankment
—	End Departure (T-intersection, dead-end, etc.)
EQP FL – Equipment Failure (Blown Tire, Brake Failure, etc.)	Equipment Failure (blown tire, brake failure, etc.)
FELL – Fell/Jumped from Motor Vehicle	Fell/Jumped from Motor Vehicle
FENCE – Fence	Fence
HYDRN – Fire Hydrant	—
FIRE – Fire/Explosion	Fire/Explosion
GR END – Guardrail End	Guardrail End Terminal
GR FAC – Guardrail Face	Guardrail Face
IMMER – Immersion, Full or Partial	Immersion, Full or Partial
ATTEN – Impact Attenuator/Crash Cushion	Impact Attenuator/Crash Cushion
JKNIF – Jackknife	Jackknife
LT TRN – Left Turn	—
LTPOLE – Lum Light Support	—
MAILBOX – Mailbox	Mailbox
MVIT – Motor Vehicle in Transport	Motor Vehicle in Transport
OT RDY – Motor Vehicle in Transport – Other Roadway	—
OTH FX – Other Fixed Object	Other Fixed Object (wall, building, tunnel, etc.)
OTH NC – Other Non-Collision	Other Non-Collision Harmful Event

(continued on next page)

Table 9. (Continued).

State Crash Data Field	MMUCC-Compliant Data Field
OT NMT – Other Non-Motorist	Other Non-Motorist
OBNFX – Other Object – Not Fixed	Other Non-Fixed Object
—	Other Non-Harmful Event
OT PST – Other Post, Pole or Support	Other Post, Pole, or Support
THER B – Other Traffic Barrier	Other Traffic Barrier
OH PST – Overhead Sign Post	—
OVRTRN – Overturn/Rollover	Overturn/Rollover
PKVEH – Parked Motor Vehicle	Parked Motor Vehicle
BIKE – Pedalcycle	Pedalcycle
PED – Pedestrian	Pedestrian
TRAIN – Railway Vehicle (Train, Engine)	Railway Vehicle (train, engine)
REENTR – Reentering Roadway	Reentering Roadway
RT TRN – Right Turn	—
ROR L – Run Off Roadway Left	Ran Off Roadway Left
ROR R – Run Off Roadway Right	Ran Off Roadway Right
SEP – Separation of Units	Separation of Units
—	Strikes Object at Rest from MV in Transport
STRUCK – Struck by Falling, Shifting Cargo or Anything Set in Motion by Motor Vehicle	Struck by Falling, Shifting Cargo or Anything Set in Motion by Motor Vehicle
THRWN – Thrown or Falling Object	Thrown or Falling Object
SIN PST – Traffic Sign Post	Traffic Sign Support
TF SIG – Traffic Signal	Traffic Signal Support
TREE – Tree	Tree (standing)
UNKN – Unknown	Unknown Fixed Object
UT PL – Utility Pole	Utility Pole/Light Support
WZ EQP – Work Zone/Maintenance Equipment	Work Zone/Maintenance Equipment

National Bridge Inventory and National Tunnel Inventory

The NBI database contains information for more than 615,000 bridges on public roads and publicly accessible bridges on federal and tribal lands. The NBI contains inventory and inspection information collected by state DOTs, federal agencies, and tribal governments. The bridge inventory and inspection data are categorized into the following seven sections:

1. Bridge identification;
2. Bridge material and type;
3. Bridge geometry;
4. Features;
5. Loads, load rating, and posting;
6. Inspections; and
7. Bridge condition.

Similarly, the NTI is also a national database that contains information describing more than 500 tunnels on public roads, including interstates, U.S. highways, and state and county roads as well as publicly accessible tunnels on federal lands. The tunnel inventory data are categorized into the following eight sections:

1. Identification,
2. Age and service,
3. Classification,

4. Geometric data,
5. Inspection,
6. Load rating and posting,
7. Navigation, and
8. Structure type and material.

U.S. DOT Bureau of Transportation Statistics Railroad Bridge Data

The NBI includes very few railroad bridges. If an agency assigns bridge crashes to the nearest bridge without accounting for railroad bridges, then there is a higher chance of wrongful linkage. Specifically, there is a chance that a railroad bridge crash could be incorrectly assigned to a nearby highway bridge. Fortunately, the Bureau of Transportation Statistics (BTS) under the U.S. DOT compiled and published a railroad bridge database.

On October 14, 2022, BTS released the railroad bridge dataset from the Federal Railroad Administration and published it as part of the National Transportation Atlas Database. Based on the Code of Federal Regulations (49 CFR Part 237), a railroad bridge is defined as "any structure with a deck, regardless of length, which supports one or more railroad tracks, or any other under-grade structure with an individual span length of 10 feet or more located at such a depth that it is affected by live loads."

While the railroad bridge dataset contains 69,510 railroad bridges, it includes very limited information on details such as ownership, structure, and traffic. Thus, the primary purpose of using this dataset is to locate railroad bridges and increase the accuracy of a spatial join between a crash and an NBI bridge. A "spatial join" is a fundamental operation within a GIS or spatial database, wherein it merges the attribute tables of two spatial layers, guided by a specified spatial relationship between their geometrical elements. In this case, it represents the merge between crash data and the NBI bridge inventory data. At a minimum, including this dataset can reduce the uncertainty of joining a crash with the wrong highway bridge in the NBI data.

Data Linkage

There are two primary methods to link crash and bridge data:

1. Common ID and
2. Spatial join.

Common ID

States can use the common ID linkage when the crash data contain a complete and accurate bridge ID that is the same ID found in the bridge inventory. This bridge ID is a universal unique identifier (UUID) for deterministic linkage between a crash record and the impacted bridge. For example, Maine's bridge ID is a UUID in both the crash data and the bridge inventory. As such, Maine can directly link a BrTS to the impacted bridge. States are encouraged to enhance crash reporting practices and collect the bridge ID as part of the crash report. This will allow the use of the common ID linkage and improve the reliability of merging crash and bridge data. Refer to Section 2.5 for further discussion of opportunities to improve crash data collection for use in BrTS analysis and research.

Spatial Join

States can use the spatial join linkage when the structure ID is not available or not properly filled out in the crash data. The spatial join is a probabilistic linkage based on the Euclidean distance (i.e., straight line distance as opposed to travel distance) between the crash location and bridge location. The accuracy of finding a correct match increases as the joined distance decreases.

The following are two primary issues related to the spatial join method given the location accuracy of both bridges and crashes.

- For states with a high bridge density, the clustering of bridges increases the likelihood of a crash being linked to the wrong bridge.
- There is a balance between accuracy and coverage of the spatial join depending on the location accuracy selected by the analyst. A short buffer distance (e.g., 50 feet) can increase the accuracy of the join but may result in many unlinked crashes. A longer buffer distance (e.g., 1,000 feet) may substantially increase the matches between crash records and bridges but may result in an incorrect linkage (e.g., crashes linked to multiple bridges or linked to the wrong bridge).

The most common spatial join method, called "closest join," involves linking a crash to the nearest bridge. Another spatial join method, called "split join," involves splitting a crash among bridges within some proximity. For the split join, agencies define a relevant distance and assign a fraction of a hit to each bridge within the distance rather than assigning 100% of a crash to the nearest bridge. If location data quality is a concern, split join may offset the impact of joining crashes to the wrong bridge.

Research conducted for this project assessed both crash assignment methods using data for Maine, North Carolina, and Wisconsin. Nine split joins were conducted: three for each state based on on-bridge strikes, under-bridge strikes, and under-bridge OHV strikes. Each bridge was assigned a fraction of a BrTS crash within 500 feet. The researchers then compared the linked results to the BrTS assigned by the closest join. The researchers used a paired t-test to determine whether the two samples were statistically different and a Fisher's exact test to determine whether the two samples were independent. The paired t-test indicated that the two samples were statistically different, and the Fisher's exact test showed that they were generally independent. This indicates that the method used to join BrTS crashes to bridges (closet join or split join) could impact the results of the analysis.

Based on this research, most crashes were within 500 feet of a bridge. When the crash was farther than 500 feet from a bridge, the accuracy of the spatial join deteriorated. Further, according to the descriptions in NBI, the latitude/longitude of a bridge generally refers to the beginning of a bridge in the direction of inventory. The average structure length of bridges in the NBI is approximately 150 feet, which suggests that for the majority of bridges, the 500-foot buffer covers the entire bridge length and its proximity.

To increase the accuracy of a spatial join, agencies should account for the missing railroad bridges in the NBI. To do so, agencies would first perform a spatial join between the crashes and railroad bridges and flag any potential railroad bridge-related crashes. This spatial join can be limited to under-bridge crashes only (i.e., overhead bridge structure strikes and the under-bridge strikes with pier or support) because a vehicle crash on a railway bridge is not expected. Based on the project team's research, the difference between including and excluding railroad bridge crashes can be very large: 60% or more are flagged as railroad bridge hits. In Wisconsin, the percentage is even higher with more than 80% of crashes flagged as potential railroad bridge hits.

Tunnel strikes are identified as vehicle strikes within 1,500 feet of a tunnel. The buffer of 1,500 feet is set as the threshold because the national average tunnel length in the NTI is 1,300 feet. The location for a tunnel is set at its entrance.

National BrTS Data Clearinghouse

A national BrTS Clearinghouse is one opportunity to help overcome challenges in identifying, diagnosing, and mitigating BrTS risk. The following are keys to success.

1. Keeping the structure inventory data up-to-date and in good quality: The NBI has missing, erroneous, and logically conflicting information (Dedman 2008; Dekelbab, Al-Wazeer, and Harris 2008; Din and Tang 2016) due to data entry errors. Similar issues afflict the NTI. As such, there is a need to work to improve the quality and timeliness of the underlying data.
2. Establishing a reliable linkage between BrTS and structure inventory data: While crash, bridge, tunnel, and roadway databases contain valuable information, they are often in separate "silos" (i.e., collected and maintained by different departments or divisions). The MMUCC provides a mechanism to link bridge crashes with NBI data through a Bridge/Structure Identification Number (NHTSA 2017), but MMUCC compliance is optional and varies among states. Further, spatial joins can be subject to errors and should be validated before analysis. A BrTS Clearinghouse will help to establish these linkages.
3. Extracting relevant data items from connected databases for collision risk analysis: The NBI, NTI, and crash databases each have multiple tables, numerous data elements, and thousands of records. The scale of the databases and the complex relationships among them make it challenging to extract useful information and to promptly make decisions regarding permits. The BrTS Clearinghouse will provide useful information for assessing risk based on the underlying data. It will also allow users to extract relevant data for more detailed analysis.
4. Developing a rigorous approach to accurately calculate the collision risk and its outcome: Most state agencies, as part of their bridge (damage) inspection procedure, have methods for rating a bridge after the impact and policies for an efficient and effective response. Few have methods for proactively assessing bridges for the risk of being hit. The BrTS Clearinghouse will provide a method and results for assessing BrTS risk.
5. Identifying and quantifying effective safety countermeasures for categories of BrTS: Quantifying the costs and benefits of targeted countermeasures will lead to more informed decisions on appropriate infrastructure and operational investments and strategies. Chapter 3 of this guide presents various countermeasures–from lower-cost signing and striping to higher-cost bridge improvements to state-level policy and operational procedures.
6. Communicating highway structure conditions or concerns effectively among different stakeholders: Mitigating and avoiding BrTS require the cooperation of many stakeholders, including state and federal agencies, motor carriers, and private service providers. Effective communication and information exchange among different parties and agencies will lead to more effective BrTS programs, especially during permit issuance for OS/OW movements. This can also support improvements to the data availability and quality.

This section presents a BrTS Clearinghouse prototype for collecting and disseminating BrTS data along with a demonstration of how agencies could use it in practice. The goal is to create a sustainable national clearinghouse for states to collect and analyze BrTS data as well as communicate bridge and tunnel clearance information. While this section presents an initial prototype, there will be a need for future efforts, including a long-term storage plan and regular maintenance. For instance, there will be a need to update the data extract, transform, and load (ETL) processes as states change their crash and roadway databases. This section does not address these maintenance issues.

Prototype Design Concept

Figure 10 shows the conceptual design of the BrTS Clearinghouse. There are several components, including state crash records (left middle), NBI and NTI (top middle), and supplemental datasets (bottom middle). The result is a structured dataset with structure-based and crash-based

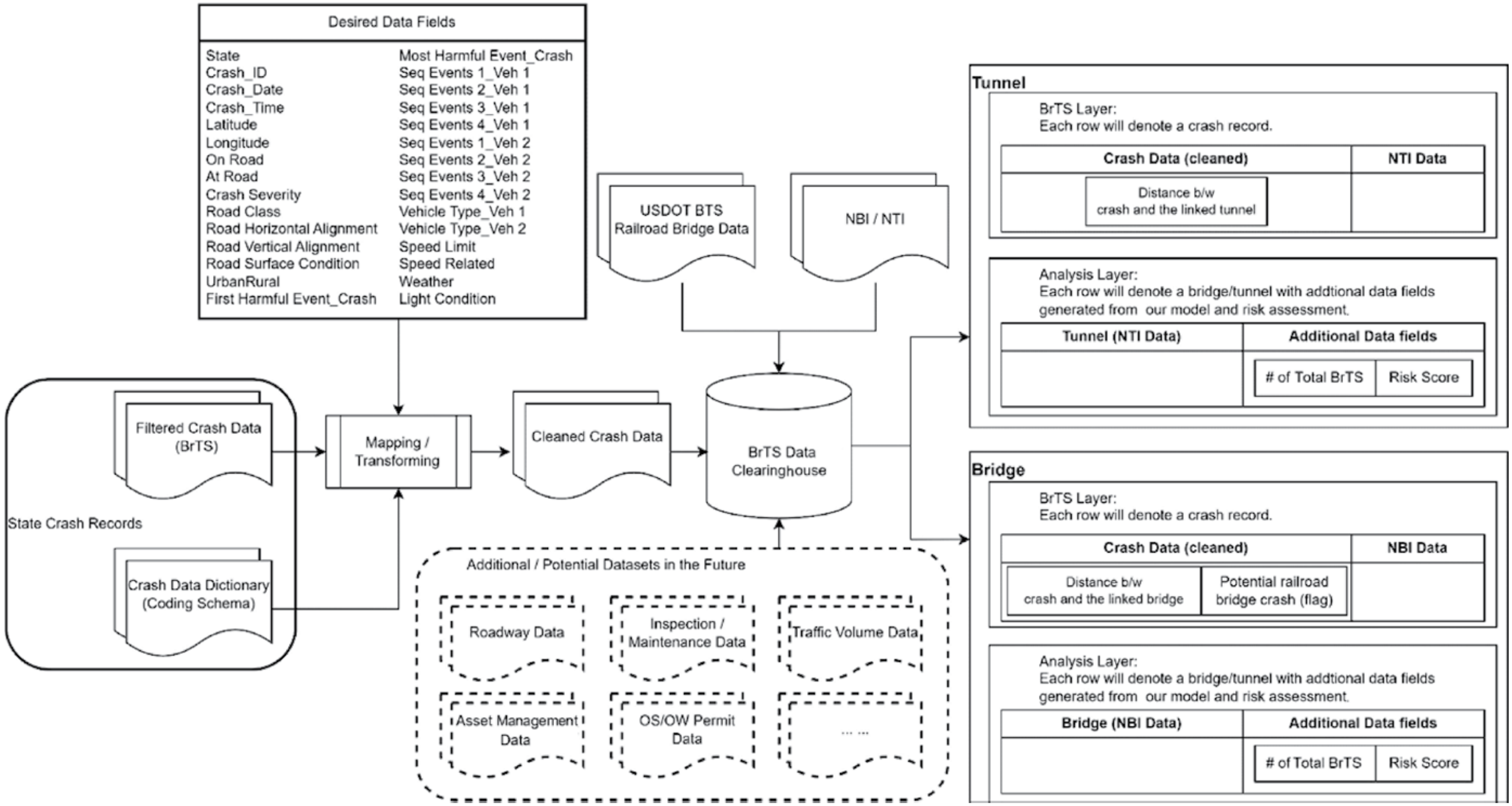

Figure 10. Design of the BrTS Data Clearinghouse.

files (right). The figure shows the collection and processing of state crash records (left middle) as a three-step process:

1. BrTS crash data requests are sent to state agencies. State agencies process existing state crash data to identify BrTS crashes that meet the inclusion criteria (i.e., crashes involving a strike to the bridge, tunnel, or its component parts).
2. BrTS Clearinghouse maintenance staff transform the state BrTS crash data to meet the established standard data element definitions. This ensures the final database file and records have consistent definitions and formats. Records that fail to convert properly are examined and either corrected or excluded. The transformation process will be improved through an iterative process unique to each source file (state database).
3. Each transformed and cleaned state BrTS crash file is added to the final file ready for analysis.

In parallel, the Clearinghouse retrieves structure data from NBI, NTI, and the U.S. DOT BTS railroad bridge dataset (top middle). The Clearinghouse integrates the structure data and crash data using either the common ID or spatial join method. If the structure ID is available in both the crash and structure data, then the common ID is used to join the data. If not, the spatial join is used based on available data (e.g., latitude/longitude, X/Y). The Clearinghouse could also incorporate additional data such as roadway characteristics, inspection and maintenance records, and traffic data (bottom middle).

The risk assessment module calculates basic statistics (e.g., number of crashes, injury severity, damage) for each bridge based on the embedded BrTS crash count models, injury severity models, and risk assessment method. The Clearinghouse creates a relational database for crash-based analysis and structure-based analysis. The flat file for crash-based analysis includes one record per BrTS crash. Table 10 shows an example of the resulting flat file. The flat file for structure-based analysis includes one record per bridge or tunnel.

At a minimum, the database will include the relevant crash data elements, the bridge or tunnel data elements, and any crucial metadata required for data management purposes. A visualization component could be developed via ArcGIS to produce corresponding layers for displaying related statistics (e.g., BrTS locations, number of BrTS for each bridge, flagged railroad bridge crashes, risk assessment score, etc.). Visualization tools could allow the user to toggle specific elements of interest such as bridge or tunnel groups or even different struck parts.

Prototype Demonstration

Fourteen states were selected to demonstrate the prototype based on the quality and completeness of crash data: Alaska, Arkansas, Connecticut, Florida, Illinois, Iowa, Maine, Mississippi, North Carolina, South Carolina, Tennessee, Utah, Washington, and Wisconsin. Specifically, these states have the essential data fields and attributes required for further analyses. The data from all 14 states can be used to identify certain bridge-related crashes. Typical situations regarding the bridge structure ID from the crash data can be categorized as the following:

1. Crash data and corresponding NBI data have the same bridge ID, which can serve as the UUID for data linkage. Only Maine has such data.
2. Crash data include one dedicated variable for recording the bridge ID, but a very small percentage of filled values are proper NBI bridge IDs (e.g., Wisconsin).
3. Crash data do not include NBI bridge IDs, which is the most common case among the currently collected data from most of the states.

For tunnel-related crashes, there is rarely a direct linkage between the NTI data and the crash data from selected states as mentioned previously. Although NTI data are set up similarly to the NBI data with a specific tunnel structure ID, the crash data do not capture the tunnel ID.

Table 10. Prototype of the BrTS Data Clearinghouse flat file.

State Crash Records

Field Name	BrTS ID	State	Date	Time	Latitude	Longitude	On Road	At Road	...
Format	CHAR[a](50)[b]	CHAR(2)	DATE	TIME	NUM(10,8)[c]	NUM(10,8)	CHAR(50)	CHAR(50)	...
Description	ID in data clearinghouse	State postal abbreviation	Date of crash YYYY/MM/DD	Time of crash	Decimal degrees	Decimal degrees	Name of road on which crash occurred	Name of intersecting road to identify location	...
	1001	WI	2018/11/09	8:45	43.87680426	−91.1832326	THIRD	WALNUT	...
	1002	WI	2020/10/02	13:20	44.08444452	−87.7236331	US 29	SR 1619	...
	1003	NV	2013/03/06	7:50	40.06118260	−118.6534580	PEACE	GLENNWOOD	...
	1004	NV	2013/05/25	21:10	40.80916510	−115.8246880	SUTTON	ARLINGTON	...
	1005	MA	2019/02/04	17:05	42.59224383	−71.2805723	NC 226	POTEAT	...
	1006	MA	2019/02/12	9:02	41.94660778	−71.2755011	SALISBURY	OLD CHARLOTTE	...

NBI/NTI

Field Name	BrTS ID	Structure Number	Structure Material	Structure Type	Minimum Vertical Clearance	Year Built	Detour Length	...
Format	CHAR(50)	CHAR(50)	CHAR(50)	CHAR(50)	NUM(3,2)	NUM(4,0)	NUM(3,0)	...
Description	ID in data clearinghouse	Structure number/ bridge identification number	Structure material	Type of structure design	Minimum vertical clearance (over-bridge roadway) or minimum vertical under-clearance (under-bridge roadway) in meters	Year the bridge was built	Kilometers	...
	1001	B32005400000000	Steel continuous	Stringer/multibeam or girder	4.84	1967	1	...
	1002	B36006500000000	Prestressed concrete continuous	Stringer/multibeam or girder	4.65	1979	24	...
	1003	B1040W	Concrete	Culvert	—	1965	1	...
	1004	I900W	Prestressed concrete	Box beam or girders – multiple	5.00	1976	1	...
	1005	B120062BBMUNNBI	Concrete	Arch – deck	—	1950	2	...
	1006	A160203YYDOT634	Steel	Stringer/multibeam or girder	5.70	1962	3	...

[a]CHAR indicates a data type storing characters in a fixed-length field.
[b]Numbers in parentheses specify data length. A single number means no decimal portion.
[c]Two numbers in parentheses also specify data length; the first is the number of integer digits, and the second is for decimal digits.

This subsection describes the procedures for the BrTS Clearinghouse prototype, along with challenges that can be addressed in future research. The current prototype is developed with the ArcGIS Online Application, which offers an interactive mapping interface to query and display crash and structure data and collision risk from the selected states. The development of the current version requires a certain level of manual effort to process the data.

Data Preparation

The first step is to obtain state BrTS crash data. Most states provided datasets to the research team using the given research team's query requirements as previously described (i.e., most/first harmful event and sequence event). Some state systems, like Wisconsin's WisTransportal, provide open access to data. In those cases, the research team used the same queries to obtain the data directly. The research team also queried the NBI, NTI, and railroad bridge datasets for the 14 selected states according to their state code. Geocoded data were transformed into decimal degrees for compatibility with ArcGIS.

Data Linkage

Maine's data were linked by Common ID join, using the common bridge number in the NBI and the crash data. Some bridges were missing from the NBI data. In Wisconsin, even though some bridge numbers were provided, the structure number was typically inconsistent with the structure numbers available in the NBI data; therefore, a spatial join was conducted. Similarly, a spatial join was conducted for the other states, as there was no provision for bridge numbers. The spatial joins produced bridge-hit counts where repetitions of each structure number could be counted.

For states other than Maine, two spatial joins were conducted: one determined how many bridges were within a 100-foot buffer and one determined how many bridges were within a 500-foot buffer around each crash. Considering that NBI does not include most railroad bridges, the team utilized the railroad bridge dataset from the BTS website to flag potential railroad bridge-related crashes when a railroad bridge is the closest bridge within a 500-foot buffer of a given crash. Similarly, as mentioned previously, the buffer of 1,500 feet is set as the threshold for potential tunnel crashes to link with the tunnels because the national average tunnel length in the NTI is 1,300 feet. The location for a tunnel is set at its entrance.

Results and Presentations

The resulting prototype is a web application that aims to establish a national-level data repository for collecting and analyzing BrTS data.

The BrTS Clearinghouse uses a data-driven method to assess BrTS risk. Transportation agencies and motor carriers can use this application to assess, quantify, and communicate the risk of bridge- and tunnel-related crashes. Refer to the subsection "Stagewise Data Clearinghouse Web Interface" for further details on how to view and query data. Notably, the functionalities listed in this guide are not exhaustive. Users can export the retrieved data to a comma-separated values (CSV) file, which is compatible with Microsoft Excel and ArcGIS.

Welcome Page. Figure 11 shows the welcome page of the prototype tool. The welcome page provides links for the project information, the BrTS Clearinghouse, and the option to request data. This page also contains two links:

- "National Data Clearinghouse for Bridge and Tunnel Strikes (BrTS)" directs users to the project website that contains project information such as a general overview of the data clearinghouse, detailed information about the project, a user guide, and the option to request data.

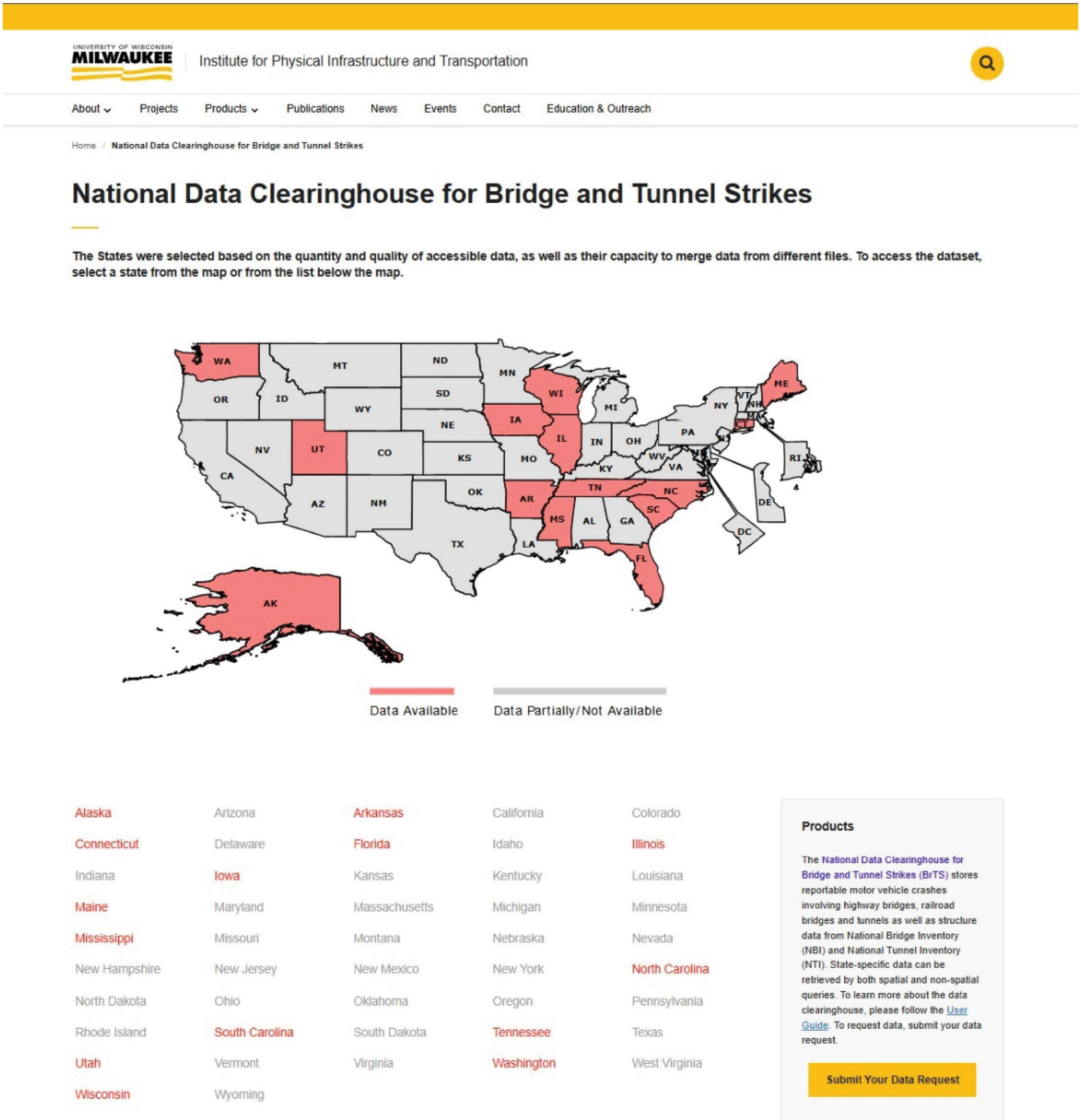

Figure 11. Welcome page example.

- "Submit Your Data Request" directs users to a data request form. The BrTS Clearinghouse stores data in an ArcGIS geodatabase where some data forms and fields may be modified or omitted from the original data due to the constraint of the geodatabase. For original data, users can submit a data request.

The map on the welcome page displays two color codes: red indicates the data are readily available for direct retrieval using the application; gray indicates the data are partially available or unavailable for the state. To access the Clearinghouse, users can select a state from the map or the list of state names located below the map. After selecting a state, a pop-up dashboard will appear, displaying a summary of data for the state. A link to "Retrieve Data" directs users to the Clearinghouse web interface. Figure 12 demonstrates this operation.

Stagewise Data Clearinghouse Web Interface. After selecting "Retrieve Data," the Clearinghouse web interface will appear within a small window that can be enlarged to full screen. The home button is in the upper left corner to navigate to the state. The default view of the web interface displays an empty U.S. map. Users can turn on layers from the "Layer List" in the tool menu on the map to gain a quick visual overview of the data. The key features of the application can be accessed through the Basic Features, Crash Data Query, and Structure Data Query tabs.

Basic Features include the following three functions (illustrated in Figure 13):

- Layer List Feature: provides the layers available for the selected state. It contains crash data and structure data. Refer to the ArcGIS Pro online documentation for more information.
- Search Feature: provides the ability to use an address to locate places on the map.
- Selection Feature: allows users to choose a layer and generate a new layer from the selection. This new layer can be utilized as a relational layer in the spatial filters.

Crash Data Query-related tabs can be found on the left side of the web interface. The tabs include "Query Bridge Crashes" and "Query Tunnel Crashes." Each tab has two subtabs, "Tasks" and "Results." The Tasks tab encompasses all the query-related logic, while the Results tab displays the outcome. If a query is left in its default state for a specific field, the query outcome includes all data items in that field.

Query Bridge Crashes includes the following five criteria (shown in Figure 14):

1. Years: To query crashes for multiple years, use the drop-down menu to select the desired years.
2. Crash Type: To retrieve crashes by type, select one or more from the available options.
3. Crash Injury Severity (scale vary by state): To retrieve crash data by injury severity, select one or more based on the available options. It is important to note that the values for injury severity may vary by state, with some using letters (A, B, C, etc.) and others using numbers (1, 2, 3, etc.).
4. Crash is closer to a highway bridge than a railroad bridge?: The available value options are "All," "No," and "Yes." In a data table, the field name used for this value is "DSCSRL." A value of 1 is Yes, 0 is No, and a null or blank value is "Not Applicable."
5. Crash is within 500 ft of a highway bridge?: The available value options are "All," "No," and "Yes." In a data table, the field name used for this value is "DSLES500." A value of 1 in this field is Yes, 0 is No, and a null or blank value is "Not Applicable."

An alternative to querying bridge crashes is to apply spatial filters. For this operation, users have two options for types of spatial filters (shown in Figure 15 and Figure 16):

1. Only return features that have a spatial relationship with features in another layer: The query results are determined based on the spatial relationship between the features in the query layer and those in the related layer. Additionally, a search distance can be applied to the geometry of the features in the related layer if desired. It is also possible to utilize the result layer of a previous query.
2. Only return features that intersect with the shape drawn on the map: A set of drawing tools is available that allows users to draw shapes on the map to define a specific area of interest.

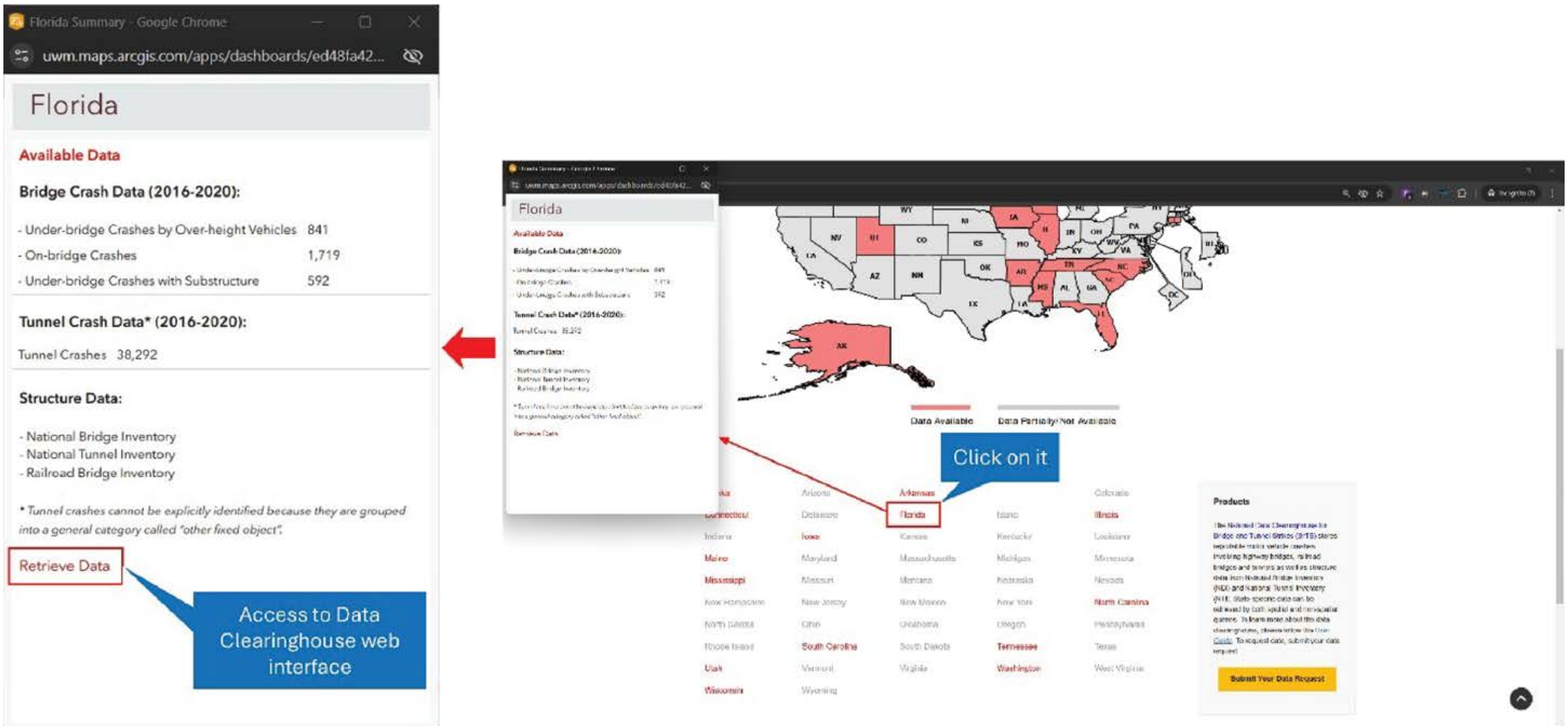

Figure 12. State list demonstration.

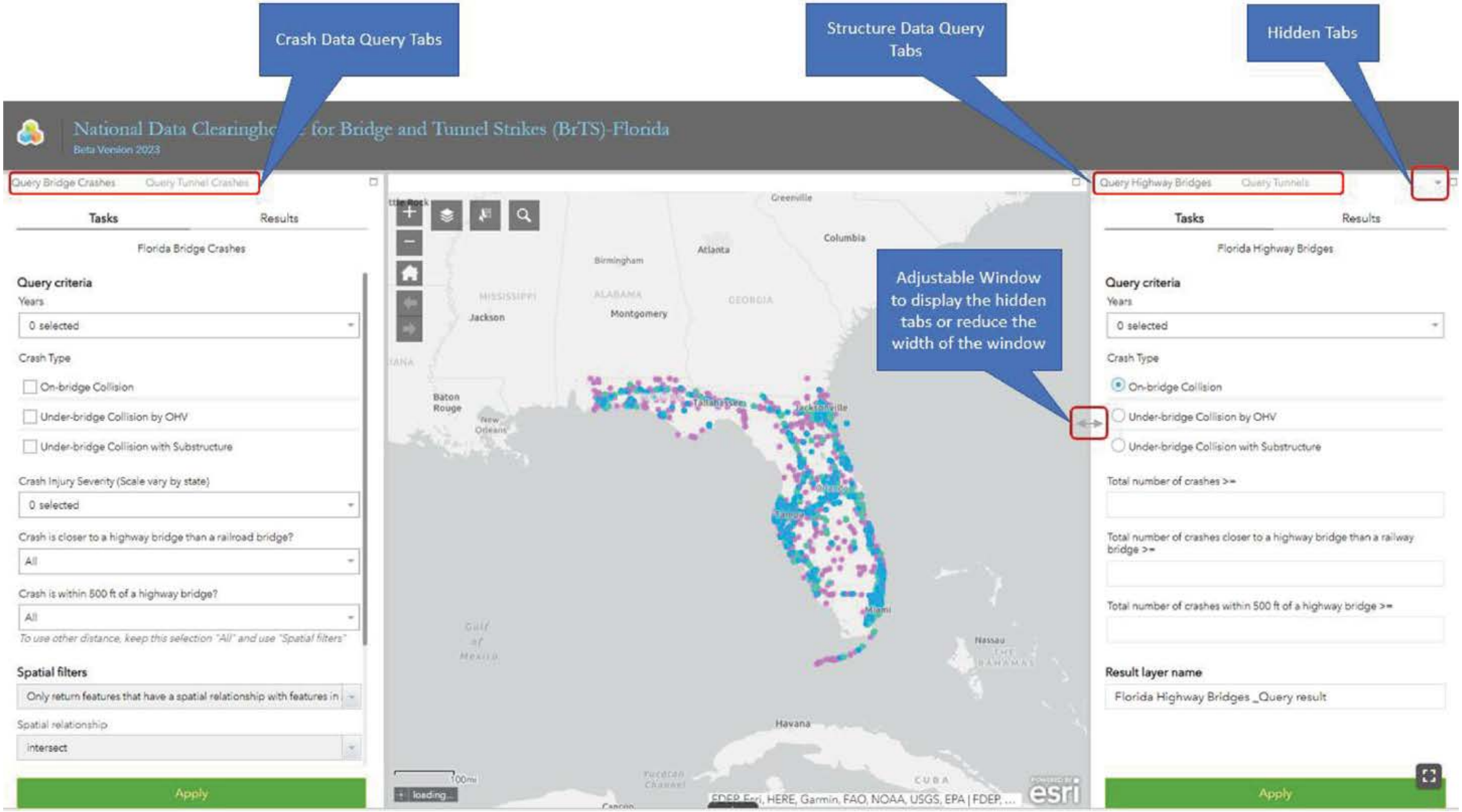

Figure 13. Basic features.

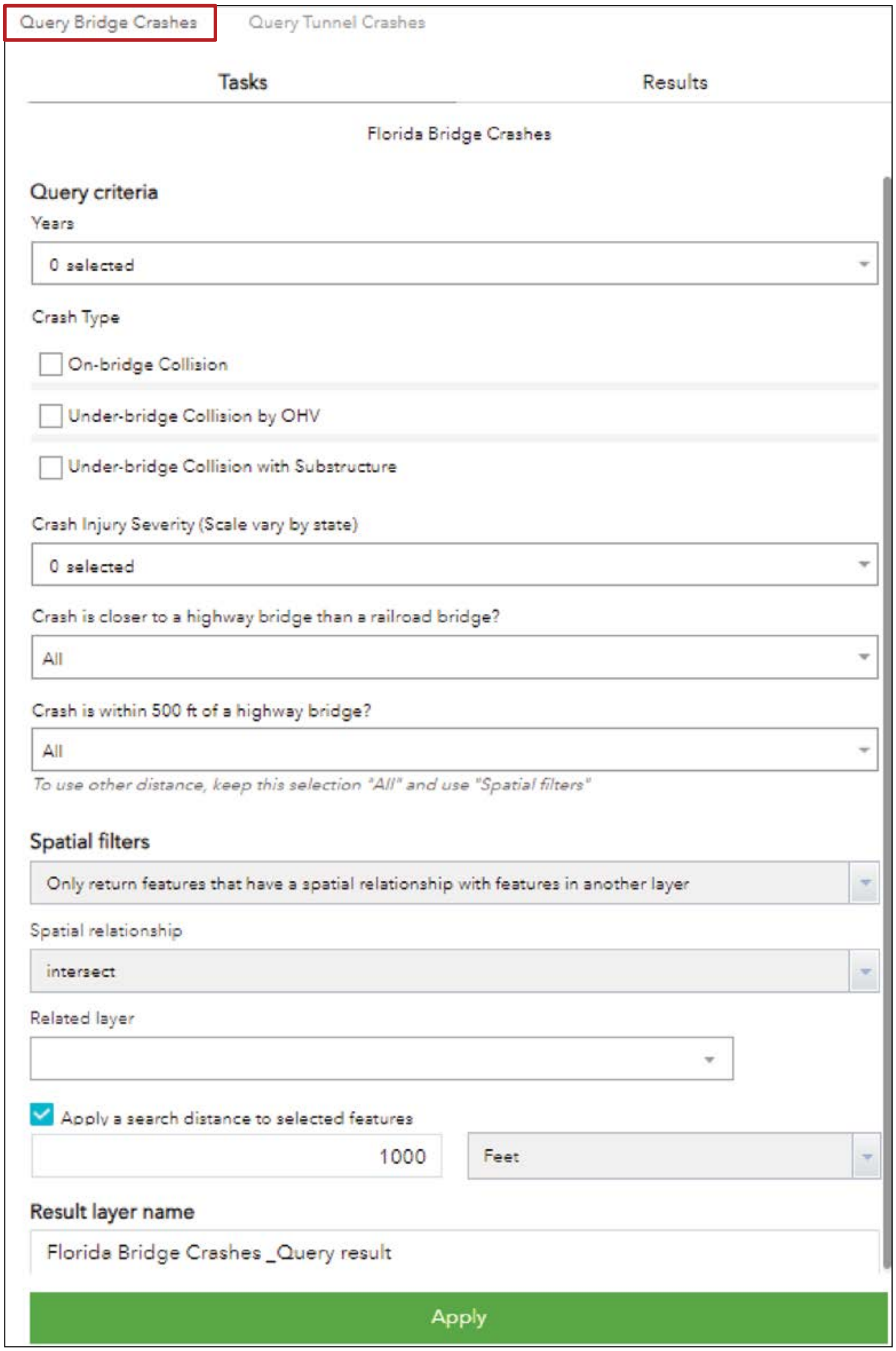

Figure 14. Query bridge crashes tab.

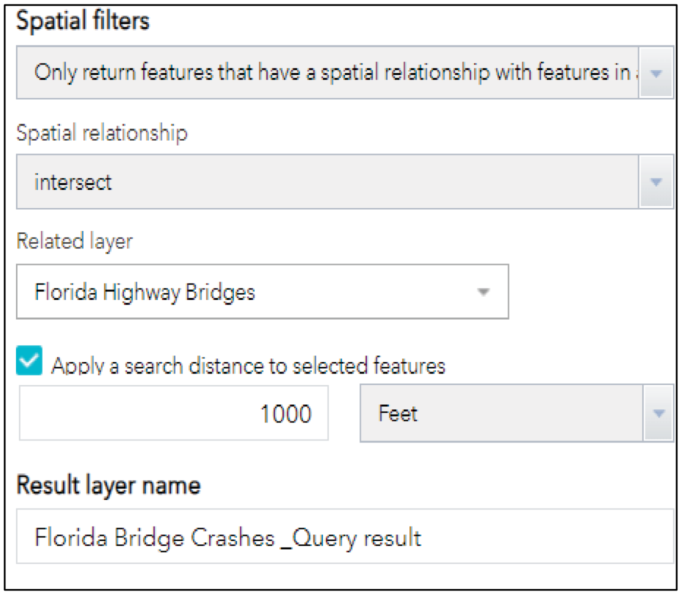

Figure 15. Spatial filters: Only return features that have a spatial relationship with features in another layer.

Query Tunnel Crashes includes the following two criteria (shown in Figure 17):

1. Years: To query crashes for multiple years, use the drop-down menu to select the desired years.
2. Crash is within 1,500 ft of a Tunnel?: The available value options are "All," "No," and "Yes." In a data table, the field name used for this value is "CRS1500FT." A value of 1 in this field is Yes, 0 is No, and a null or blank value is "Not Applicable."

The same spatial filters described above for bridge crash queries can also be used for querying the tunnel crashes.

Structure Data Query-related tabs can be found on the right side of the web interface. The tabs are "Query Highway Bridge," "Query Tunnels," and "Query Railway Bridges." Each of these tabs contains two subtabs: "Tasks" and "Results." The Tasks tab includes all the query-related

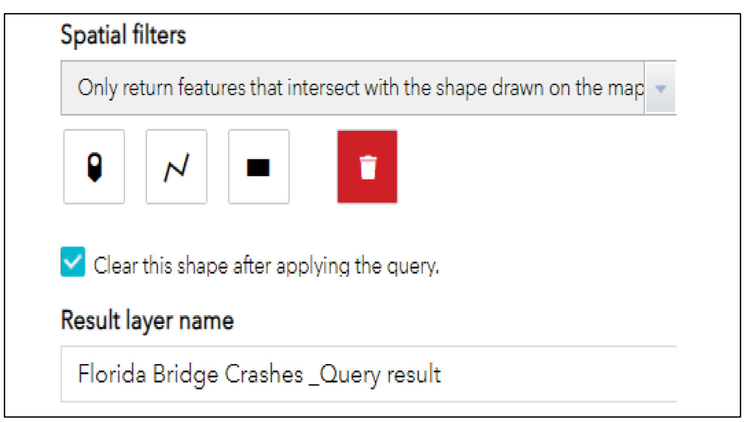

Figure 16. Spatial filters: Only return features that intersect with the shape drawn on the map.

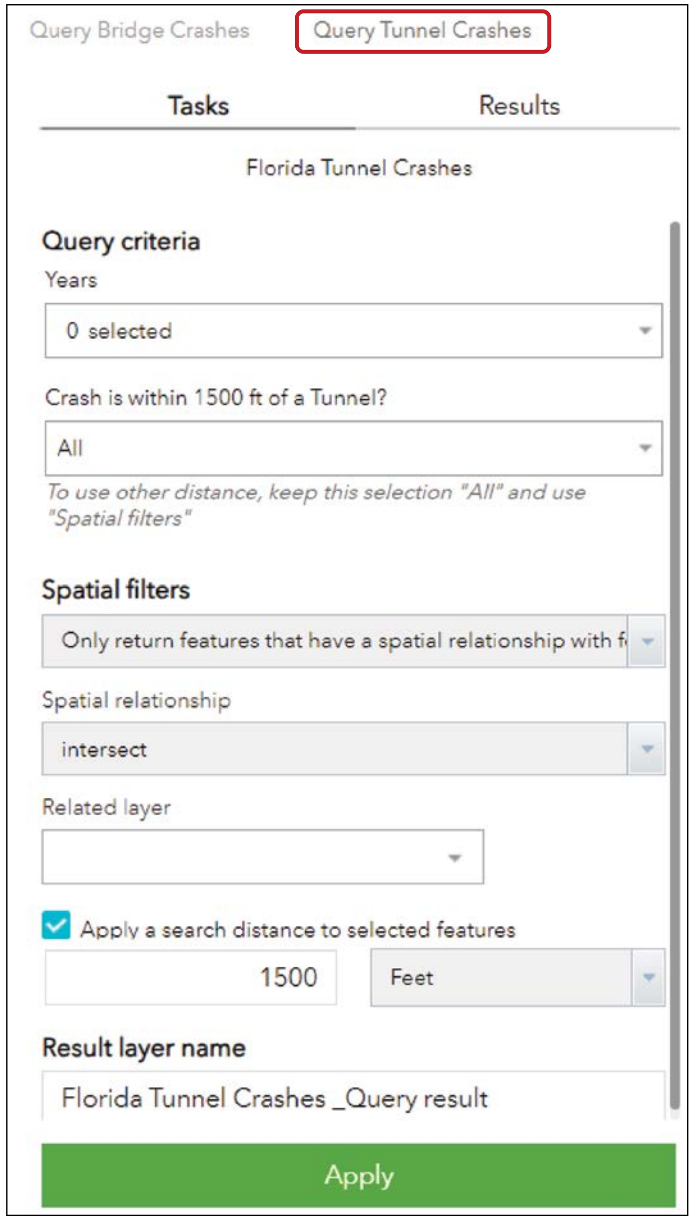

Figure 17. Query tunnel crashes tab.

logic, while the Results tab displays the query result. If a query is left unchanged for a particular field, the query result includes all records for that field.

Query Highway Bridges includes the following six criteria (shown in Figure 18):

1. Years: To query crashes for multiple years, use the drop-down menu to select the desired years.
2. Crash Type: To query crashes by type, select one or more from the available options.
3. Total number of crashes ≥: Display the highway bridges that have a crash count equal to or greater than the integer value entered. In a data table, the field name used for this value is "SUM_DSALL."
4. Total number of crashes closer to a highway bridge than a railway bridge ≥: Display the highway bridges that have a crash count equal to or greater than the integer value entered and where crashes are closer to a highway bridge than any nearby railway bridge. In a data table, the field name used for this value is "SUM_DSCSRL."

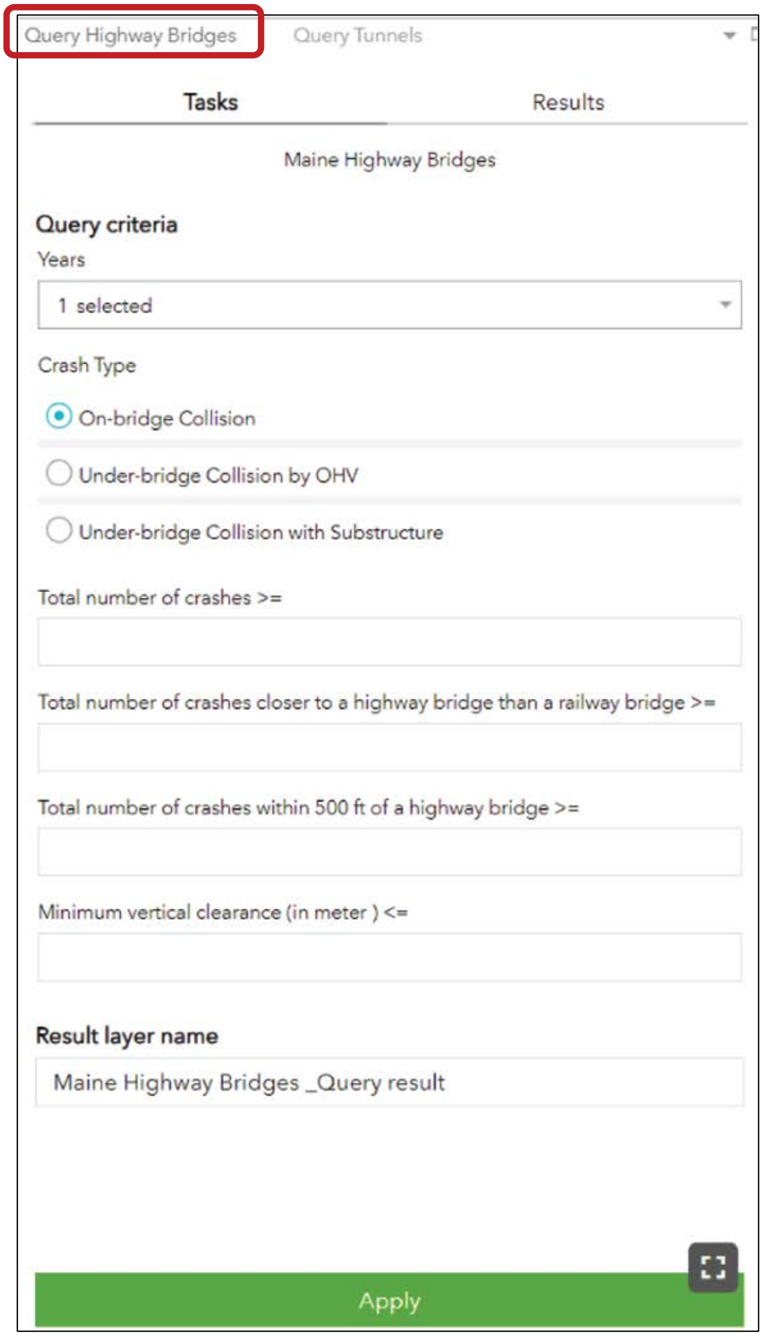

Figure 18. Query highway bridges tab.

5. Total number of crashes within 500 ft of a highway bridge ≥: Display the highway bridges that have a crash count equal to or greater than the integer value entered within a 500 ft radius of the bridge. In a data table, the field name used for this value is "SUM_DSLES500."
6. Minimum vertical clearance (in meter) ≤: Display the highway bridges with a minimum vertical clearance equal to or less than the integer value entered. In a data table, the field name used for this value is "MIN_VERT_CLR_010."

Additionally, after applying the user-specific query, the results will be displayed and symbolized with the associated "risk score" as shown in Figure 19. As described in the earlier Section 2.3, "Applying Risk Factors to Prioritize Locations," agencies can assess BrTS risk through various

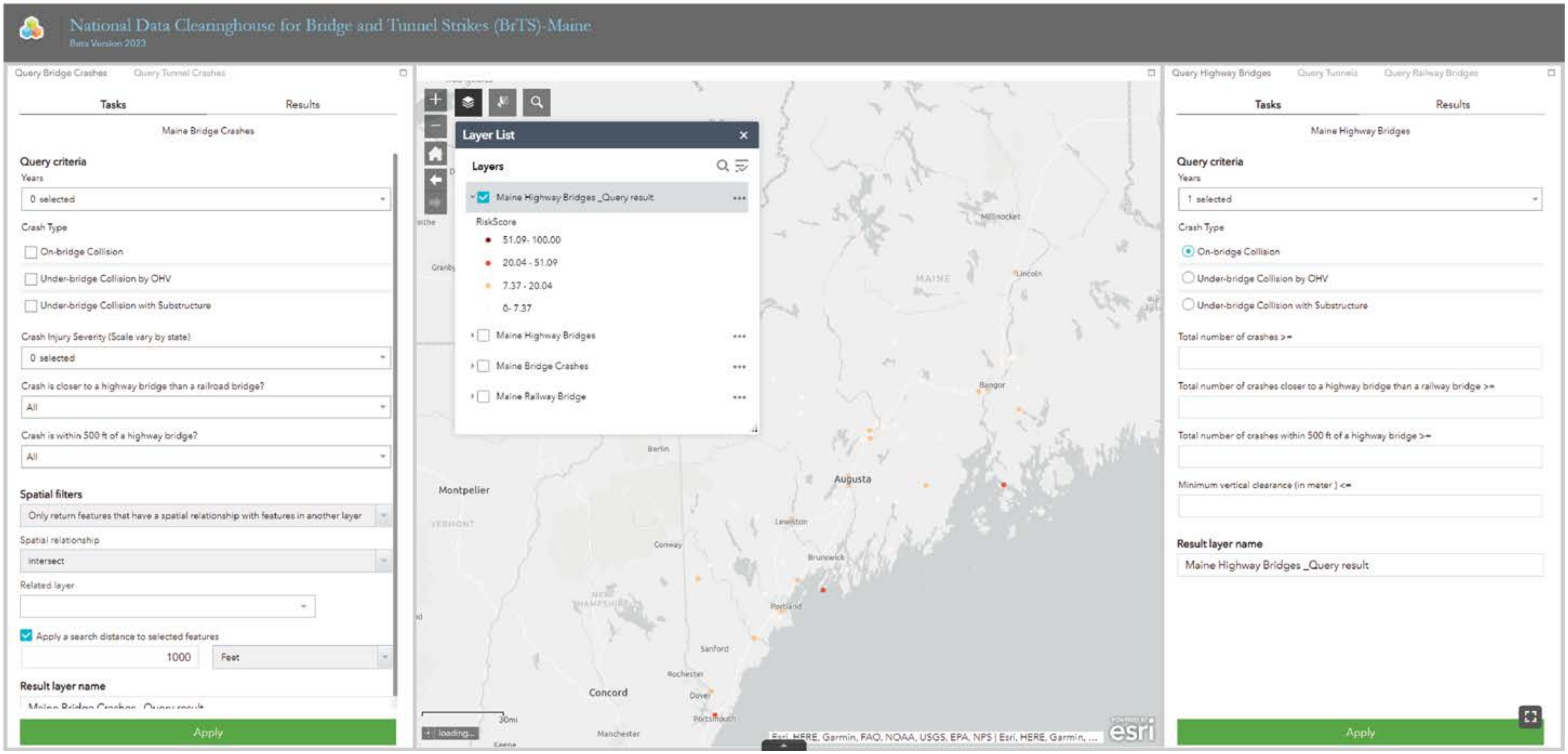

Figure 19. BrTS risk score (for Maine).

methods. The risk score is a numeric value indicating the relative risk for each bridge or tunnel based on location-specific characteristics. The risk score supports a proactive approach to identifying and mitigating high-risk locations. Currently, the risk score is only available for the state of Maine. For all other states, the risk score fields contain placeholder values. In this case, the risk score is calculated and normalized for each bridge on a scale of 0 to 100 using the following process:

1. Predicted crashes by severity = (predicted crashes) * (predicted % of KABCO injury severities).
2. Cost = $\sum$(comprehensive crash cost by severity * predicted crashes by severity).
3. Standardized risk score = 100 * (Total cost – Total cost_{min})/(Total cost_{max} – Total cost_{min}).
4. For display purposes, the Jenks Natural Breaks classification method is applied. The Jenks Natural Breaks method, also known as Jenks Optimization or the goodness of variance fit (GVF), is a data-classification technique for creating choropleth maps by identifying significant data breaks. It excels with multimodal datasets and those with a high variance, for which in our case, the results do show high variance.

The average crash-cost values are based on the recommended national KABCO comprehensive crash unit costs in the FHWA guide, *Crash Costs for Highway Safety Analysis* (Harmon, Bahar, and Gross 2018).

Query Tunnels includes the following two criteria (shown in Figure 20):

1. Years: To query crashes for multiple years, use the drop-down menu to select the desired years.
2. Total number of crashes within 1,500 ft of a Tunnel ≥: Display the tunnels that have a crash count equal to or greater than the integer value entered within a 1,500 ft radius of the tunnel. In a data table, the field name used for this value is "SUM_CRS1500FT."

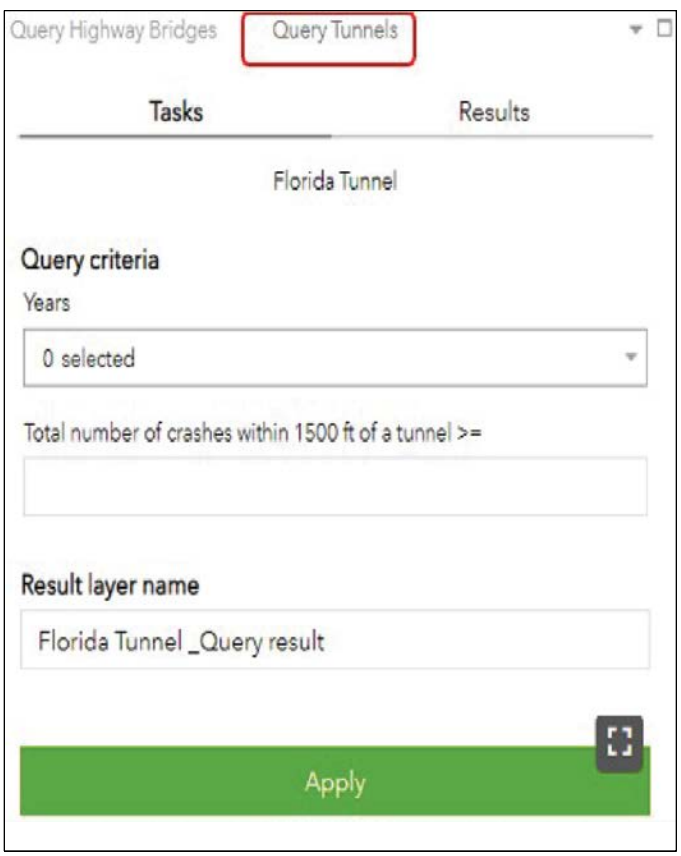

Figure 20. Query tunnels tab.

Query Railway Bridges includes the following five criteria (shown in Figure 21):

1. Years: To query crashes for multiple years, use the drop-down menu to select the desired years.
2. Crash Type: Select one or more from the available options.
3. Total number of crashes ≥: Display the railway bridges that have a crash count equal to or greater than the integer value entered. In a data table, the field name used for this value is "SUM_RLDSALL."
4. Total number of crashes within 500 ft of a railway bridge ≥: Display the railway bridges that have a crash count equal to or greater than the integer value entered within a 500 ft radius of the bridge. In a data table, the field name used for this value is "SUM_RLDSLES500."

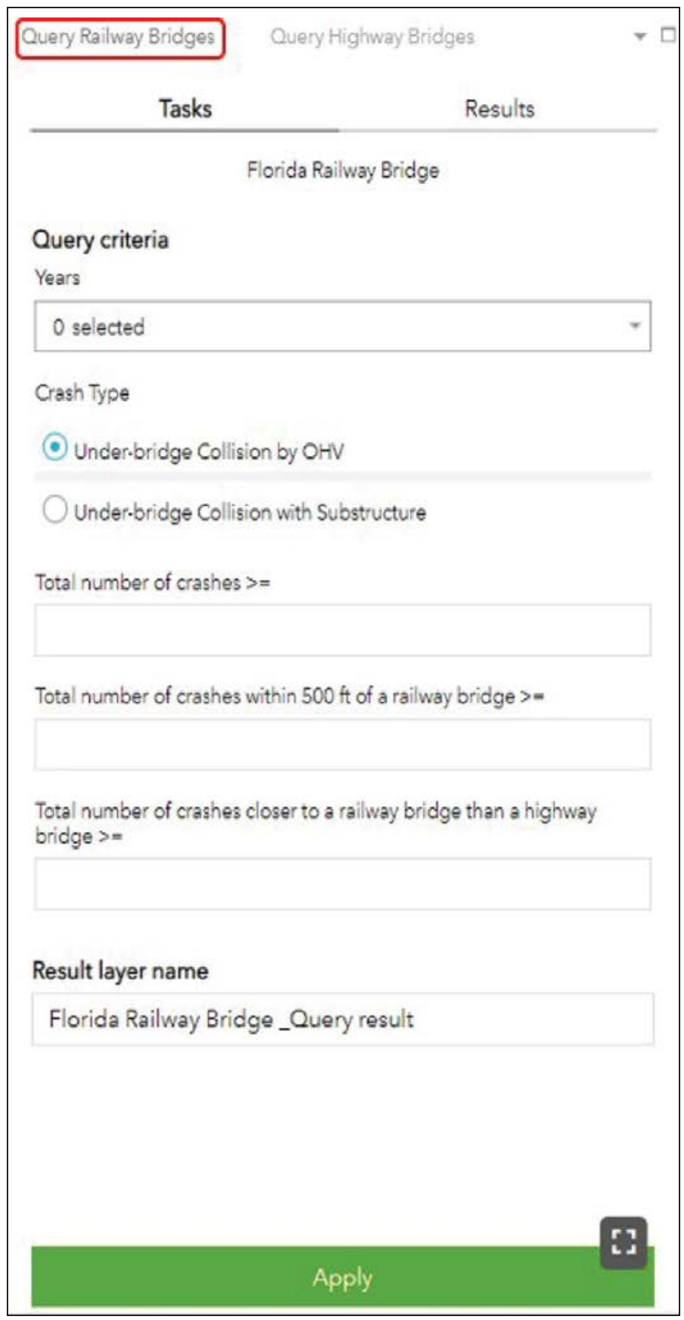

Figure 21. Query railway bridge tab.

5. Total number of crashes closer to a railway bridge than a highway bridge ≥: Display the railway bridges that have a crash count equal to or greater than the integer value entered and where crashes are closer to a railway bridge than any nearby highway bridge. In a data table, the field name used for this value is "SUM_RLDSCSRB."

All of the abovementioned functions allow users to find specific data based on their interests. After applying the queries, use the following steps to access the options for the query results: generate the results by selecting the "Apply" button, then select the "Results" tab. A drop-down window will appear listing various available options. The operation for downloading the data is illustrated in Figure 22. As shown in the figure, one of the options is to download the results in one of three formats.

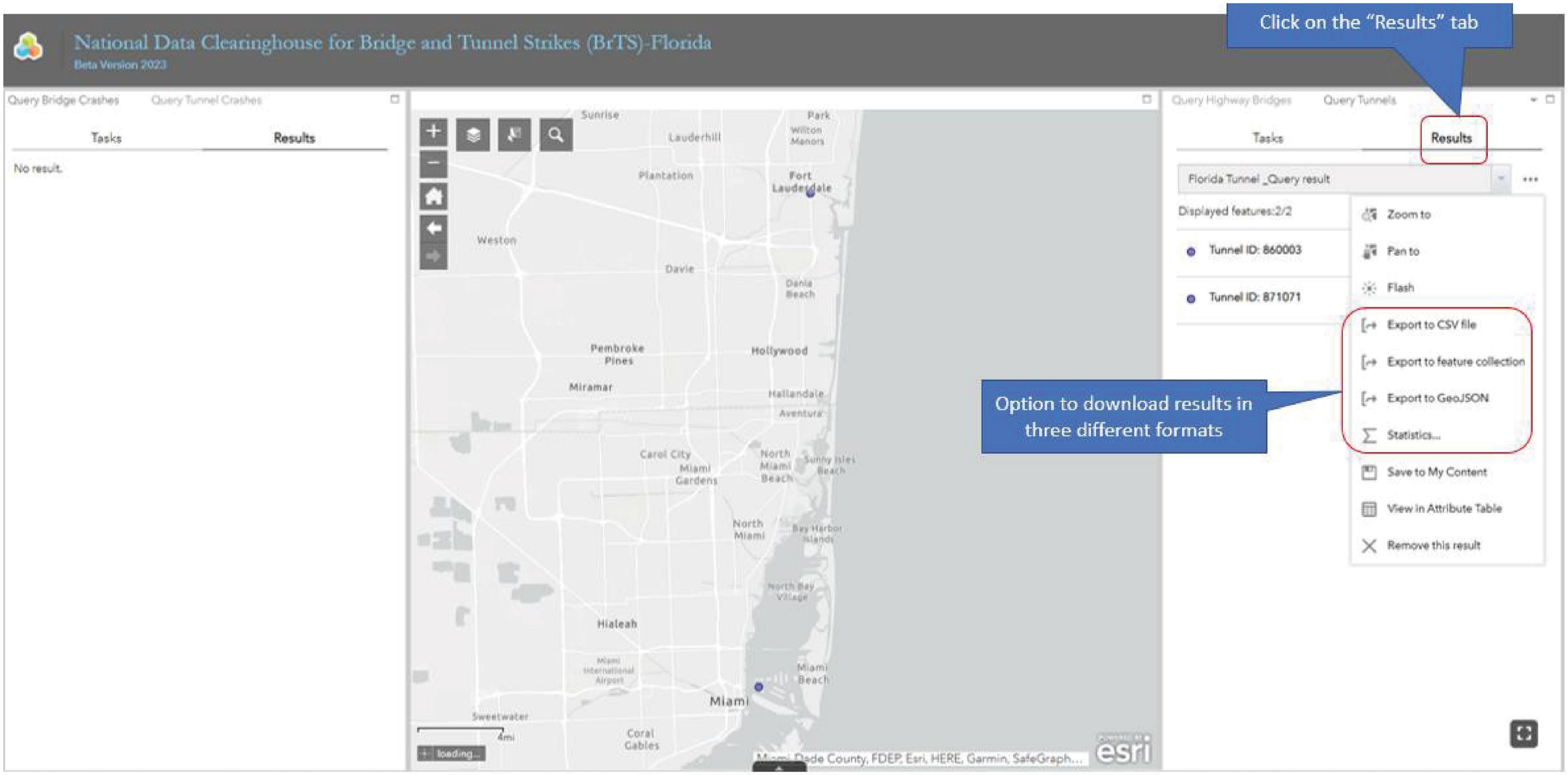

Figure 22. Downloading data from the data clearinghouse with user-specified query.

CHAPTER 3

Bridge and Tunnel Strike Countermeasures

Once an agency identifies factors that contribute to BrTS, the next step is to identify appropriate countermeasures to target the underlying issue or issues. The key to effectively addressing risk is to identify countermeasures that directly target the risk factors at hand to a level that is commensurate with the level of risk at the location of interest. For instance, if a bridge is at high risk of being struck and a bridge strike would have significant impacts on operations, then an agency might consider two options: raising the bridge height during the next bridge replacement or installing turnarounds. The result of this step is a list of potential options, not the final recommendation.

Countermeasure selection starts with a larger list of options that are pared down to the preferred alternatives through more detailed analysis. This chapter focuses on the first part of the process—countermeasure identification. The next chapter focuses on the second part—alternatives analysis. This chapter begins with a discussion of general considerations and a summary of common BrTS risk factors with applicable countermeasures. The remainder of the chapter provides detailed descriptions of individual countermeasures, including cost, effectiveness, service life, and other considerations.

Agencies will benefit from diagnosing BrTS contributing factors before selecting countermeasures. By understanding the crashes and risk factors, agencies can target corrective measures and improve the cost-effectiveness of investments.

Systemic diagnosis involves network-level analysis to identify focus crash-types, focus facility-types, and risk factors (refer to Chapter 2, "Bridge and Tunnel Strike Risk Assessment," for further details).

Site-specific diagnosis involves a review of site-specific crash history, traffic operations, and general site conditions.

3.1 General Countermeasure Considerations

To inform countermeasure selection, agencies would consider the following (Atlanta Regional Commission 2022):

- Safe System principles: Countermeasures that align with Safe System principles are those that minimize the potential for crash frequency and severity, and build in redundancy (e.g., serve as a backup if another system component fails).
- Community context: Agencies should consider the surrounding land use, function of the roadway, and community context when selecting countermeasures. It is also useful to engage with the community to determine their wants and needs. Agencies can use public feedback to guide countermeasure selection and then justify the final selection with data-driven analysis.
- Multiple potential alternatives: It is desirable to identify and develop multiple *potential* countermeasures for comparison. This helps to identify the most effective and efficient option. It may be useful to develop a flow chart or decision matrix to assist practitioners in selecting appropriate countermeasures or mitigation strategies.
- Cost-effectiveness: Ideally, agencies would select a countermeasure that is highly effective at reducing the focus crash-type. Agencies should also consider construction and maintenance costs because more effective countermeasures (e.g., increasing clearance heights and widths) are often associated with higher costs.

- Service life: The *Highway Safety Manual* defines countermeasure service life as "the number of years in which the countermeasure is expected to have a noticeable and quantifiable effect on the crash occurrence at the site" (HSM 2010). Service life is used in benefit-cost analysis to convert annual costs and benefits to present values or vice versa. Understanding the countermeasure service life helps to account for the time value of costs and benefits, particularly when the analysis period is different from the service life or when the service life differs among alternatives.

3.2 Matching Countermeasures to BrTS Risk Factors

This section presents a summary of common BrTS risk factors with applicable countermeasures. The list of countermeasures and strategies includes bridge and tunnel design features, roadway design and operational characteristics, agency policies, oversize-vehicle routing systems, routing compliance for oversize loads, pilot car/escort vehicle guidance, and roadside and onboard vehicle technologies among others identified in the literature review.

Table 11 provides a summary of common BrTS risk factors and applicable countermeasures for on-bridge crashes. Table 12 provides a summary of common BrTS risk factors and applicable countermeasures for under-bridge or tunnel crashes.

3.3 Countermeasure Summaries

This section introduces six general categories of countermeasures: (1) passive systems, (2) sacrificial systems, (3) active systems, (4) vehicle-based systems, (5) nonphysical countermeasures, and (6) other tried strategies. Each countermeasure is then described in detail, including

Table 11. BrTS risk factors and applicable countermeasures for on-bridge crashes.

On-Bridge Countermeasure	High Traffic Volumes[a]	Narrow Bridge Width[b]	Bridge or Approach on Horizontal Curve	Bridge Length[c]
Advance warning signs and markings	—	✓	✓	✓
Horizontal alignment warning signs	—	—	✓	—
Changeable message signs (CMS)	—	✓	—	—
Flashing signs or beacons	—	✓	—	✓
Enhanced lateral clearance	✓	✓	✓	✓
Enhanced bridge and underpass lighting	✓	✓	✓	✓
High-friction surface treatment	✓	—	✓	—
Route surveys	✓	✓	✓	—
Pilot car/escort vehicle policies	✓	✓	✓	✓

Note: — = Not a risk factor or not applicable.
Suggested thresholds (Hans, Bektas, and Phares 2016):
[a]Traffic volume > 400 vehicles/day (paved roads) or > 50 vehicles/day (unpaved roads).
[b]Bridge width narrower than approach roadway (paved roads) or narrower than 20 ft (unpaved roads).
[c]Bridge length > 150 ft (paved roads) or > 35 ft (unpaved roads).

Table 12. BrTS risk factors and applicable countermeasures for under-bridge or tunnel crashes.

Under-Bridge or Tunnel Countermeasure	High Traffic Volumes[a]	High Heavy-Vehicle Volumes	Narrow Shoulder Width	Horizontal Curvature Present	Low Clearance Height[b]	Narrow Tunnel Width	Abrupt Light Changes at Entrance/Exit
Advance warning signs and markings	—	✓	✓	✓	✓	✓	—
Horizontal alignment warning signs	—	✓	—	✓	—	—	—
Changeable message signs (CMS)	—	✓	—	—	✓	—	—
Flashing signs/beacons	—	✓	✓	✓	✓	✓	—
Bridge and tunnel fascia treatments	—	✓	—	—	✓	—	—
Hanging chains, strips, bells, or bars	—	✓	—	—	✓	—	—
Enhanced lateral clearance	✓	✓	✓	✓	—	✓	—
Enhanced tunnel lighting	✓	✓	✓	✓	✓	✓	✓
Enhanced bridge and underpass lighting	✓	✓	✓	✓	✓	—	✓
Transverse rumble strips	—	—	—	—	✓	—	—
Crash beams and portal frames	✓	✓	—	—	✓	—	—
Routing systems	—	—	—	—	✓	—	—
Early warning detection systems	—	—	—	—	✓	—	—
In-cab technology	—	—	—	—	✓	—	—
Connected vehicle technologies	—	—	—	✓	✓	✓	—
Subscription service	✓	—	—	✓	✓	✓	—
OHV and axle load restrictions	✓	✓	—	—	✓	—	—
OHV permits	✓	✓	—	—	✓	—	—
Vehicle checklists	—	—	—	—	✓	—	—
In-cab height placard	—	—	—	—	✓	—	—
Route surveys	✓	✓	✓	✓	✓	✓	—

(continued on next page)

Table 12. (Continued).

Under-Bridge or Tunnel Countermeasure	High Traffic Volumes[a]	High Heavy-Vehicle Volumes	Narrow Shoulder Width	Horizontal Curvature Present	Low Clearance Height[b]	Narrow Tunnel Width	Abrupt Light Changes at Entrance/Exit
Pilot car/escort vehicle policies	—	—	✓	—	✓	✓	—
Route atlas	—	—	—	—	✓	—	—
Commercial GPS policies	—	—	—	—	✓	—	—
Training and CDL certification	✓	✓	—	—	✓	—	—
Post-training/certification driver education and outreach programs	✓	✓	—	—	✓	—	—

Note: — = Not a risk factor or not applicable; CDL = commercial driving license.
Suggested thresholds (Hans, Bektas, and Phares 2016):
[a]Traffic volume > 400 vehicles/day (paved roads) or > 50 vehicles/day (unpaved roads).
[b]Clearance below bridges on freeways is typically 16 feet, 4 inches, and for overhead mounted signs it is 17 feet, 4 inches.
Low-clearance bridges and tunnels are defined here as having a vertical clearance of 14.5 feet or less at the lowest point.

the approximate cost, effectiveness, service life, and other considerations, such as where to use them and, where applicable, potential enhancements. The section concludes with a discussion of data quality improvements that can support a wide range of decisions, including the identification of high-priority locations, diagnosis of risk and crash contributing factors, selection of appropriate countermeasures, and evaluation of past investments.

Passive Systems: The purpose of these countermeasures is to improve driver awareness of bridge and tunnel restrictions through warning signs and enhanced delineation. Additional passive mitigation measures are provided to reduce crash severity. Height warning signing shows the clearance of the bridge or tunnel; sometimes these signs flash. Signing information is almost always 3 inches less than actual clearance, but this can vary from state to state. Inconsistencies among states may lead to inconsistent driver behaviors (e.g., states that give a larger margin of error may lead to drivers taking more risk in their decision to try to pass under the bridge). There is an opportunity to standardize this practice nationally to improve driver expectancy and behavior, especially when hauling across state lines. The following countermeasures are categorized as passive systems:

- Advance warning signs and markings.
- Horizontal alignment warning signs.
- Changeable message signs (CMS).
- Flashing LEDs within signs.
- Bridge and tunnel fascia treatments.
- Hanging chains, strips, bells, or bars.
- Enhanced lateral clearance.
- Enhanced tunnel lighting.
- Enhanced bridge and underpass lighting.
- Transverse rumble strips.
- High-friction surface treatments (HFST).

Sacrificial Systems: The purpose of these countermeasures is to reduce structural damage to bridges and tunnels through impact-absorbing systems installed on the face of the structure.

This countermeasure is intended to reduce structural damage if a BrTS incident occurs but often causes significant damage to the colliding OHV. A collision with traditional sacrificial systems may also scatter debris that could injure nearby road users. Sacrificial systems include the following:

- Crash beams and portal frames.
  - Crash beams, installed on the face of a bridge or tunnel structure, are generally comprised of steel plates, I-beams, or a combination of both. This is intended for low-speed roads.
  - Portal frames, installed as a separate structure in front of a bridge or tunnel structure, are generally composed of steel plates, I-beams, or a combination of both. This is intended for low-speed roads.
- Energy-dissipative system.
  - This system combines a box beam with energy-absorbing materials (e.g., aluminum honeycomb) for the protection of bridge girders from overheight impacts.

Active Systems: The purpose of these countermeasures is to improve driver awareness of bridges and tunnels through detection- or location-based warning systems. These include the following:

- Routing systems.
- Early warning detection systems.
  - Height detection systems: OHV detection (OHVD) systems have many ways of telling if a vehicle is too tall, such as LADAR (LAser Detection And Ranging) technology or a breaker beam setup. These detection systems work in conjunction with flashing signing typically to warn the driver.
- Smart Roadside commercial motor vehicle monitoring.
- License plate camera recognition system.
- Structure monitoring systems.

Vehicle-Based Systems: The purpose of these countermeasures is to improve driver awareness of bridge and tunnel restrictions through technology. The following is a list of vehicle-based systems.

- In-cab technology [e.g., CB (citizen band) radio warning systems].
- Connected vehicle technologies: Uses signal towers placed throughout the highway and provides individual trucks with real-time updates from transportation managers. This system lets drivers know about upcoming weather, hazardous conditions, road work, and other issues.
- Subscription service: Allows trucking managers to put in safety zones that warn the driver of obstacles or warnings. This system also detects driver speed and location for management information.
- Raised dump body light-and-sound warning system.
- Truck-mounted systems to monitor vehicle load.

Nonphysical Countermeasures: The purpose of these countermeasures is to improve driver awareness of bridges and tunnels through institutional policies, permitting procedures, outreach, and driver education programs.

- OHV and axle load restrictions: A restricted (R-posted) bridge does not have the reserve capacity to accommodate vehicles over the legal weight but can still safely carry legal weights. These bridges are identified with signing stating, “No Trucks with R Permits.”
- OHV permits: A permit authorizes the movement of an oversize and/or overweight vehicle for a specific time on permissible hauling days. Applications are required, and the permit will identify restrictions and an approved route.

- Vehicle checklists: Checklists should include measuring the height and width of trucks as well as engine and cab inspection. Checklists increase the driver's awareness of the vehicle constraints, reducing incidents.
- In-cab height placard: Adjustable placards show the height of the truck (including cargo) in the cab for reference while driving in the event that a low-clearance sign is present. Drivers should compare the signing to the placard to ensure the truck can make it under.
- Route surveys: Advance drive-throughs of the route in question are taken using a pole or other measuring stick to identify any particular issues on the route. This is typically done by the carrier to confirm specific types of loads that may be repetitive or by an escort vehicle company trained to recognize potential infrastructure and navigational issues in conjunction with intended load specifications.
- Pilot car/escort vehicle policies.
- Road atlas: All low-clearance bridges on any highway or local road are displayed for drivers to reference. Drivers should be using this in conjunction with other navigation software.
- Commercial navigation system policies: Unlike typical navigational tools, specific applications for the trucking industry include routing that addresses vertical and horizontal clearances.
- Training and commercial driver's license (CDL) certification: Training ensures a truck driver is knowledgeable about driving larger vehicles and informs them of dangers that come with the career. The certification is mandatory for all commercial trucking.
- Post-training/certification driver education and outreach programs: These programs provide material to insurance companies, industry organizations, motor carriers, and drivers with license renewals.

Data Quality Improvements: Improving the reliability and accessibility of data promotes informed decisions, including the OHV permitting process. For instance, there is a need to accurately describe the load size; the permitting process will not provide an optimal route without an accurate load size. There is also a need for agencies to maintain complete and up-to-date inventory data for structure size and roadway conditions (e.g., a 3-inch overlay causes a 3-inch reduction in vertical clearance). Finally, there is a need for accessible data; some states do not provide this readily. There is an opportunity to leverage the use of burgeoning data exchanges to share and broadcast updated information, including information on the location of work zones and related restrictions.

Passive Systems

The purpose of these countermeasures is to improve driver awareness of the presence and characteristics of bridges and tunnels through warning signs and enhanced delineation. Additional passive mitigation measures can reduce crash severity. The following countermeasures are categorized as passive systems:

1. Advance warning signs and markings.
2. Horizontal alignment warning signs.
3. Changeable message signs (CMS).
4. Flashing signs/beacons.
5. Bridge and tunnel fascia treatments.
6. Hanging chains, strips, bells, or bars.
7. Enhanced lateral clearance.
8. Enhanced tunnel lighting.
9. Enhanced bridge and underpass lighting.
10. Transverse rumble strips.
11. High-friction surface treatments (HFST).

Figure 23. Low-clearance advance warning sign. (Source: VHB)

Advance Warning Signs and Markings

Description

Low-clearance advance warning signs (W12-2) are required for "vertical clearances less than 14 feet 6 inches, or vertical clearances less than 12 inches above the statutory maximum vehicle height, whichever is greater" (MUTCD 2023). When required, clearance height shall be posted in advance of the structure. In addition, a low-clearance overhead sign (W12-2a or W12-2b) may be installed on the structure to supplement the advance warning sign (Figure 23 and Figure 24). Advance warning signs may include low-clearance warnings, specific clearance heights, and other relevant information to warn drivers of an upcoming low-clearance or narrow bridge or tunnel structure. Advance signing could also include directional components (e.g., truck detour or exit) to guide OHVs to another roadway.

Where to Use

Consider advance warning signs for use on all bridge and tunnel approaches based on engineering judgment, even when not required or recommended by the *Manual on Uniform Traffic Control Devices* (MUTCD). Advance warning signs should be located at a sufficient distance before the bridge to allow drivers to detour, turn around, or stop. Refer to Section 2C.25 of the

Figure 24. Miscellaneous warning and weather-related signs (Source: MUTCD 2023, Figure 2C-6).

MUTCD for specific provisions (MUTCD 2023). Illumination and reflectivity are critical to ensure nighttime visibility.

Agencies should consider the following factors when assessing the potential use of advance warning signs.

- Clearance height at structure: Height measurements should be reviewed any time pavement thickness changes below the structure. Rutting or other pavement deformations should also be investigated, as vertical deflections may encroach on provided vertical clearances. The MUTCD requires low-clearance signs "to warn road users of vertical clearances less than 14 feet 6 inches, or vertical clearances less than 12 inches above the statutory maximum vehicle height, whichever is greater" (MUTCD 2023).
- Alternate routes: If heavy vehicles are not accommodated by the structure height, consider alternate route signing upstream of the last exit point before the structure. Additional regulatory signs such as "NO COMMERCIAL VEHICLES" or "NO TRUCKS" may be needed at upstream entry points to prohibit large vehicles from using the road.

Safety Effectiveness

Passive signing is estimated to be 10% to 20% effective in reducing BrTS incidents (Cawley 2002).

Enhancements

Agencies can consider the following enhancements to advance warning signs and markings:

- Flashing beacons.
- Doubled-up (i.e., signs on both sides of the road) or oversize signs.
- Repeating warning signs on the approach to the structure.
- In-lane retroreflective pavement markings such as "LOW BRIDGE" or "NO TRUCKS."
- Transverse rumble strips.
- Hanging chains, strips, bells, or bars in conjunction with low-clearance warning signs located on entry ramps upstream of the structure.
- Pull-over areas directly upstream of the structure to allow OHVs to safely stop and wait for rerouting instructions or a police escort.
- Alternate route signing installed at entrance ramps or similar upstream of the structure.

Another opportunity is to explore the effectiveness and comprehension of traditional warning signs, particularly for non-English speaking drivers. The concern is that non-English speaking drivers may not understand low-clearance warning signs. This is a specific concern for areas near ports and international borders and in jurisdictions where multiple languages are common. Future research could explore driver comprehension of different warning signs such as signs that indicate the specific height restriction (e.g., 11′-6″) versus "LOW BRIDGE" or "NO TRUCKS." The research could also explore the effectiveness of providing supplemental signs with multiple languages or units of measure (metric). Note the current MUTCD does not have provisions for the use of multilingual signs (MUTCD 2023); research in this area would support future rulemaking on MUTCD updates.

Costs and Service Life

Static signs and markings are relatively low cost and can typically be installed using maintenance resources. FHWA's *Countermeasure Service Life Guide* estimates a service life of 15 years for new sign installations (Himes et al. 2021). The Vermont Agency of Transportation (VTrans) notes that "agencies should monitor the retroreflectivity of the signs. Regular washing is recommended to maintain reflectiveness" (VTrans 2023).

Static signs are relatively low cost, starting around $500 per sign.

More Information

The relevant provisions are contained in Section 2C.25 of the 11th edition of the MUTCD (https://mutcd.fhwa.dot.gov/pdfs/11th_Edition/Chapter2c.pdf) (MUTCD 2023).

Horizontal Alignment Warning Signs

Description

Advance horizontal alignment "warning signs warn drivers that the horizontal road alignment is changing ahead, which may require speed reduction and careful attention. In-curve warning signs (such as chevrons) delineate the outside edge of the road on curves and reinforce the intended path of travel" (MUTCD 2023). Bridges and tunnels with curves on or within the structure or on the approaches may benefit from advance horizontal alignment warning signs.

Where to Use

Agencies can consider multiple advance horizontal alignment warning signs and the chevron alignment signs (W1-8) shown in Figure 25, on any road, bridge, or tunnel where horizontal curves are not readily expected or visible for drivers, or where there is already a history of roadway departure crashes (MUTCD 2023). The MUTCD either recommends or requires devices to indicate a change in horizontal alignment depending on the roadway type and traffic volume. The selection of devices, such as curve warning signs, is based on the speed differential between the advisory speed for the horizontal curve and the posted speed limit, statutory speed limit, or the 85th percentile speed on the approach to the curve (MUTCD 2023). Refer to MUTCD (2023) Table 2C-4B and Table 2C-6 in Section 2C for specific provisions on sign selection and the use of an advisory speed plaque based on the estimated speed differential. Note that consistency in messaging across similar sites is critical for establishing driver expectancy and promoting effective roadway operations (VTrans 2023).

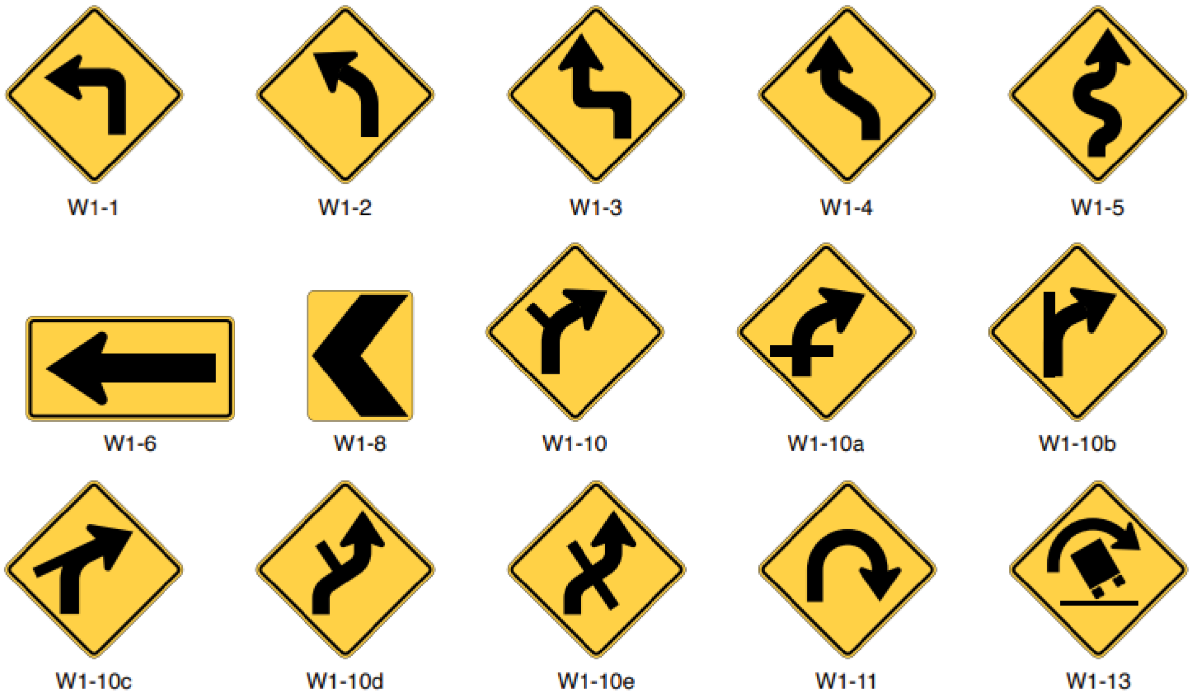

Figure 25. Horizontal alignment signs per the MUTCD (Source: MUTCD 2023, Figure 2C-1).

Safety Effectiveness

Chevrons reduce nighttime crashes on curves by 25% [CMF (Crash Modification Factor) Clearinghouse ID 2438 (Srinivasan et al. 2009a)] and nonintersection fatal and injury crashes by 16% [CMF Clearinghouse ID 2439 (Srinivasan et al. 2009b)].

Enhancements

Agencies can consider the following conspicuity enhancements to horizontal alignment warning signs at bridges and tunnels. VTrans notes these conspicuity enhancements "are intended for implementation with an incremental approach based on local site conditions, funding, and engineering judgment" (VTrans 2023).

- A one-direction large arrow sign (Figure 25, W1-6) may be used either as a supplement or alternative to chevron alignment signs or delineators in order to delineate a change in horizontal alignment.
- For safety improvements on curves with existing warning signs, consider oversize and/or doubled-up (i.e., signs on both sides of the road) advance warning signs. Refer to MUTCD Table 2C-2 for conventional and oversize sign dimensions (MUTCD 2023).
- Retroreflective strips (same color as the sign background color) on signposts can be added to existing or new signs when the desired effect is not achieved.
- Fluorescent yellow reflective sheeting can improve conspicuity, particularly in areas with frequent fog or shadows.
- Flashing beacons can help draw attention to signs but should be used sparingly because drivers may tend to ignore devices that are overused.

Costs and Service Life

FHWA's *Countermeasure Service Life Guide* estimates a service life of 15 years for horizontal alignment warning signs (Himes et al. 2021). VTrans notes that "agencies should monitor the retroreflectivity of the signs and regular washing is recommended to maintain reflectiveness" (VTrans 2023).

Static signs are relatively low cost, starting around $500 per sign.

More Information

"Enhanced Delineation for Horizontal Curves" (FHWA, n.d.-b).

Changeable Message Signs

Description

CMSs—also called variable message signs, digital message signs, matrix signs, or variable message boards—are digital traffic control devices capable of relaying short messages to drivers (Figure 26). They are often installed upstream of low-clearance structures in conjunction with additional warning devices. Low-clearance bridges and tunnels are defined here as having a vertical clearance of 14.5 feet or less at the lowest point.

Where to Use

Consider overhead or roadside CMS installations for low-clearance or narrow bridge and tunnel structures based on engineering judgment. Messaging should follow applicable MUTCD provisions. Agencies can consider the following factors when assessing the potential use of CMS systems:

- Power source: Permanent CMS system installations require power, which may be wired to direct connections or solar powered depending on the manufacturer.
- Flexibility: Unlike static signs, CMS systems can be programmed to display additional information as needed, such as AMBER alerts, emergency Homeland Security messages, transportation-related messages, or other safety-related information.

Figure 26. Examples of CMSs (Source: VHB).

Safety Effectiveness

CMS systems are estimated to be 10% to 20% effective in reducing BrTS incidents.

Enhancements

CMS systems are often used in conjunction with active systems, such as early warning detection systems that estimate the height of approaching vehicles and provide real-time feedback for drivers using CMS or other methods.

Costs and Service Life

FHWA's *Countermeasure Service Life Guide* estimates a typical service life of 10 years for a CMS (Himes et al. 2021).

Costs depend on the power source, mounting type/location, and length of need for underground conduits. As a starting point, CMS installations may cost around $45,000 per sign.

More Information

Manual on Uniform Traffic Control Devices (MUTCD 2023).

Flashing LEDs Within Signs

Description

Flashing LEDs within signs consist of intermittent lights surrounding or embedded in a sign to increase the conspicuity of the sign. These are considered a conspicuity enhancement and may be most beneficial under nighttime operation (Figure 27).

Where to Use

This conspicuity enhancement can be used with any warning signs (e.g., horizontal alignment warnings, low clearance, or narrow structure warnings), particularly under nighttime operations. Illumination and flashing rates should follow MUTCD Chapter 2A provisions (MUTCD 2023). Agencies can consider the following factors when assessing the potential use of flashing signs:

- Power source: Permanent installations require power, which may be wired to direct connections or solar depending on the manufacturer.
- Mounting location: Signs may be mounted overhead or on a roadside post. Flashing LEDs are installed as part of the sign.

Safety Effectiveness

Research is not yet available for applications of flashing signs/beacons as BrTS countermeasures.

Enhancements

None applicable at this time for this system.

Costs and Service Life

FHWA's *Countermeasure Service Life Guide* estimates flashing warning signs have a service life of approximately 10 years (Himes et al. 2021).

Costs depend on the power source, mounting type/location, and length of need for underground conduits. As a starting point, flashing signs may cost around $15,000 per sign.

More Information

Low-Cost Treatments for Horizontal Curve Safety 2016, Chapter 4 (Albin et al. 2016).

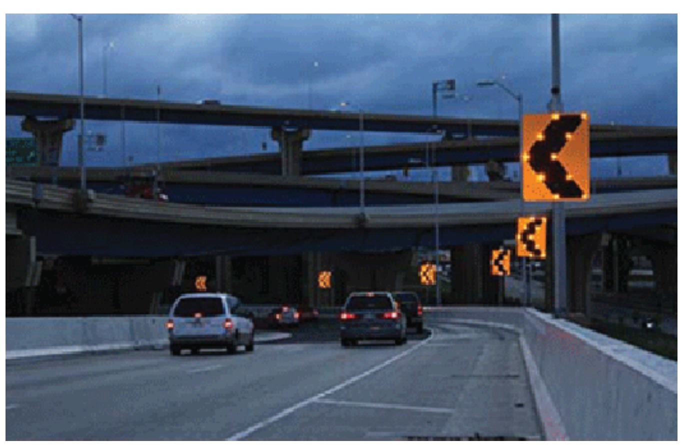

Figure 27. Example of flashing chevron signs on a bridge structure with a horizontal curve (Source: Albin et al. 2016).

Bridge and Tunnel Fascia Treatments

Description

Bridge and tunnel fascia treatments provide high-visibility delineation on the face of the lowest structural elements to visually reinforce low clearances. They are generally continuous installations of retroreflective material across the entire structure (Figure 28). As they are located on the structure itself, they are used as a supplemental countermeasure in conjunction with advance low-clearance warning signs. Bridge and fascia treatments are not a substitute for MUTCD signage.

Where to Use

Consider bridge and tunnel fascia treatments at all such structures based on engineering judgment.

Safety Effectiveness

Research is not yet available for applications of bridge and tunnel fascia treatments as BrTS countermeasures.

Enhancements

Agencies can consider the following enhancements to fascia treatments:

- Advance warning signs, flashing beacons, CMS systems, or other messaging devices; and
- Transverse rumble strips.

Costs and Service Life

Painted fascia treatments are generally low cost at around $20 per linear foot and are expected to have a service life of 20 to 25 years; however, cost and service life will vary depending on materials, humidity, and length of need. Regular maintenance is recommended to maintain reflectivity and visibility.

More Information

"Bridge Strike Mitigation" (NYC 2009).

Figure 28. High-visibility bridge fascia treatment (Source: VHB).

Hanging Chains, Strips, Bells, or Bars

Description

Hanging metal chains, strips, bells, or bars, also known as telltale signs, provide auditory feedback upstream of the bridge or tunnel to warn drivers if their vehicle height exceeds the minimum vertical clearance provided at the structure. These systems consist primarily of an overhead structure with chains, strips, bells, or bars that hang down and terminate at the minimum clearance height for the bridge or tunnel structure downstream (Figure 29). OHVs strike the system and receive loud feedback while the corresponding signing warns them of the likely BrTS collision ahead.

Where to Use

Consider this countermeasure upstream of low-clearance bridge and tunnel structures based on traffic speeds, traffic volumes, OHV BrTS crash history, and engineering judgment. Low-clearance bridges and tunnels are defined here as having a vertical clearance of 14.5 feet or less at the lowest point. Agencies should consider the following factors when assessing the potential use of hanging chains, strips, bells, or bars:

- Traffic speeds: Ambient noise tends to increase as vehicle speeds increase, which in turn diminishes the feedback provided by this countermeasure. Installations perform best when

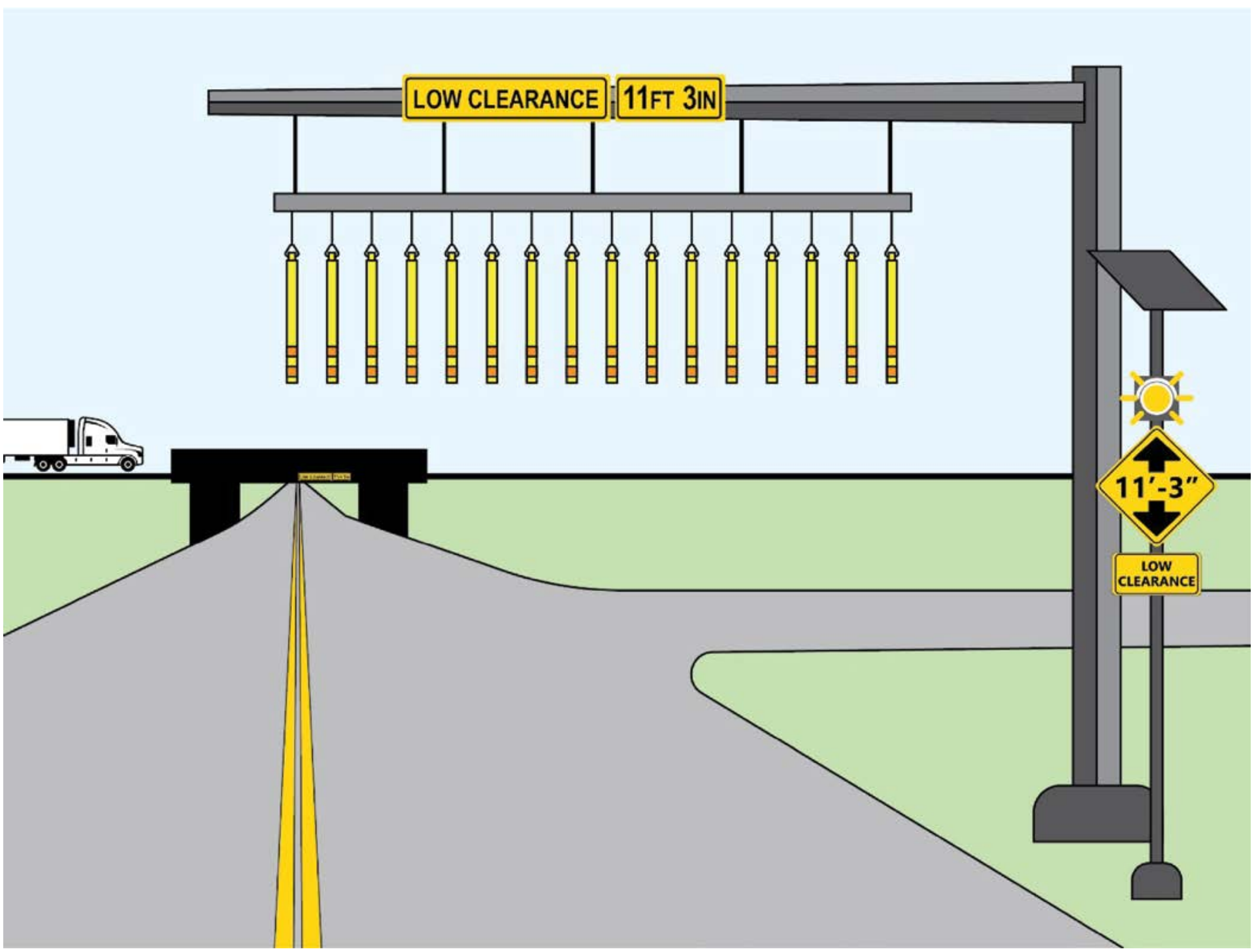

Figure 29. Hanging bar Illustration (Source: VHB).

vehicle speeds are very low (Caltrans 2019). As travel speeds increase, the propensity for damage to vehicles, occupants, and surrounding road users also increases.
- Entrance ramps: One or more upstream entrance ramps may be suitable locations for these installations to alert OHVs far from the structure to provide time to react and give the driver the opportunity to exit the roadway, ideally, while they are traveling at lower speeds than on the approach to the structure.

Safety Effectiveness

Research is not yet available on the safety effectiveness of hanging chains, strips, bells, or bars.

Enhancements

Agencies can consider the following enhancements to hanging chains, strips, bells, and bars:

- Upstream signing is recommended to warn drivers of the upcoming device.
- Downstream signing is recommended to communicate why the vehicle struck the device and to provide route guidance to divert the vehicle away from the low-clearance structure.

Costs and Service Life

Using overhead sign installations as a surrogate, FHWA's *Countermeasure Service Life Guide* estimates a service life of 15 years (Himes et al. 2021). Hanging chains, strips, bells, or bars may be damaged when struck by an OHV. Regular maintenance and timely replacement of broken members are recommended to maximize effectiveness and service life. One project in San Antonio, Texas, cost approximately $55,000 to install a pair of hanging chains with high-visibility PVC pipes at a low-clearance bridge (City of San Antonio 2017).

Enhanced Lateral Clearance

Description

When shoulder width on the approach differs from shoulder width provided at a bridge or tunnel structure, BrTS incidents are more likely to occur. This situation is common, as physical constraints are often more restrictive for the structure than on the approaches (Figure 30). Increasing lateral clearance between the edge of the travel lane and the face of the structure may reduce BrTS incidents.

Figure 30. Bridge with narrow lateral clearance (Source: Albin et al. 2016).

Where to Use

Consider increasing lateral clearance to bridge and tunnel walls/barriers at horizontal curves or locations with a history of roadway departure crashes. Enhanced lateral clearance to walls/barriers can provide recovery space for drivers who leave the travel land and therefore may reduce roadway departures crashes.

Safety Effectiveness

Narrow shoulders and proximity to barriers promote slower speeds but may increase the potential for barrier strikes. Research has shown that bridge width should include at least 3 feet of shoulder on both sides of the road or at least one-half the shoulder widths on approach roadways, whichever is greater. One study estimated the crash rate increases by approximately 60% if the total shoulder width drops from 6 feet (i.e., the desirable minimum) to 3 feet; in contrast, increasing the total shoulder width from 6 feet to 9 feet decreases the estimated crash rate by approximately 42% (Mak 1987).

Enhancements

None applicable at this time for this system.

Costs and Service Life

FHWA's *Countermeasure Service Life Guide* estimates bridge widening has a service life of 30 years (Himes et al. 2021). Costs can vary significantly based on bridge type, estimated increase in bridge width, and site-specific design parameters.

More Information

Mitigation Strategies for Design Exceptions, Chapter 3 (Stein and Neuman 2007).

Enhanced Tunnel Lighting

Description

Crashes near tunnel entrances and exits tend to be more severe than crashes along the interior zones, and abrupt changes in lighting may be a contributing factor. Lighting transitions from light to dark conditions are especially difficult for older drivers as this aspect of vision tends to degrade over time.

Enhanced tunnel lighting targets two components—the roadway and the walls (Figure 31). Tunnel lighting may be improved by implementing zonal lighting and differing daytime and

Figure 31. Tunnel lighting and white tunnel walls in Washington, DC (Source: FHWA 2005).

nighttime lighting plans. Recommendations for roadway and wall lighting for varying tunnel lengths and each region of the tunnel are provided in the *2023 FHWA Lighting Handbook* (Gibbons et al. 2023).

Where to Use

All tunnels may benefit from lighting. This is especially critical where continuous roadway lighting is already provided upstream and/or downstream of the structure, in tunnels with pedestrians or cyclists, or where unusual or difficult geometry exists in the tunnel or on the approaches. Agencies can consider the following factors when assessing the potential to use tunnel lighting.

- Location: Particularly for low-clearance tunnels (a vertical clearance of 14.5 feet or less at the lowest point), lighting should not be installed on the bottom of the lowest structural elements to avoid encroaching on provided vertical clearances.
- Presence of horizontal curves: Horizontal curves require alignment changes, which may lead to roadway departure crashes; improving lighting through curves may reduce these crashes.
- Nighttime crashes: A nighttime lighting study can help determine the adequacy of illumination along the structure and approaches. Consider improving lighting around related signs and other warning features upstream of the structure. The *2023 FHWA Lighting Handbook* contains information regarding appropriate light placement and illumination levels for maximizing visibility of pedestrians, signs, and other vertical obstructions (Gibbons et al. 2023).
- Daytime crashes: A daytime lighting study can help evaluate the ambient light inside the tunnel. According to the *2023 FHWA Lighting Handbook*, daylight extends approximately 25 feet into the tunnel from the entry portal and roughly 50 feet inward from the exit portal (Gibbons et al. 2023). Any remaining tunnel length may warrant illumination, especially if the tunnel is longer than the calculated stopping sight distance for the travel speeds.

Safety Effectiveness

The CMF Clearinghouse does not include quantitative estimates of the safety impacts of improved tunnel lighting.

Enhancements

Agencies can consider the following enhancements to tunnel lighting:

- Headlight requirements for all drivers in the tunnel (both day and night).
- Painting the walls white may enhance tunnel lighting.
- Horizontal bands or patterns of light sources or reflective material installed along tunnel walls may improve visibility of pedestrians or other vertical objects and may also improve delineation of horizontal curves, if present.
- Varying illumination levels, type of lighting, color, or other parameters at different points along the structure may be beneficial depending on tunnel design and length. Refer to the *2023 FHWA Lighting Handbook* for more information on lighting requirements for each zone of a tunnel (Gibbons et al. 2023).

Costs and Service Life

Tunnel lighting should be regularly inspected and maintained to ensure continuous, effective operation. FHWA's *Countermeasure Service Life Guide* estimates lighting installation has a service life of 15 years (Himes et al. 2021).

Costs and service life vary depending on lighting manufacturer, power source, and road closure restrictions. One project in Colorado on US-550 cost roughly $675,000 for tunnel lighting upgrades to LEDs in 2018 (Colorado DOT, n.d.). On the higher end, in the Ted Williams Tunnel in

Boston, Massachusetts, tunnel lighting was upgraded to LEDs in 2019, costing roughly $37 million (Massachusetts DOT 2019).

More Information

The *2023 FHWA Lighting Handbook* provides information for lighting short tunnels (e.g., under 400 ft from portal to portal and where the exit portal is visible at the tunnel entrance), long tunnels, and underpasses (Gibbons et al. 2023).

Enhanced Bridge and Underpass Lighting

Description

Bridge and underpass lighting plays a key role in reducing BrTS incidents. Promoting high visibility throughout the entire structure length and on the approaches can improve driver awareness of the infrastructure constraints and reduce the likelihood of lane departure. Abrupt changes from light to dark at underpasses and overpasses are especially difficult for older drivers as this aspect of vision tends to degrade over time.

Enhanced underpass lighting targets three components—roadway, sidewalks, and walls. Recommendations and additional resources for both general roadway lighting (which applies to over-bridge lighting) and underpass and overpass lighting are provided in the *2023 FHWA Lighting Handbook* (Gibbons et al. 2023). Figure 32 is an example application of adaptive LED bridge lighting with changeable color and lighting levels installed on the Sakonnet River Bridge in Rhode Island.

Where to Use

Lighting for bridges and underpasses is especially critical where continuous roadway lighting is already provided upstream and/or downstream of the structure for structures that also accommodate pedestrians or cyclists or where unusual or difficult geometry exists at the structure or the approaches. Agencies can consider the following factors when assessing the potential to use bridge and underpass lighting.

- Location: Particularly for low-clearance underpasses (a vertical clearance of 14.5 feet or less at the lowest point), lighting should not be installed on the bottom of the lowest structural elements to avoid encroaching on provided vertical clearances. Lighting may have negative ecological impacts, so careful consideration of the surrounding environment is recommended when designing bridge and underpass lighting.
- Presence of horizontal curves: Horizontal curves require alignment changes, which may lead to roadway departure crashes; improving lighting through curves may reduce these crashes.

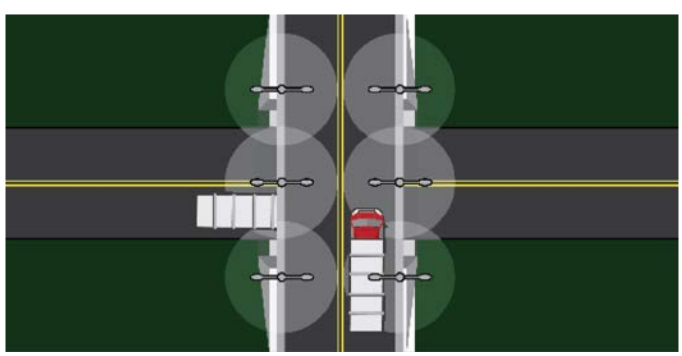

Figure 32. Adaptive bridge lighting in Rhode Island (Source: VHB).

- Nighttime crashes: Consider a nighttime lighting study to determine whether illumination is adequate along the entire structure, underneath the structure, and on all approaches. Consider also improving lighting around bridge-related signs and other warning features upstream of the structure. The *2023 FHWA Lighting Handbook* contains information regarding appropriate light placement and illumination levels for maximizing visibility of pedestrians, signs, and other vertical obstructions (Gibbons et al. 2023).
- Daytime crashes: Consider a daytime lighting study to evaluate ambient light at underpasses. Underpasses may warrant supplemental daytime lighting based on the support structure design (i.e., continuous walls versus intermittent columns), vertical clearance above the travel lanes, and the distance vehicles travel underneath the structure.

Safety Effectiveness

Research is ongoing regarding the safety impacts of improved bridge and underpass lighting. The CMF Clearinghouse reports a 32% crash reduction for installing lighting on roadways without street lighting (Abdel-Aty et al. 2014).

Enhancements

Agencies can consider the following enhancements to bridge and underpass lighting:

- Requiring drivers to use headlights (both day and night).
- Painting the walls white may enhance underpass lighting.
- Installing horizontal bands or patterns of light sources or reflective material along walls may improve visibility of pedestrians or other vertical objects and may also improve delineation of horizontal curves, if present.

Costs and Service Life

Bridge and underpass lighting should be regularly inspected and maintained to ensure continuous, effective operation. Costs and service life vary significantly depending on the lighting manufacturer, bridge and underpass characteristics, and power source. FHWA's *Countermeasure Service Life Guide* estimates lighting installation has a service life of 15 years (Himes et al. 2021).

More Information

The *2023 FHWA Lighting Handbook* provides guidance for lighting roadways, tunnels, and underpasses/overpasses (Gibbons et al. 2023).

Transverse Rumble Strips

Description

Rumble strips create an auditory and vibratory response, encouraging drivers to reduce their speeds and turn their attention to surrounding messaging from signs, CMS systems, and pavement markings.

Rumble strips are either grooves that are milled into the pavement or bumps comprised of raised strips of material applied on the pavement surface. These are commonly used in a longitudinal manner parallel to the traffic flow to reduce roadway departures. More applicable applications to mitigate BrTS crashes include transverse rumble strips installed across the travel lane (Figure 33). Transverse rumble strips are used for alert purposes and are often installed on approaches to intersections, toll plazas, horizontal curves, work zones, bridges, and tunnels.

Where to Use

Transverse rumble strips may be used on the approach to bridges and tunnels, particularly where distracted driving crashes frequently occur. Overuse of transverse rumble strips within

Figure 33. Transverse rumble strips on an intersection approach (Source: VHB).

the road network can contribute to drivers ignoring the devices. Agencies may avoid the use of rumble strips and consider alternative options or designs in the following scenarios:

- Raised rumble strips should not be used in regions where snowplowing is conducted and
- Noise generated from rumble strips can be an issue for nearby residences.

Safety Effectiveness

Rumble strips are estimated to be 10% to 20% effective in reducing BrTS incidents.

Enhancements

Agencies can consider the following enhancements to transverse rumble strips:

- Transverse rumble strips may be more effective when used in conjunction with additional messaging devices, such as advance warning signs, CMS systems, pavement markings, or similar, to convey the purpose of the transverse rumble strip installation.
- Transverse rumble strips can be painted white per the MUTCD Section 3K.02 (MUTCD 2023), but not in locations where they could be confused for crosswalks or stop lines.

Costs and Service Life

Transverse rumble strips are generally low-cost and can range from less than $1 per linear foot to $5 per linear foot depending on the length of the project, whether the surface is concrete or asphalt, and if they are installed as a stand-alone project or part of a larger project (Boodlal et al. 2015). Transverse rumble strips can be installed as part of a resurfacing project. FHWA's *Countermeasure Service Life Guide* estimates transverse rumble strips have a typical service life of 10 years (Himes et al. 2021).

More Information

Effectiveness of Rumble Strips on Texas Highways: First Year Report (Carlson and Miles 2003).

High-Friction Surface Treatments

Description

HFST are pavement treatments that can reduce crashes associated with friction demand issues. This includes a reduction in pavement friction during wet conditions as well as high-friction demands due to vehicle speed or roadway geometric design. HFST involves the application of very high-quality aggregate to the pavement using polymer binders to restore or maintain pavement friction in needed areas.

Where to Use

HFST can address issues in areas where vehicles may brake excessively and/or where pavement surfaces may become prematurely polished such as

- Sharp horizontal curves,
- High-volume intersection approaches,
- Interchange ramps, and
- Bridges.

Safety Effectiveness

HFST has been demonstrated nationally and internationally to provide significant increases in friction for spot applications. FHWA's "Proven Safety Countermeasures" website reports the following reductions for HFST applications (FHWA, n.d.-f):

- Sixty-three percent for injury crashes at ramps (Merritt et al. 2020).
- Forty-eight percent for injury crashes at horizontal curves (Merritt et al. 2020).
- Twenty percent for total crashes at intersections (Harkey et al. 2008).

Enhancements

A possible enhancement to HFST would be a drainage study to identify contributing factors for high incidences of wet-weather crashes.

Costs and Service Life

State DOTs report HFST costs ranging from $25 to $50 per square yard (FHWA, n.d.-d). HFSTs are highly durable, and treatments have an expected life cycle of approximately 10 years. While the initial cost is high, the life cycle makes HFST a feasible investment, especially compared to geometric improvements to areas with high numbers of crashes. A recent study from South Carolina DOT indicates the benefit-cost ratio has proven HFST to be a very cost-effective countermeasure (FHWA, n.d.-c).

More Information

Several case studies detail real-world HFST applications available via the FHWA's "Case Studies and Noteworthy Practices" resource page, including applications of HFST in California, Florida, Georgia, Iowa, Kentucky, New York, Pennsylvania, South Carolina, South Dakota, Tennessee, Texas, and Washington (FHWA, n.d.-a.).

Sacrificial Systems

The purpose of these countermeasures is to reduce structural damage to bridges and tunnels through impact-absorbing systems installed on the face or in front of the structure. The following countermeasures are categorized as sacrificial systems:

1. Crash beams and portal frames and
2. Energy-dissipative system.

Crash Beams and Portal Frames

Description

Crash beams and portal frames absorb some of the impact energy just before OHVs collide with structures. Crash beams and portal frames primarily protect infrastructure and may have a negative impact from a safety standpoint for road users in the vicinity of the crash. Their design and capabilities vary by manufacturer, and there are tradeoffs between the strength of the beam and the ability of the beam to dissipate energy without damaging the bridge structure.

Crash beams may be comprised of steel plates, I-beams, or a combination of both, and are generally attached to the face of a bridge or similar structure. Portal frames are the same as crash beams, except they are installed as a separate structure in front of the bridge and absorb impact independently from the structural members of the bridge (Figure 34). If an OHV collides with a crash beam or portal frame, the beam will deform to a certain extent to absorb some of the impact, and it will also cause damage to the vehicle. These effects are exacerbated as vehicle speeds increase. Most importantly, crash beams and portal frames do not *prevent* structural deformation of the bridge or tunnel structure; rather, they serve to *limit* the resulting damage to the structure by absorbing some of the impact energy before the vehicle collides with the main structure. Limiting structural damage to the bridge or tunnel may, in turn, decrease the rehabilitation costs and duration.

Where to Use

Crash beams and portal frames are commonly used at low-clearance railroad bridges (a vertical clearance of 14.5 feet or less at the lowest point) on low-speed roads. Crash beams and portal frames may cause substantial damage to the OHV that impacts the beam, which in turn may cause debris from the OHV or the beam to be scattered onto the road, roadside, or nearby vehicles. Careful consideration of safety impacts is recommended before selecting crash beams or portal frames as a countermeasure, and they should not be installed on high-speed roads.

Safety Effectiveness

The sacrificial system is estimated to be 30% to 50% effective in reducing BrTS incidents (Cawley 2002). Research is ongoing regarding the safety impacts of crash beams and portal

Figure 34. Portal frame (Source: VHB).

frames, their ability to prolong the life of the bridge or tunnel structure, and the effectiveness of different beam materials and configurations.

Costs and Service Life

Beams often need to be replaced after each BrTS incident, so service life depends on the number of structure strikes occurring post-installation. Costs vary; one source estimates $60,000 per installation (Cawley 2002).

More Information

Experimental Analysis on Effectiveness of Crash Beams for Impact Attenuation of Overheight Vehicle Collisions on Railroad Bridges (Ozdagli et al. 2020).

Energy-Dissipative System

Description

While sacrificial systems primarily include the installation of crash beams to prevent an OHV from impacting low-clearance bridges, FHWA is developing, through a Transportation Pooled Fund Study, an energy-dissipative system prototype using a potential combination of a box beam (e.g., steel) with energy-absorbing materials (e.g., aluminum honeycomb) for the protection of bridge girders from overheight impacts (Figure 35). This innovative protection system can provide an effective measure for preventing damage to presently vulnerable concrete and steel bridge girders while sustaining moderate to severe damage to the system. Previous studies on cushion systems, or sacrificial systems mounted to the bottom portion of the exterior girders consisting of energy-absorbing material to dissipate energy caused by impact, have demonstrated that minimal damage occurs to both the bridge and the vehicle if an impact takes place (Aly and Hoffman 2022).

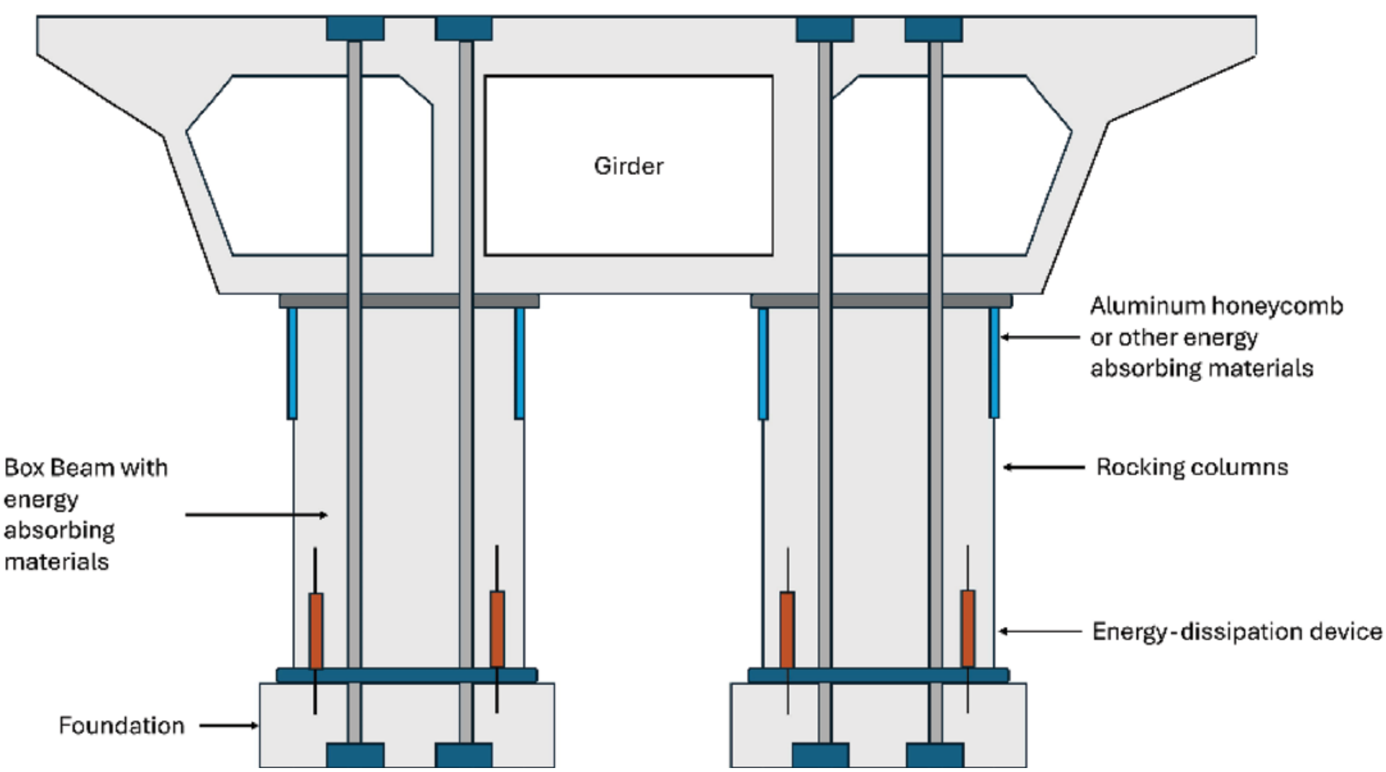

Figure 35. Prototype of energy-dissipation devices.

Where to Use

Energy-dissipative systems are typically located on the bottom portion of exterior girders of bridges. This includes energy-absorbing materials such as aluminum honeycomb. For limited access facilities, this type of treatment would generally apply to the first bridge in the series from each entry point.

Safety Effectiveness

An energy-dissipative system acts as a reactive sacrificial system in the case of BrTS to mitigate the damage to both the bridge and commercial vehicle. This countermeasure is in the prototype and development phase.

Costs and Service Life

The system may need to be replaced after each BrTS incident, so service life depends on the number of BrTS occurring post-installation. Costs vary as the prototype is under construction. Depending on the features desired and areas covered, there may be multiple vendors that can meet an agency's needs. Agencies are encouraged to conduct due diligence in evaluating the options available.

Active Systems

The purpose of these countermeasures is to improve driver awareness of bridges and tunnels through detection- or location-based warning systems. The following countermeasures are categorized as active systems:

1. Routing systems.
2. Early warning detection systems.
3. Smart Roadside commercial motor vehicle monitoring.
4. License plate camera recognition system.
5. Structure monitoring systems.

Routing Systems

Description

Routing systems for oversize vehicles are designed to improve safety and protect infrastructure. Agencies often use these systems to issue permits more efficiently and to ensure an accurate and reliable route (Figure 36).

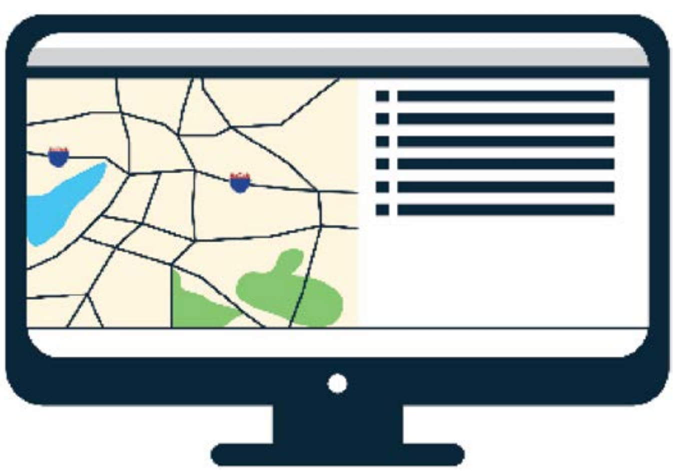

Figure 36. Example routing system (Source: VHB).

Where to Use

Routing systems are used when planning a route and issuing a permit.

Agencies can consider the following factors when assessing the potential use of routing systems:

- Features desired.
- Maintenance of underlining data.
- Technical support.
- Data storage.
- Expandability.
- Interface and communication features.
- Security of input data/hauler information.
- Virus protection.
- Cost.

Safety Effectiveness

Accurate routing systems can minimize human error in route planning, thereby improving the efficiency and effectiveness of this countermeasure. Accurate and reliable routing and permit issuance may be the single most effective countermeasure to mitigate BrTS, assuming the hauler follows the approved route.

Enhancements

Haulers may have difficulty understanding information or restrictions from the different systems used by different authorities. Standardization, such as the following, would be valuable:

- Standardize the routing system used by all jurisdictions within a state.
- Standardize the routing system used by all states.

Costs and Service Life

Costs vary by software provider and the features included with OHVs being just one area. The software needs to be maintained and kept current with restrictions that develop or are eliminated. Depending on the features desired and the area covered, there may be multiple vendors that can meet an agency's needs. Conduct due diligence in evaluating the options available.

Early Warning Detection Systems

Description

Early warning detection systems or OHVD systems are often installed upstream of low-clearance bridge or tunnel structures (a vertical clearance of 14.5 feet or less at the lowest point) at a sufficient distance for heavy vehicles to stop or exit the road before collision with the structure (Figure 37). Most systems consist of a transmitter on one side of the road (e.g., laser, infrared lights) and a receiver on the other; between these two elements, a beam of light or similar spans the roadway at a specified height and relays a notification to a connected system if the beam is broken by an OHV passing through it. The systems may also trigger video recordings of the incident or notify emergency response personnel. Driver feedback occurs immediately, and associated warning signs, beacons, or otherwise provide real-time notifications that encourage the driver to stop. The warning sign may flash yellow beacons and may or may not include an alarm (parabolic shielded bell, electronic siren, horn, etc.) to alert the driver. Variable message signs may also be used to instruct the driver to stop on the side or take some exit prior to reaching the structure. These systems typically can detect speeds up to 75 mph and are typically installed 1,000 feet before the structure to provide sufficient stopping distances. This type of system is already in use in the United States, UK, Germany, Australia, and Canada. Some systems use other light sources such as visible, red, or infrared light as well as modulation schemes to provide improved performance. Additionally, one OHVD system usually covers multiple traffic lanes

Figure 37. Components of an early warning detection system installed in Glenville, NY (Source: VHB).

and can utilize dual beams to provide improved direction discernibility, system redundancy, and reduced false alarms. Further discussion on individual technologies for these systems is provided below.

Where to Use

Early warning detection systems vary significantly by manufacturer. These systems are reactive and may produce false positives under adverse weather conditions depending on the measurement device used. False positives, especially if they occur frequently, may cause drivers to ignore warning devices. Agencies should consider the following factors when assessing the potential use of early warning detection systems:

- Adverse weather: High winds and other severe weather may cause false positives in the system. Consider a system designed for weather conditions specific to the region.
- Ambient light: Some systems can reject ambient light, which reduces false positives and improves system performance.
- Animals: Consider the surrounding environment, as birds and other small animals may cause false positives.
- Power: These systems require a constant power source, which may vary by manufacturer.

Safety Effectiveness

Active warning systems are estimated to be 50% to 80% effective in reducing BrTS incidents (Cawley 2002). Maintenance for early warning detection systems may differ from passive systems, such as more frequent repairs and more frequent inspection as well as having more vulnerable systems components. From a human factors perspective, the danger of an active system failure could also be more detrimental compared to a passive system since failures may not be salient to road users. For example, if drivers rely on active early warning detection systems as the last defense in preventing a BrTS, a lack of indication from such a system may signal to the driver that there is no danger of collision with the structure, when in fact a failure has occurred. The frequency of inspections and preventive maintenance may need to take into consideration these factors; regular inspections for functionality will be critical, and any components found to be nonfunctioning may need to be placarded inoperative in some way so that drivers are aware the unit or system is not currently reliable.

Enhancements

Digital signs (CMS or similar) and flashing beacons may provide real-time notifications for OHVs as they approach a low-clearance structure. These may be programmed to relay a constant warning message if the measurement system is not functional or is offline and may also alert authorities of a power failure.

Pull-over areas provided directly upstream of the structure allow OHVs to wait outside of the travel lanes for rerouting instructions or a police escort.

Like many strategies, this relies on the driver to properly interpret the message and take corrective action as appropriate or as instructed. One opportunity to enhance the effectiveness of this strategy is to be as direct and instructive as possible with any required actions. For instance, rather than stating "overheight vehicles must turn," a message could state "overheight, turn right at pull-off."

Costs and Service Life

The cost, service life, and functionality of these systems vary by manufacturer. Costs reported in 2011 across eight states ranged from $150,000 to $200,000 per installation (Agrawal, Xu, and Chen 2011). Note there are also maintenance (e.g., changing sensors) and operations (e.g., utility) costs associated with these systems, which are typically greater than passive systems.

More Information

North Carolina DOT installed a laser-based detection system for OHVs in Durham, North Carolina, for a low-clearance bridge that provides a grade-separated railroad crossing in a downtown area. The detection system is coordinated with flashing beacons and the traffic signal for an adjacent intersection. Notably, the signal turns red upon detecting an OHV and subsequently reduces collision speeds when collisions occur. Further, there is a dynamic sign indicating "Overheight Must Turn" (John A. Volpe NTSC 2018, 37). (Note: This example illustrates an application of an advanced warning detection system and is not meant to serve as an example of MUTCD-compliant warning signs.)

The City of Sydney, Australia, installed a unique tunnel warning system for the Sydney Harbor Tunnel, which serves roughly 100,000 vehicles per day. When the system detects OHVs approaching the tunnel, it triggers a "curtain" of water falling across the tunnel entrance onto which a giant STOP sign is projected as a pseudo-holographic image (Laservision, n.d.).

Light detection and ranging (LiDAR). LiDAR sensors are potentially able to be installed on bridge faces above the posted clearance height pointing toward oncoming traffic. LiDAR sensors can be positioned in the middle of the traffic lane and transmit a thin triangular sheet of light toward the road surface to form an invisible light barrier across the road (Figure 38). The sensor processes any reflected laser pulses from oncoming vehicles and can activate warning messages before an OHV passes underneath a low-clearance bridge. This product also has potential uses for bridges over water to detect ships that may be overheight.

Infrared. Most installed OHVD systems operate similarly with an optical transmitter and receiver unit using a light transmission beam (Figure 39). These optoelectronic sensors utilize different light sources to function, including infrared. While infrared sources present a moderate cost compared to camera-based systems, they have limitations, including being highly susceptible to false alarms for any number of reasons, including lost alignment between transmitter

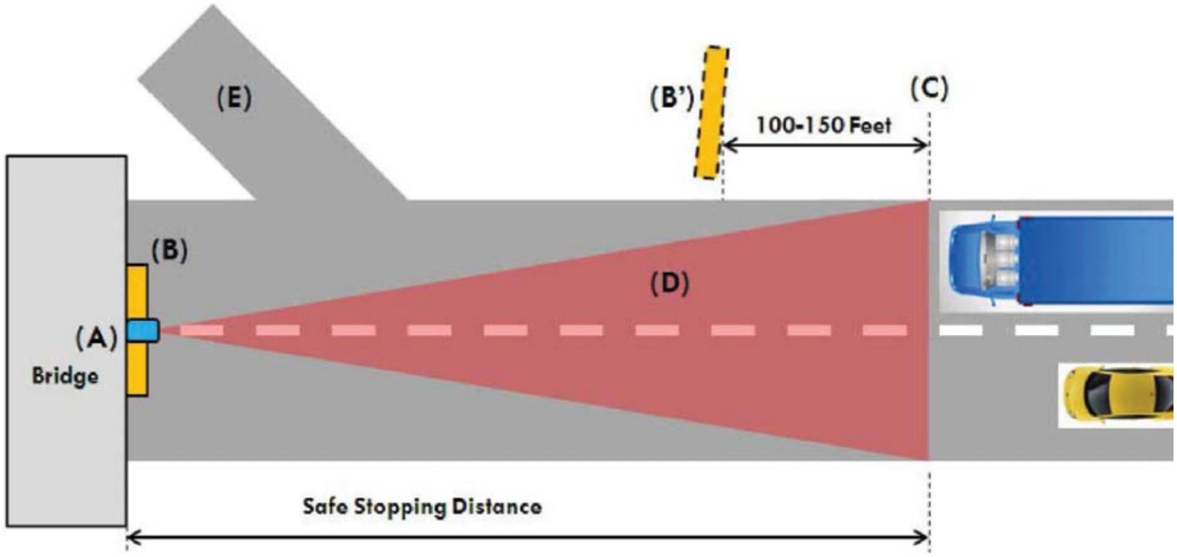

Figure 38. Typical LiDAR early warning OHVD system installed on a bridge face (Singhal, Kamga, and Agrawal 2018).

and receiver, fog, vehicle antennas, flying debris and birds, or ice or snow formations. These costs can increase when considering installation costs including the cost of roadway closures and associated structural and electrical installation costs.

Radar. Some radar applications exist for early warning detection systems. For example, some products use two integrated narrow-angle laser transmitters to measure two consecutive overlapping speed profiles from a commercial vehicle, allowing the system to profile the vehicle's height, among other information. Systems built in Australia have been known to trigger false alarms if any object or debris becomes airborne and crosses the radar beam.

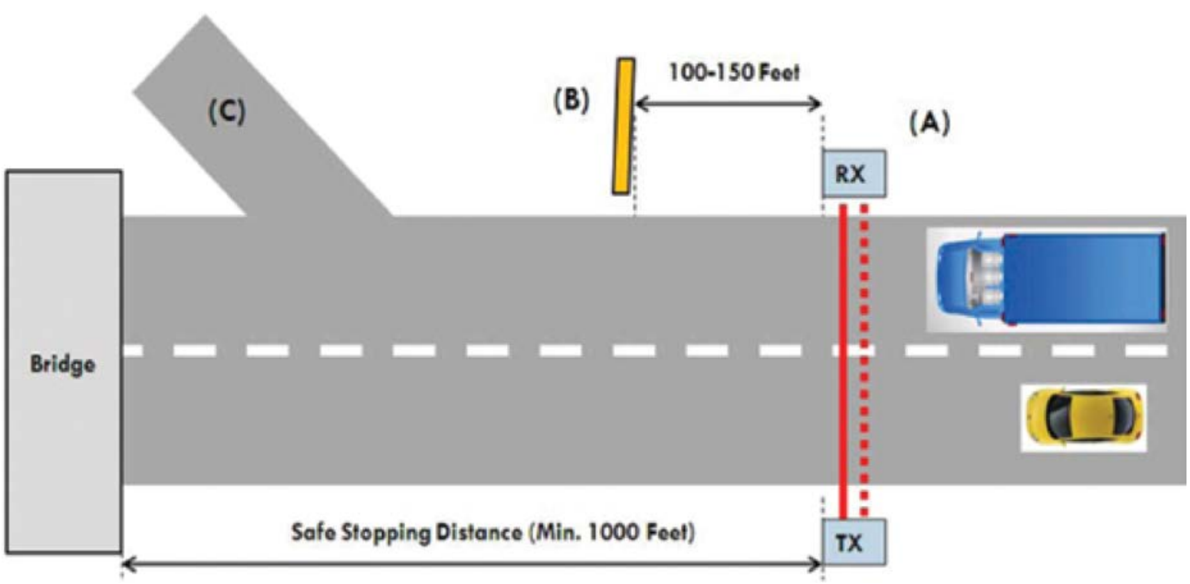

Figure 39. Typical LiDAR early warning OHVD system (Singhal, Kamga, and Agrawal 2018). RX = receiver; TX = transmitter.

Camera. Some systems may use a single calibrated or multiple video camera system to gauge and prevent OHV strikes through an early warning detection system. This typically features a camera mounted on the side of the road at the height of the low-clearance bridge or object. Camera angle calibration is determined using a reference object and may allow other features of the roadway or vehicle to be captured in the event of or in preventing a strike, such as the height of the vehicle, number plate of the vehicle, and a record of the vehicle at the scene. Cameras face certain limitations in inclement weather, including rain or fog or at night (if OS/OW vehicles are allowed to operate within that state or municipality at night), and lighting around the bridge must be adequate. A camera-based solution may be cheaper than a laser or infrared light warning system or transmitter. Efforts to introduce camera-based systems have been undertaken, including in Cambridge, England.

Smart Roadside Commercial Motor Vehicle Monitoring

Description

Smart roadside commercial motor vehicle monitoring systems feature a variety of technologies that enable the scanning of commercial vehicles (Figure 40). Smart roadside systems measure and record a vehicle's height, length, and width; can photograph and scan a vehicle's license plate; potentially produce a three-dimensional (3D) model of the vehicle; scan and record the vehicle's axle count, spacings, and potential load; determine the vehicle type and classification; and verify the vehicle against a valid issue permit for accuracy and compliance. Different vendors may include some or all of these features and are generally able to record this information while the commercial vehicle is in motion. Technologies incorporated into these monitoring systems may include LiDAR scanners, cameras, and cloud databases. Eye-safe cameras or other sensors (including LiDAR or infrared) that can scan an object—in this case, a commercial motor vehicle—multiple times per second, enabling fully automated length, width, and height measurement with the vehicle speed and movement direction. Software suites may also include the ability

Figure 40. Example commercial motor vehicle monitoring system (Source: Washington State DOT).

to display movements in real-time and store information in a local database through a cloud-based system.

Where to Use

Agencies should consider the following factors when assessing the potential use of connected vehicle technologies:

- Reliability of broadcast signals.
- Costs to install and maintain broadcasts.
- Cybersecurity and privacy concerns associated with connected vehicle information.
- Liability.

Safety Effectiveness

These systems focus on the enforcement of high-risk carriers. Automated vehicle attribution can improve precision and reduce human error, thereby increasing road safety while preserving infrastructure integrity. This offers a proactive safety measure to check a commercial motor vehicle's height and weight and potentially alert the driver in case of routing noncompliance or an unexpected hazard in the path of travel.

Enhancements

Enhancements may include software suite enhancements, such as the ability to produce a 3D model of the vehicle, or infrastructure enhancements, such as the use of multiple cameras to gauge a vehicle's weight while in motion.

Costs and Service Life

The service life of the key ITS technologies—including camera/sensor systems (LiDAR/Infrared)—is the main limiting factor. Service life for these technologies varies widely. LiDAR systems can have an expected warranty of only 2 years at a minimum. As these technologies are integrated; if one system fails, the whole system may become nonfunctional. A single, automated vehicle dimensions measurement laser sensor may cost $1,600 to $2,000 per unit; however, many of these units may be necessary to complete a smart roadside commercial motor vehicle monitoring system.

More Information

Illinois DOT is utilizing a pilot project to explore this technology at the Maryville weigh station on I-70 using 31 cameras to measure freight loads as they approach the scale and compare to permit details.

License Plate Camera Recognition System

Description

Also known as an automated license plate reader (ALPR), a license plate camera recognition system can record a vehicle that has struck a bridge. ALPR technology utilizes cameras and alphanumerical recognition software to read license plates as they pass (Figure 41). ALPR technology has been used primarily for law enforcement purposes by police throughout the United States.

Where to Use

Generally, license plate camera recognition systems are permanently mounted to infrastructure, including bridges and light poles, or fixed to infrastructure components near bridges and other key infrastructure points. When purchasing ALPRs, agencies will need to determine the potential future ancillary purposes of license plate camera recognition systems—such as to complete traffic studies or implement tolling—and address data privacy concerns and data storage and retention processes.

Figure 41. License plate reader technology process (Zmud et al. 2016). AVI = automatic vehicle identification.

Safety Effectiveness

ALPRs are primarily used for enforcement and compliance with registration, vehicle size, vehicle weight, and operational requirements. These cameras allow an agency to monitor damage caused by heavy vehicles on roadways and ensure commercial motor vehicle compliance. Technical challenges include accuracy and reliability issues with both equipment and databases, especially on older models of equipment, and maintenance. Most use of ALPRs is reactive (Zmud et al. 2021).

Costs and Service Life

The cost of a single ALPR camera can be up to $20,000, not including installation, fiber optics, and other soft costs (Eberline 2008).

More Information

More widespread use of license plate camera recognition systems includes the ability to monitor traffic flow, flag unpaid license and registration vehicles, monitor insurance compliance, and explore other transportation policies/solutions, such as congestion charges, tolls, and high-occupancy travel lanes.

Structure Monitoring Systems

Description

Structure monitoring systems, as illustrated in Figure 42, continuously monitor infrastructure and infrastructure health, including bridges and tunnels. Advanced structural monitoring methods allow for the early detection of possible structural deterioration with the goal of extending the lifespan of structures. These systems monitor the structure and are capable of recording strike incidents and transmitting warning messages to authorities to inspect, or if needed, shut

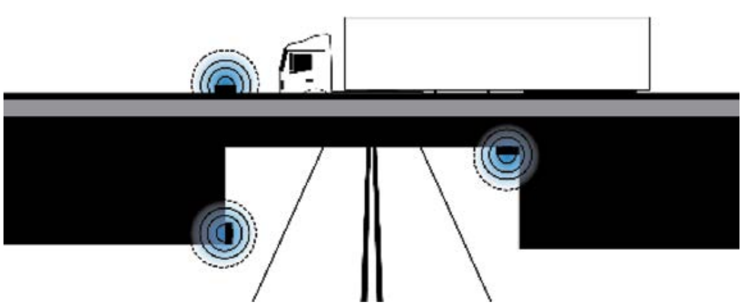

Figure 42. Structural monitoring sensor on a bridge (Source: VHB).

down the facility. This can be done through a wireless sensor network form that combines a large number of sensor nodes in the monitoring area into a network system, generally through wireless communication technology.

Where to Use

Structure monitoring systems are typically installed in key areas underneath or on top of bridges. They utilize a variety of sensors including

- Strain gauges,
- Strain meters,
- Inclinometers,
- Crack and joint sensors,
- Tilt sensors, and
- A variety of accelerometers.

These systems may monitor the foundation and super- or substructures of bridges.

Safety Effectiveness

These systems allow agencies to immediately detect a structure impact or collision and determine if crews are needed on-site to survey the damage. Structure monitoring systems that continuously monitor a piece of infrastructure may also reduce the likelihood of premature or unexpected damage or events and provide inspectors with a plethora of historical data on bridge and tunnel performance (Deng et al. 2023).

Enhancements

Some structure monitoring systems may include options for building information management, digital twinning, or utilizing artificial intelligence for structures. Some systems provide a variety of structural health monitoring including using nondestructive testing technologies, remote online monitoring, seismic monitoring, and beam-fatigue analysis.

Costs and Service Life

Structure monitoring systems can assist agencies in prolonging the deterioration and preserving the state of good repair of structures, which can have an expected service life of 100 years. Costs of sensors associated with structure monitoring systems vary from hundreds of dollars up to thousands of dollars per unit, while the number of units varies for the intended purpose (up to hundreds of strain gauge sensors may be necessary to create an adequate structure monitoring system) (Dalia et al. 2018).

Vehicle-Based Systems

The purpose of these countermeasures is to improve driver awareness of bridges and tunnels through technology and in-vehicle systems. The following countermeasures are categorized as vehicle-based systems:

1. In-cab technology.
2. Connected vehicle technologies.
3. Subscription service.
4. Raised dump body light-and-sound warning system.
5. Truck-mounted systems to monitor vehicle load.

In-Cab Technology

Description

Dating back to 1945, CB radio provides short-range communication services and real-time traffic and emergency updates for truckers across the country. Most CB radios and base station transmitters have a broadcast range of up to 15 miles. Jurisdictions can install broadcast stations in the vicinity of low-clearance bridge or tunnel structures (those with a vertical clearance of 14.5 feet or less at the lowest point) to periodically send automated, recorded messages to drivers with their radios turned on while in range of the broadcast station to warn them of the structure ahead.

Where to Use

Agencies can consider the following factors when assessing the potential use of CB radio warning systems:

- Cell phone service: CB radios are particularly useful where gaps in cell phone coverage persist, such as in rural areas. CB radios may be the only method of communication available to drivers on parts or all of their routes.
- Broadcast station: Collaborate with local broadcast stations to determine appropriate CB radio stations for broadcasting low-clearance information. CB radios can use up to 40 discrete channels, but professional truckers commonly use only 2 or 3, and selection depends on the given route.
- Area: CB radios are not recommended in urban areas as the broadcast distance could capture many truckers on unrelated routes, which may decrease the effectiveness of messaging as drivers learn to ignore the warnings.

Safety Effectiveness

Research is not yet available for the safety effectiveness of in-cab technology as a BrTS countermeasure.

Enhancements

Multiple sources of messaging are recommended to capture as many drivers as possible. While commercial drivers still commonly use CB radios, pushing alerts through other media, such as mobile applications, may capture more of the large-vehicle driving population.

Costs and Service Life

One source suggests an average cost of $300 per CB radio transmitter (Cawley 2002). Service life estimates vary depending on maintenance and manufacturer.

Connected Vehicle Technologies

Description

Using signal towers or compact roadside units along the highway, individual trucks receive real-time updates about weather, road conditions, and road work, including clearance warnings (Figure 43). The system should provide enough advanced warning for drivers to reroute or stop before hitting a structure.

Where to Use

Agencies should consider the following factors when assessing the potential use of connected vehicle technologies:

- Reliability of broadcast signals.
- Costs to install and maintain broadcasts.
- Cybersecurity and privacy concerns associated with connected vehicle information.
- Liability.

Safety Effectiveness

Connected vehicles can reduce the costs associated with BrTS. Roadside units are effective when there is a corresponding unit in the vehicle cab to receive the signal. Other systems that

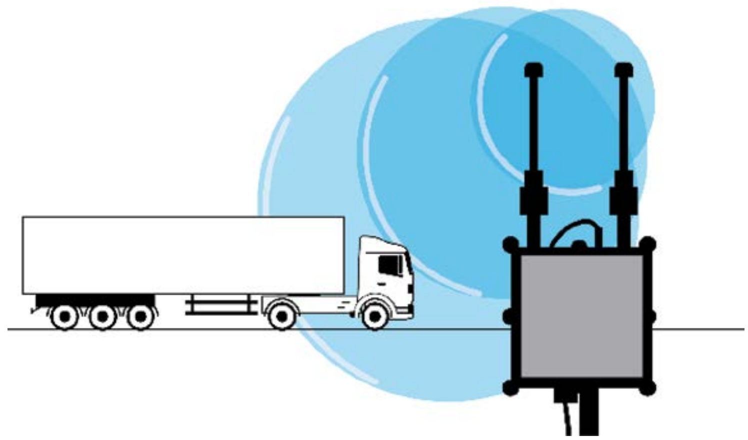

Figure 43. Example roadside unit (Source: VHB).

broadcast information widely to apps or specialty devices may also be effective. While it is generally accepted that connected vehicle technologies can mitigate BrTS by providing drivers with warnings about potential hazards, the effectiveness has yet to be quantified.

Enhancements

There appears to be a need for transportation agencies or infrastructure operators to communicate appropriate freight- and trucking-related road network information that may influence driver assistance systems (e.g., changes to road geometry, bridge clearances, temporary traffic diversions, electrical charging stations). These upgrades are part of a larger set of options.

Agencies could also use roadside units to collect BrTS data (e.g., number of impacts or preliminary damage assessments).

Costs and Service Life

Roadside units cost approximately $500 although costs vary. To receive the broadcast, each truck needs a receiver.

More Information

FHWA's Connected Vehicle Pilot program deployment in New York City provided eight roadside units to broadcast bridge clearance information and other details. This application was deployed in limited conditions during the pilot (HDR, n.d.).

Subscription Service

Note: Several subscription-based service companies offer safety alerts for low bridges. At the time of this guide, products on the market that offer in-cab, low-bridge warnings include but are not limited to Drivewyze, GreenRoad, Sentinel, High-Tech Sign, Garmin, and EXEROS Technologies.

Description

A subscription-based service uses a mobile application to communicate messages to commercial drivers. As shown in Figure 44, these messages can include safety notifications regarding rollover zones, low bridges, steep grades, runaway ramps, brake-check areas, weight restrictions, work zones, high collisions, and more.

Figure 44. Example message (Source: VHB).

Some services can collect driver safety information from a variety of sources. Agencies can coordinate with providers and their partners to disseminate safety and restrictive notifications as needed, such as when a major storm is approaching. Some services also partner with major data collection agencies to provide real-time notifications regarding traffic congestion, work zone presence, and a variety of other safety-related travel measures.

Commercial drivers actively using these services can receive push notifications to their mobile device when they are within a geofenced area that has an alert set up, such as for a low bridge. The geofence is large enough to provide the driver adequate time to make decisions before reaching the low bridge. The service provides low-structure alerts for clearance heights (e.g., 14.5 feet or lower).

Where to Use

Consult with service providers to ensure coverage is available in your area.

Safety Effectiveness

Research is not yet available for these services as a BrTS countermeasure.

Enhancements

Some services provide additional information such as infrastructure (parking, rest stops, etc.) and other notifications (weather alerts) as part of a paid subscription. Consult service representatives for more information.

Costs and Service Life

Subscription-based services typically operate as a monthly subscription service. At the time of this publication, the cost for some basic packages was under $20 per month and included safety notifications for low-clearance structures. Low-clearance bridges and tunnels are typically defined as having a vertical clearance of 14.5 feet or less at the lowest point, but this may vary by the service provider. Service life is indefinite, depending on the company's continuation of services.

Raised Dump Body Light-and-Sound Warning System

Description

Dump body safety devices warn heavy dump truck drivers when there is a problem with their dumper (Figure 45). A dump body is a metallic body whose upper part is generally open and intended for transporting bulk materials. This safety equipment uses both an audible warning device and a warning light to let the driver know when the bucket is still raised while the truck is moving. When a dump body is raised, this can exceed the normal traveling height of the vehicle and may result in a bridge or overhead object collision.

Figure 45. Raised dump body (Source: VHB).

Where to Use

Most dump body safety devices feature a light-up display and audible warning device located within the cab of the truck. Certain models may not activate until the truck reaches a certain speed and are meant for vehicles that move at reduced speeds during unloading to limit inconveniences for the driver.

Safety Effectiveness

These systems act as a preventive safety measure on specific types of commercial vehicles only.

Enhancements

Some models include options for limiting that alarm at low speeds, other speed adjustments, and additional warning inputs. Vendor models vary including different intensities of alarm noise, light flashing frequency, and outside temperatures that the raised dump body systems can withstand. There is an opportunity to consider national vehicle standards for raised dump body warnings.

Costs and Service Life

While exact service life may vary, many vendors supply models with a 2-year warranty. The unit costs around $100, not including installation costs and maintenance.

Truck-Mounted Systems to Monitor Vehicle Load

Description

Truck load monitoring systems may monitor information on a commercial vehicle, including the total vehicle load or axle load or the vehicle's height (Figure 46) and any changes to the load.

Where to Use

While sensor components of this system must be mounted on the vehicle, such as on the vehicle's body, trailer, or on top of a truck, these systems generally include an in-cab warning system to alert the driver about shifting vehicle loads or low-clearance hazards.

Safety Effectiveness

Some models may include an aerodynamic sealed sensor unit capable of measuring the height of an overhead hazard and sending a read-out to the in-cab unit to alert the driver. Others may include a dash video insert that will measure and detect the height of the vehicle even as the load changes. Some systems are geofenced and may only operate in certain states based on integrated bridge and other low-height clearance restriction data. Most systems generally include an audible alarm to alert the driver to any excess axle load or low-clearance hazard. Some modern systems may use two cameras together to increase depth perception.

Figure 46. Overheight detection and driver warning system example (Source: VHB).

Enhancements

Certain truck-mounted, vehicle load monitoring systems may include a telematics unit or GPS tracker to communicate information to an online fleet management software or the driver's smartphone.

Costs and Service Life

Camera-based technology with a software suite generally costs from around $500 to $1,000 and may more, depending on installation costs (Maghiar, Jackson, and Maldonado 2017).

Nonphysical Countermeasures

The purpose of these countermeasures is to improve driver awareness of bridges and tunnels through institutional policies, permitting procedures, and driver education programs. The following countermeasures are categorized as nonphysical countermeasures:

1. OHV and axle load restrictions.
2. OHV permits.
3. Vehicle checklists.
4. In-cab height placard.
5. Route surveys.
6. Pilot car/escort vehicle policies.
7. Route atlas (Motor Carriers' Road Atlas, Truckers Atlas).
8. Commercial navigation system policies.
9. Training and CDL certification.
10. Post-training/certification driver education and outreach programs.

OHV and Axle Load Restrictions

Description

There are several options for posting signs to restrict vehicles. A "Passenger Vehicles Only" sign restricts any commercial vehicles, including delivery or single-unit trucks. "No Truck" regulatory signs are posted at the beginning of the ramps that lead into the roadway section (Figure 47). Axle load restrictions generally refer to weight limits based on distance between axles for bridge formula calculations. Axle spacing is typically measured from the center of the axle to the center of the axle between the outermost wheel or group of wheels.

Figure 47. Example of axle load restriction (Source: VHB).

Where to Use

Agencies can consider the following factors when assessing the potential use of OHV and axle load restrictions:

- Limited commercial businesses on that corridor.
- Operational efficiency or congestion relief.
- Load rating of structures in the corridor.
- Pavement construction and design.

Unintended consequences can include increased truck traffic on parallel or adjacent roads and difficultly for trucks and delivery vehicles to access certain businesses and destinations.

Safety Effectiveness

Truck restrictions can mitigate BrTS by limiting the size and weight of trucks allowed on certain roads and bridges. This can help deter trucks that are too tall or too heavy to safely pass under or over bridges and tunnels. The effectiveness is dependent on driver compliance, which may require supplemental enforcement. There is limited research on the safety effectiveness of vehicle restrictions. Truck lane restrictions can reduce the number of rear-end collisions involving trucks in mixed traffic settings. Truck lane restrictions and vehicle restrictions along certain corridors can also improve traffic flow.

Enhancements

Periods of increased enforcement may be necessary to deter trucks on a posted corridor. In addition, education and outreach are appropriate if there are changes to the allowed traffic on a corridor.

Costs and Service Life

The total cost of posting a truck restriction on a highway will vary depending on the length of the highway segment, the type of restriction implemented, and the level of enforcement. Enforcement and monitoring may be necessary, which can increase the cost associated with signing alone. Costs of truck restrictions can be significant to motor carriers (e.g., increased travel time, routing decisions, hours of service, potential litigation). Agencies should consider all costs before implementing such a restriction.

More Information

For more information on truck lane restrictions, agencies can refer to individual state statutes. There are multiple restrictions on the use of policy to restrict traffic.

OHV Permits

Description

A permit authorizes the movement of an OS/OW vehicle for a specific time period on permissible hauling days. An authority (e.g., state, city, county, town, village) may require a permit for vehicles or loads that exceed legal dimensions in their laws (Figure 48). Applications are required and the permit issued will identify restrictions and an approved route.

Where to Use

Agencies may consider the following factors when assessing the current or potential use of policies and procedures for OHV permits:

- Simple and timely application process.
- Resources and tools needed to issue permits.
- Application and permit fees.

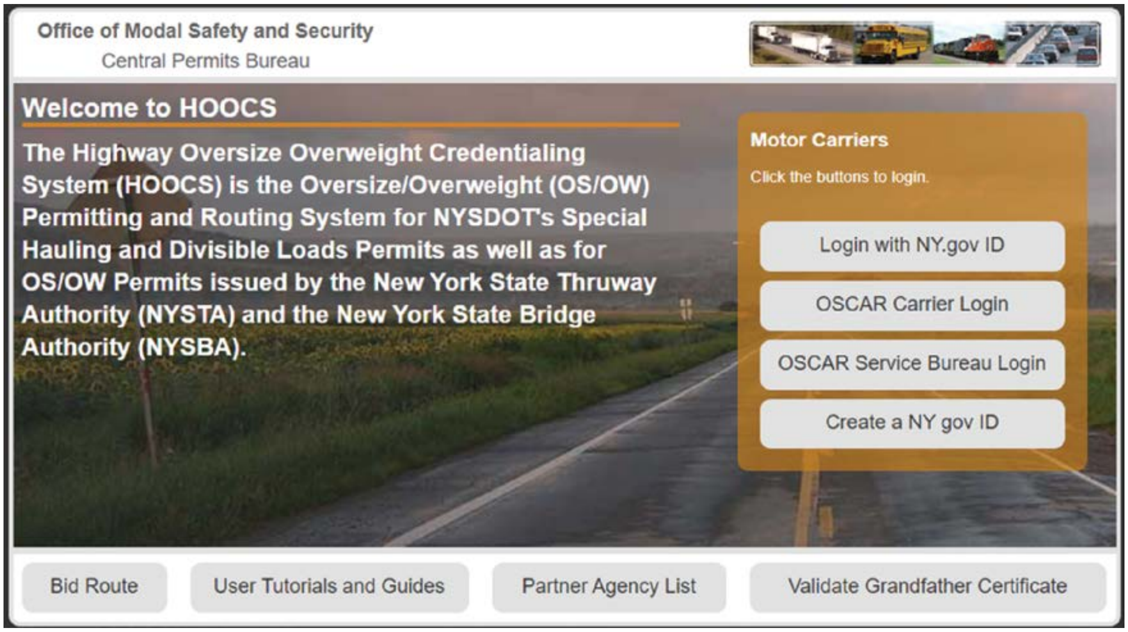

Figure 48. Example of New York State's consolidated overheight permit website for three jurisdictions (Source: https://hoocs.dot.ny.gov/HOOCS/).

- Information necessary to issue a permit, such as
  - Applicant/company/carrier contact information,
  - Current insurance coverage,
  - Vehicle information,
  - Load information, and
  - Trip information.
- Quality assurance process and accuracy of information.
- Communication methods with applicants (e.g., online, email, phone).

Safety Effectiveness

Accurate and reliable routing and permit issuance may be the single most effective countermeasure to mitigate BrTS, assuming the hauler follows the approved route.

Enhancements

Haulers may have difficulty understanding information or restrictions from the different systems used by different authorities to issue a permit for a single trip. The following are opportunities to enhance the effectiveness of the permitting process:

- Standardize the permitting process across jurisdictions (one-stop shopping). Note that AASHTO developed a recommended standardized permit form to encourage harmonization of permit information as documented in *Permit Data Harmonization Model Permit & Best Practices* (Athney Creek Consultants 2022).
- Improve coordination and data sharing of permits across states.
- Automate permit issuance systems in those jurisdictions with a manual process.

Costs and Service Life

The cost varies by jurisdiction and depends on whether a single-use, monthly, or annual permit is requested. Price may also vary by route distance. The permit issued will specify the time constraints (e.g., good for 5 weekdays from 30 minutes after sunrise to 30 minutes before sunset).

Table 13 is an example of state permit fees (NYSDOT 2023).

Table 13. Example of state permit fees.

Trip	Fee
Single trip	$40
Monthly – 100-mile radius	$60
Special vehicle combination	$100
Annual – 100-miles	$360
Special vehicle combination	$500

More Information

Most states, cities, counties, towns, and authorities have a permit policy and procedure in place. Information is typically available through the jurisdiction's website, and most are processed online.

Vehicle Checklists

Description

Checklists increase driver awareness of vehicle constraints, cargo securements, and driver preparedness. Checklists can be created for pre-, mid-, and post-trip completion. Checklists should include measuring the height and width of trucks as well as engine and cab inspection. Figure 49 and Figure 50 show examples of vehicle checklists.

Where to Use

Agencies should consider the following factors when assessing the potential use of vehicle checklists:

- Height measurement training: Drivers often incorrectly measure vehicle and cargo heights, so relevant and ongoing training is critical for reducing BrTS incidents.
- Cargo inspection: Cargo can shift during transit, and drivers should be aware of and react to possible changes in their maximum load height throughout the trip.
- Complacency: As with any repetitive task, drivers may become less attentive over time to standardized checklists. Checklists should be kept to a manageable length to reduce the potential for complacency.

Safety Effectiveness

Research is not yet available on the safety effectiveness of vehicle checklists as a BrTS countermeasure.

Enhancements

Agencies can consider the following enhancements for vehicle checklists:

- Update in-cab height placards at the start of each trip.
- Require drivers to report their maximum load height and other key checklist items to the managing organization before a trip commences.
- Provide drivers with instructions and tools or equipment to measure load height more accurately (e.g., technologies to create a 3D model of the truck) to reduce common mistakes in measuring load height.

Costs and Service Life

Vehicle checklists can be developed by an individual or managing organization with minimal labor hours. Personnel executing the checklists must spend time before, during, and/or after the trip on the task, which may impact trip scheduling and hours of service.

Professional drivers' route and vehicle check

Data		**Driver's name**	
Vehicle #		**Trailer fleet / Serial #**	
Route	From	To	Via
Load type	☐ Box ☐ Plant & Machinery ☐ Car transporter	☐ Container ☐ Skip ☐ Other (specify)	☐ Curtainsider ☐ Waste

Route and vehicle check	
Have low bridges on your route been identified?	☐ Yes ☐ No
What is (are) the location(s) of the lowest bridge(s) on the route?	
What is the limit on vehicle height under bridges on your route?	_______ft _______ins _______metres
Are the load and equipment properly secured and safe?	☐ Yes ☐ No
What is the maximum traveling height of your vehicle?	_______ft _______ins _______metres
Is the maximum height of your vehicle less than the limit on vehicle height under bridges on your route?	☐ Yes ☐ No
What is the maximum width of your vehicle?	_______ft _______ins _______metres

Know your vehicle height and width.
Know your route. Obey traffic signs.
Don't hit and run.

Figure 49. Example vehicle checklist for unpermitted loads [Source: adapted from Prevention of Bridge Strikes (Network Rail 2012)].

SUGGESTED PRE-TRIP CHECKS PRIOR TO moving an Over-dimensional load under a NYSDOT SPECIAL HAULING PERMIT

The following are suggested items to check prior to moving the load. While reviewing these items as part of a pre-trip inspection does not guarantee that you will not experience any permit violations, we strongly urge you to implement a program to review the permit against the vehicle and load before moving the load. Please feel free to share this information with your staff, drivers, route survey companies and certified escorts. These suggestions will be revised periodically as necessary.

Conduct a formal pre-departure check of the vehicle and load against the permit to be certain they match <u>exactly</u>. In the event there are any discrepancies, <u>do not</u> move the load until you either obtain an amendment or a new permit:
(Title 17, NYCRR, Subpart 154-1.7, Identification of Vehicle and Load)

- ☐ Plate number of power unit matches permit
- ☐ Plate number of trailer unit matches permit
- ☐ Height of load matches permit
- ☐ Width of load matches permit
- ☐ Length of load matches permit
- ☐ Weight of load matches permit
- ☐ Registration of vehicle matches permit
- ☐ Registered weight matches NYS H.U.T. permit
- ☐ Number of axles used matches permit
- ☐ Axle spacings match permit
- ☐ Tire load weight ratings match permit
- ☐ Other special requirements as noted on permit
- ☐ County or municipal permit(s) obtained, if required
- ☐ NYS Thruway permit obtained, if required
- ☐ Bridge Authority permit obtained, if required

If required to have one or more certified escorts accompany the load:

- ☐ The operator of the load and the escorts has met prior to departing to review the permit for any special requirements or instructions. (New York State Certified Escort Manual, VIII. Proper Escort Procedures, 1. Before the Trip Begins)
- ☐ Escort driver has ensured the permitted load has proper signage, lighting, flags and meets the special requirements designated on the permit BEFORE escorting. **If the permitted load is not in conformance with the permit, the escort vehicle is not to escort until all requirements have been met.** (New York State Certified Escort Manual, VIII. Proper Escort Procedures, 1. Before the Trip Begins)
- ☐ The escort driver(s) have New York State certification and that the certificate has not expired. (New York State Certified Escort Manual, V. (A) Hauling Permit Travel Regulations Governing the Movement of Over-dimensional Loads, 16. Escort Driver Certification Required)
- ☐ Escort vehicle(s) are properly equipped. (New York State Certified Escort Manual, VII. Escort Vehicles, 2. Mandatory Equipment

General requirements for all permitted loads:

- ☐ The routes of travel as shown on the permit are to be used with NO EXCEPTIONS. (New York State Certified Escort Manual, V. (A) Hauling Permit Travel Regulations Governing the Movement of Over-dimensional Loads, 17. Operational Provisions, p))
- ☐ The correct warning sign bearing the legend, “OVERSIZE LOAD” is being used, is of the proper color and dimensions and is properly mounted. (New York State Certified Escort Manual, V. (A) Hauling Permit Travel Regulations Governing the Movement of Over-dimensional Loads, 12. Warning Signs, a) – e))
- ☐ Flags of the correct dimensions, mounted on staffs and securely fastened to the vehicle or load are used. (New York State Certified Escort Manual, V. (A) Hauling Permit Travel Regulations Governing the Movement of Over-dimensional Loads, 7. Flags, a) – c))
- ☐ The required warning lamps are being used and are operational. (New York State Certified Escort Manual, V. (A) Hauling Permit Travel Regulations Governing the Movement of Over-dimensional Loads, 10. Warning Lights for Permitted Loads)
- ☐ Load is properly secured with the appropriate number of tiedowns and that there are no defects in chains, tiedowns, etc. (FMCSR Subpart I – Protection Against Shifting and Falling Cargo, Section 393.100)

You are urged to read and become familiar with the various laws rules and regulations that govern the movement of over dimensional loads in New York State. The following resources can be found on our website, www.nypermits.org under the tab labeled, “Laws, Rules, Regulations”: Federal Motor Carrier Safety Regulations contained in Title 49 Code of Federal Regulations (CFR); the Vehicle and Traffic Law of the State of New York, Title 3, Article 10, Section 385, entitled “Dimensions and Weights of Vehicles”; Title 17, NYCRR, Subpart 154-1 entitled “Non-divisible Load Permits”, and the New York State Certified Escort Manual.

Figure 50. Example permitted OHV checklist (NYSDOT, n.d.).

Service life is variable; checklists can be continually updated as the vehicle fleet, driver needs, and cargo makeup change, or due to anything that may impact the serviceability of vehicles, safety of driving personnel, or safety of other roadway users.

In-Cab Height Placard

Description

An in-cab height placard is an adjustable message board that displays the total height of the truck for referencing at low-clearance warning signs. This is especially beneficial when the driver is unfamiliar with the vehicle, such as with box truck rentals or for commercial drivers with inconsistent vehicle/cargo assignments. An in-cab height placard can be as simple as a piece of paper with the total height of the vehicle/cargo written on it. As long as it is within the field of view of the driver (in a way that does not obstruct their view of the road), drivers will not have to memorize the height and can reference it as needed when they see low-clearance warning signs.

Where to Use

Commercial motor carriers, box truck rental companies, RV rental and sales companies, and any other large-vehicle distributors and drivers can benefit from using in-cab height placards. Vehicle height must be accurately measured and confirmed each time any changes are made to the cargo or vehicle. Height measurements may require special tools or training depending on the vehicle/load configuration.

Safety Effectiveness

Research is not yet available for applications of in-cab height placards as BrTS countermeasures.

Enhancements

None applicable at this time for this system.

Costs and Service Life

Material costs and service life are generally negligible for this countermeasure. Height placards should be updated any time modifications are made to cargo or vehicles.

Route Surveys

Description

A common requirement for permitting oversize vehicles is the completion of a route survey. Route surveyors are trained to drive with specific constraints in mind related to the intended transport. They can identify low-clearance bridges (a vertical clearance of 14.5 feet or less at the lowest point), narrow roadways, railroad crossings, low-hanging electrical wires, overhead obstructions, difficult road geometry, and other impediments that may obstruct the intended route based on the load and vehicle characteristics. Route surveyors often use a height pole attached to the vehicle to verify vertical clearance at bridge and tunnel structures. Route surveyors also work with the trucking company and local authorities to identify alternative viable routes where needed. Performing a route survey identifies problems before the route commences, improving the chances for a successful trip and directly reducing the likelihood of BrTS incidents.

Where to Use

Route surveys are commonly required by law for oversize vehicles, but they are also beneficial for any heavy vehicles driving on public roads. Some commercial motor carriers perform route surveys before establishing a new, repetitive route.

Safety Effectiveness

Safety is prioritized over the shortest route, so selected routes may involve increased distances and roads with lower operating speeds. Research is not yet available for the safety effectiveness of route surveys as BrTS countermeasures.

Enhancements

Technology, such as dashboard cameras and voice recorders, may improve route surveys.

Costs and Service Life

There is a fixed cost associated with training the route surveyor. Variable costs include the time and fuel to complete the task. The variable costs will depend on the length of the route and the time to complete the survey. Route surveys should be performed close to the commencement of the trip and updated periodically; communicating with local jurisdictions can help identify work zones, pavement overlays, and any other planned changes along the identified route.

More Information

Pilot/Escort Vehicle Operators: Training Manual (Hamilton 2017).

Pilot Car/Escort Vehicle Policies

Description

Oversized vehicles are commonly required to travel with a leading and/or trailing pilot car/escort vehicle operator (P/EVO) (Figure 51). P/EVOs are used to warn road users of a potential oncoming hazard and to guide large vehicles through or around downstream obstacles that may impede travel. P/EVOs are commonly outfitted with signs, flags, warning lights, and other equipment depending on the governing agency. High visibility is critical for a successful transport. Through constant communication with the driver of an oversize vehicle, P/EVOs can help with stopping and turning maneuvers and communicate downstream travel constraints via CB radio or otherwise.

Where to Use

In many states, oversize vehicles are unable to travel on public roads without an accompanying P/EVO. Laws vary regarding the number of P/EVOs required and minimum thresholds (e.g., vehicle and cargo dimensions and gross weight) that trigger the need for a P/EVO. Many states require cross-coordination among several agencies for a successful oversize-vehicle permit and transport process.

Safety Effectiveness

Research is not yet directly available for applications of P/EVOs as BrTS countermeasures.

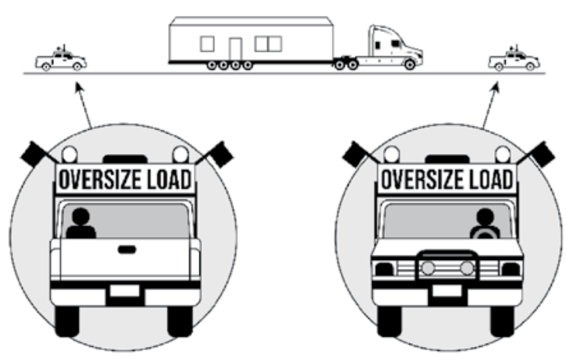

Figure 51. Example of a pilot car/escort vehicle (Source: VHB).

Enhancements

Defensive driving courses can improve P/EVO training programs. While P/EVO training courses already exist, they are not required in all states. One opportunity is to require this training and certification in all states with a mandatory refresher every 3 years to remain certified. Another opportunity is to require the use of commercial navigation systems for P/EVO certification (refer to Commercial Navigation System Policies section for further discussion on commercial navigation systems). Vehicle selection for both P/EVOs and heavy vehicles is also increasingly important as new suites of sensors for collision mitigation become available, including side view assist, forward collision warning/mitigation, lane departure warning/mitigation, and electronic stability control, among others.

Costs and Service Life

There are fixed costs and variable costs associated with P/EVOs. P/EVOs are generally required to be trained and/or certified for the task, so there is a fixed cost associated with their training. Some jurisdictions require state-specific vehicle permits; amber light permits; and/or insurance in the form of automotive liability, general liability, and/or professional errors and emissions policies. The variable costs include the time and fuel to complete the task at hand. The variable costs will depend on the length of the route and the time to complete the trip.

More Information

Pilot/Escort Vehicle Operators: Best Practices Guidelines (Hamilton and Owens 2017).

Road Atlas

Description

A road atlas displays low-clearance bridges (a vertical clearance of 14.5 feet or less at the lowest point) on any highway or local road for drivers to reference (Figure 52). Drivers can use a road atlas in conjunction with other navigation software.

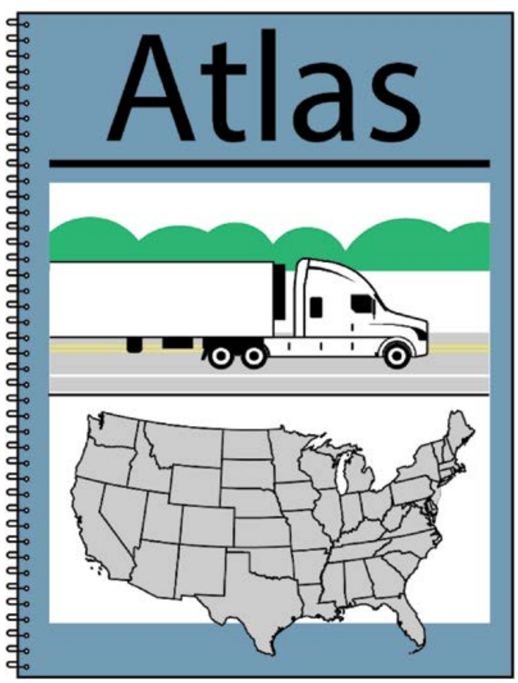

Figure 52. Example of an atlas that includes bridge and tunnel low-clearance information (Source: VHB).

Where to Use

An atlas should not be used while driving. Drivers and carriers can use an atlas when

- Engaged in planning and selecting a route,
- Stopped en route to verify or confirm a route, and
- Diverted from a route for emergencies resulting in road closures or diversions or for any other reason.

An atlas is also useful in areas with no cellular or internet service.

Safety Effectiveness

Lack of route planning by haulers has been determined to be one of the leading causes of BrTS (Agrawal, Xu, and Chen 2011; Martin and Mitchel 2004). An atlas is a cost-effective tool to plan routes, particularly for small or occasional carriers.

Enhancements

Atlas publishers could offer digital updates on a regular basis to atlas purchasers.

Costs and Service Life

Atlases are available for purchase online from retailers and publishers as well as in bookstores. They range in price from $15 to $60. While atlases are updated annually, older atlases will include most low-clearance bridges, as low-clearance bridges tend to be older.

More Information

An online atlas is more likely to be current. A printed atlas may not have the most current information and should be used in conjunction with other countermeasures.

Commercial Navigation System Policies

Description

GPS-based navigation systems used by the general driving population do not provide low-clearance warning notifications for bridge or tunnel structures. Commercial navigation applications have this information built in, and they can be programmed to automatically avoid problematic routes and provide audible warnings when approaching low-clearance structures. These specialized commercial navigation applications may reduce BrTS incidents when their use is encouraged and/or required and enforced by motor carriers, law enforcement, and policymakers.

Where to Use

Agencies may consider the following factors when assessing the potential use of commercial navigation system policies:

- Functionality: Key functionality of commercial navigation systems includes GPS-based (not cellular), regular and free software updates, visual and audible warnings, large screen size, customizable based on vehicle height, mounting options, lane assist, and turn-by-turn guidance.
- Source of vertical clearance information: The reliability of these systems is often dependent on the timeliness and accuracy of data from transportation agencies. There is a need for transportation agencies to maintain and provide access to a timely and reliable database of low-clearance structures that is integrable with major commercial navigation.
- Collaboration with manufacturers: Ensuring the devices are gathering information from the correct sources will improve the effectiveness of commercial navigation system policies. There is also a need for the manufacturers to push updates to the devices and for drivers to check for updates regularly to confirm the system is relaying the most recent information.

Safety Effectiveness

NYSDOT estimated that more than 90% of truck drivers were following automobile GPS guidance (i.e., not using a commercial navigation system with horizontal and vertical clearance data) at the time of a bridge strike on parkways (Agrawal, Xu, and Chen 2011).

Enhancements

Some commercial navigation systems provide additional safety-related information beyond vertical clearance data. This could be required for P/EVO certification. Consult individual GPS manufacturers for more information on available services.

Beyond the provision of vertical clearance data for permanent structures, there is an opportunity for transportation agencies to post temporary or recent changes on 511 (e.g., short-term, construction-related activities that affect vertical clearance). Further, there is an opportunity for commercial navigation systems to consume and provide this data to users.

Costs and Service Life

One source suggests an average cost of $200 to $900 per device, depending on desired features, plus a possible nominal monthly fee (Elgin 2023). Service life depends on the selected manufacturer. Base data sources and navigation systems must be updated regularly to capture new information.

Training and CDL Certification

Description

CDL training and certification improve truck drivers' knowledge about driving larger vehicles, including the associated risks and opportunities to mitigate those risks. It is estimated that a high number of crashes are caused by human factors, including failure to use safety belts, driving too fast for conditions, inadequate surveillance of the roadway environment and failure to notice potential hazards, driver fatigue, driver distraction, following too closely, and inadequate evasive action to prevent collisions.

Drivers hauling cargo can benefit from load securement training to help prevent damage to the infrastructure and cargo and understand DOT regulations. Many load securement or cargo control training offerings include aiding drivers in understanding and assessing various aspects of load securement. For example, for load securement systems involving chains, drivers should understand the working load limit or rated capacity of the chain or sling components as well as the minimum breaking force as tested and verified by the manufacturer of the chain or sling components. Training also covers other aspects of load securement, including relevant regulations, inspection intervals, required securement points based on load dimensions, and securement strategies/types of tie-downs. Common cargo securement violations include failing to secure vehicle equipment, failing to load vehicles to prevent load shifts, insufficient tie-downs, loose or unfastened tie-downs, and damage to securement systems or tie-downs.

Where to Use

This is mandatory for all commercial truck drivers.

Safety Effectiveness

Regular cargo and tie-down inspection intervals are required for compliance with regulations as well as to enhance safety. For example, it is recommended that drivers inspect their cargo before the vehicle is taken on the road, within the first 50 miles of any trip, and then at regular intervals based on whichever occurs first: every 150 miles, every 3 hours of driving, or each duty status change. Regular inspection can prevent load shift issues by allowing drivers to detect movement or shifting of a load before it becomes a safety hazard.

Enhancements

In the aviation industry, training has proven highly effective for commercial pilots. Training is done using a standardized curriculum and meeting training requirements outlined in 14 CFR Part 135 and 142. This standardization has aided in the effectiveness of training as all carriers are required to meet the same standards and provide the same training at the same frequency to all pilots. Standardized curricula are created for specific aircraft types and include applicable regulations, resources for maintaining training syllabi, differences in training types (initial hires, initial equipment, transitions, upgrades, recurrent, adaptive recurrent, or requalification) as well as recommended topics covered and sample checklists to utilize during training. This standardization would benefit motor carriers looking to improve their driver training programs and training effectiveness; it would also ensure that all motor carriers' employees are operating with the same skill sets throughout the nation.

Costs and Service Life

Costs and training frequency requirements vary.

Post-Training/Certification Driver Education and Outreach Programs

Description

Driver education and outreach programs may benefit both professional trucking industries and nonprofessional drivers (e.g., those with passenger vehicle licenses operating rented or purchased large vehicles). Examples of education and outreach may include newsletters, seminars, coordination with driving schools, inclusion of a section related to BrTS in CDL testing, outreach with carrier organizations and independent operators, websites, annual safety courses, or any combination. Possible education or outreach programs may include the following:

- For professional truck drivers: This may include routine refresher courses on measuring vehicle and cargo height, selecting routes appropriate for their vehicle height, and ensuring commercial GPS systems with low-clearance structure warnings are used.
- For nonprofessional drivers: This may include coordination with local moving truck rental companies, RV retailers, and motor vehicle licensing offices to improve awareness of vehicle heights and roadway restrictions. Drivers may be unaware that truck prohibitions and low-clearance warnings apply to them, as formal education on this subject is often not provided upon issuance of driver licenses for passenger vehicles or when renting a vehicle.

One challenge to driver education is the diversity of the trucking industry where carriers range in size from large companies with more than 1,000 drivers to single-person owner-operators. Another challenge is bad operators (e.g., chameleon carriers that change the company name after being put out of business). It is generally difficult to change the behavior of these operators who intentionally violate rules and regulations.

Where to Use

Agencies can consider the following factors when assessing the potential use of driver education and outreach programs:

- Crash history: Consider targeting outreach and education programs to the appropriate offending driver population, based on whether BrTS incidents are occurring due to professional truck drivers or nonprofessional drivers in similarly large vehicles. Further investigation may reveal patterns in BrTS incidents to narrow the target audience for education and outreach programs, such as whether these incidents are more often related to fleet operators or independent operators.
- Trucking industry needs: Consider a collaborative approach with trucking industry leaders to establish viable truck routes and standardized procedures for avoiding low-clearance structures.

Safety Effectiveness

Research is not yet directly available for applications of post-training/certification driver education and outreach programs as BrTS countermeasures.

Enhancements

Agencies can consider the following enhancements to driver education and outreach programs:

- In-cab height placards: This may be particularly beneficial for nonprofessional drivers renting or purchasing vehicles when a formal training program is not required to operate the vehicle.
- Enforcement of truck prohibitions through fines or other techniques: This may improve adherence to truck restriction policies and subsequently reduce BrTS incidents. This may require coordination with law enforcement and policymakers in adjacent states or jurisdictions as well as tribal community representatives.
- Newsletters or similar: Photographs of bridge hits, congestion caused by bridge hits, and associated statistics may be beneficial, particularly if this information is distributed in response to permit requests.
- Consider requiring periodic (e.g., annual) refresher courses to promote continuous awareness of the associated social and economic costs of BrTS events and how to prevent them.

Costs and Service Life

Costs and service life vary depending on the agency offering certifications, frequency of staff turnover for personnel receiving training, and frequency of refresher courses.

Other Tried Strategies

In addition to the extensive list of countermeasures in the previous sections, transportation agencies and local governments have tried other strategies to prevent or mitigate BrTS. The following are select examples of these strategies:

1. Lane reduction.
2. Ramp closure.
3. Increased fines and enforcement.

Lane Reduction

If there are multiple lanes under a bridge or in a tunnel, there is an opportunity to reduce the number of lanes. A lane reduction intends to shift the travel path of vehicles to the location where there is the greatest clearance height and avoid areas under the bridge where there is low clearance. Other benefits of lane reduction can include reduced travel speeds, increased driver awareness of warning signs, and added shoulder width for pedestrian or bicycle facilities.

Example Application: In June 2023, the NYSDOT implemented this strategy on the four-lane Route 370 (Onondaga Lake Parkway) for a distance of 1,200 feet on each side of the CSX railroad bridge, which is intended to calm traffic and give OHVs additional time to heed the warning signs and avoid the bridge. The lane restrictions are being evaluated for their effectiveness and their impact on traffic conditions.

Ramp Closure

Ramp closures could involve complete closure to all vehicles or partial closures that prohibit certain vehicles from using specific ramps. The intent is to prevent larger vehicles from accessing roads with low-clearance bridges or tunnels.

Example Application: The NYSDOT implemented this strategy by closing a I-81 northbound ramp to State Highway 370 (Onondaga Lake Parkway) to eliminate trucks from directly accessing the parkway. The ramp closure is being evaluated to assess the impact and effectiveness of the lane reduction on the parkway.

Increased Fines and Enforcement

Local governments can increase fines for unpermitted and overweight vehicles as well as increase enforcement to support local laws. This strategy does not apply to transportation agencies, only to local communities and governments.

Example Application: In combination with lane reduction and ramp closure, the Village of Liverpool, New York, in January 2024, began enforcing its expanded truck ban, first with warnings and then with hefty fines. In the summer of 2023, the village board approved an expanded ban on trucks and tractor-trailers weighing over 5 tons from traveling through the village. The ban is designed to reduce truck traffic on Onondaga Lake Parkway as a further measure to prevent tall vehicles from hitting the famously low CSX railroad bridge. The enforcement began with signs informing drivers of the ban, a 1-week grace period, and then enforcement. The four-figure fines—ranging from $1,200 to $4,700—increase based on vehicle weight. An exception is made for local deliveries. The ban was formally introduced to motor carriers by a certified letter from the village and had to be approved by Onondaga County and the towns of Salina and Clay. While truck traffic from I-81 has been reduced with the ramp closure, which prevented many strikes, trucks from Liverpool still hit the bridge.

Data Quality Improvements

The purpose of this strategy is to improve the quality (completeness, accuracy, and accessibility) of data used to inform decisions, including the OHV permitting process. For instance, without accurate data on structure size, roadway conditions, and load size, the permitting process will not provide an optimal route. In some states, these data are collected but not easily accessible by motor carriers and those involved in the permitting process. In other cases, these data become stale over time. For instance, a 3-inch overlay causes a 3-inch reduction in vertical clearance that should be updated and reflected in the data. Transportation agencies can support this initiative by providing complete, up-to-date, and accessible inventory data for structure size and roadway conditions. Motor carriers and drivers can support this initiative by providing accurate data on the load size. There is an opportunity to leverage the use of burgeoning data exchanges to share and broadcast updated information, including information on the location of work zones and related restrictions.

As discussed in Section 2.5, there are opportunities to improve the quality of data related to BrTS crashes. Specifically, law enforcement and transportation agencies can move toward electronic crash reporting and adopt the suggested data fields in MMUCC to improve uniformity and consistency for identifying BrTS from the crash data. Further, agencies can consider installing cameras or other technology at high-risk locations to better capture the true number of BrTS crashes. Refer to Section 2.5 for further discussion on collecting, integrating, and disseminating relevant data to investigate and mitigate BrTS crashes.

CHAPTER 4

Countermeasure Selection Process

There are often multiple options for addressing crash contributing factors, ranging from higher-cost structure improvements to a specific location to lower-cost signing improvements at multiple locations or more wide-reaching policy strategies. The cost of structural repairs, structure closures, and related injuries may exceed the high installation costs associated with some countermeasures. The countermeasure options typically differ in the level of effectiveness, where higher-cost countermeasures may be more effective at mitigating high-risk locations, while lower-cost countermeasures may be more effective at mitigating risk across the system. As such, agencies should perform a benefit-cost analysis as part of the countermeasure comparison and selection process to quantify and compare the existing systemwide risk and change in systemwide risk under different alternatives. For instance, what is the benefit of a $1 million investment to a single bridge versus a $1 million investment across the system? Given a list of potential countermeasures that target the underlying risk or crash contributing factors, the next step is to perform a more detailed analysis of alternatives to identify the preferred alternative (e.g., most effective, most efficient). This chapter describes quantitative and qualitative measures for selecting and prioritizing countermeasures, focusing on alternatives analysis.

4.1 Quantitative Methods

Benefit-cost analysis and the Safe System Approach are two quantitative methods for prioritizing countermeasures. Benefit-cost analysis can help identify the most economically efficient alternative (i.e., greatest return per dollar spent) by comparing the present-value benefits and costs. The Safe System Approach can help identify the most safety-effective alternative (i.e., greatest potential to prevent death and serious injury) by comparing the countermeasure characteristics to the Safe System principles. The following is an overview of the benefit-cost analysis and Safe System Approach, including references to readily available resources for more information.

Benefit-Cost Analysis

Benefit-cost analysis utilizes monetized project benefits and costs where analysts assign dollar values to the various benefits (or disbenefits) for comparison against the monetary project costs. For example, if there is an expected change in crash frequency associated with a project alternative, compared to the base condition, then the analyst would multiply the expected change in crashes by the average crash cost. Safety-focused benefit-cost analysis includes the expected change in crash frequency, preferably by crash severity. The following is a list of other potential benefit (or disbenefit) categories that could result in changes due to the need for construction or detours around bridges that are under repair after a BrTS.

- Changes in cost for infrastructure repair and maintenance.
- Changes in cost for vehicle and cargo damage.

- Changes in travel time and delay.
- Changes in travel time reliability.
- Changes in vehicle operating cost.
- Changes in emergency service disruption.
- Changes in air emissions.
- Changes in noise.

Project costs typically include the following:

- Design and engineering.
- Land acquisition.
- Construction.
- Reconstruction/rehabilitation.
- Preservation.
- Routine maintenance.
- Mitigation (e.g., noise barriers).
- Utility relocation.
- Energy (e.g., for active warning signs).

For further information on benefit-cost analysis, refer to FHWA's *Highway Safety Benefit-Cost Analysis Guide* (Lawrence et al. 2018)

Safe System Approach

As described in Chapter 3, agencies may consider Safe System principles in selecting and prioritizing countermeasures. Countermeasures that align with more of the following Safe System principles are generally preferred:

- Death/serious injury is unacceptable: Agencies should not prioritize mobility over safety. Countermeasures that minimize the potential for crashes and minimize the severity of crashes should be a priority.
- Humans make mistakes: It is understood, and even expected, that humans using the transportation system will make mistakes and that those mistakes will lead to crashes. The intent is not to design a system that is completely void of all crashes. Instead, the intent is to design and operate the transportation system to accommodate human mistakes.
- Humans are vulnerable: A Safe System is one that minimizes forces in collisions to a level that does not exceed the limits of human tolerance.
- Responsibility is shared: It is unacceptable to solely blame road users for their lack of safety on a system that they have little to no involvement in planning, designing, and operating. Roadway owners and operators, vehicle and technology manufacturers, state policymakers, and law enforcement officers share responsibility with the road users in creating a Safe System.
- Safety is proactive: Agencies have an opportunity to address fatal and serious injury crashes before they occur. A Safe System proactively identifies and mitigates risk factors to reduce the chance of death and serious injury. This should be parallel to reactively addressing historical safety issues.
- Redundancy is crucial: Agencies can improve the safety of a system by building in redundancy. If one component fails, another component can prevent or mitigate the severity of a crash. A true Safe System provides enough redundancy to accommodate underlying risk factors without resulting in death or serious injury.

For further information on the Safe System Approach, refer to FHWA's *Integrating the Safe System Approach with the Highway Safety Improvement Program: An Informational Report* (Finkel et al. 2020).

4.2 Qualitative Methods

- In addition to quantitative factors, there are several qualitative factors for selecting and prioritizing countermeasures. Chapter 3 described basic qualitative factors for selecting initial countermeasures. Agencies can use those along with the following factors and the quantitative measures from the previous section to prioritize countermeasures for a select location (or projects within a larger program).
- Other planned projects and schedules: Countermeasures that can be implemented sooner and easier may be a higher priority, especially if those countermeasures can be implemented as part of a project that is already planned and programmed. Countermeasures implemented as part of other planned projects reduce construction-related costs and impacts (e.g., traffic delays) and generally provide cost savings for the overall program. The planning and scoping phase is the best time to identify and add safety components to a project, not the design phase (Atlanta Regional Commission 2022).
- Environmental and right-of-way impacts: Countermeasures with positive environmental benefits may receive higher priority than similar countermeasures with no or negative environmental impacts. Those needing right-of-way acquisition may receive lower priority because this presents a potential risk to project schedule and budget (Atlanta Regional Commission 2022).
- Agency familiarity or comfort with countermeasure: Agencies may consider factors such as "familiarity" as part of the countermeasure selection process, prioritizing those that have been implemented successfully in the past. It is also appropriate to consider countermeasures that may be different from typical agency policies or practices, assuming there is sufficient evidence to justify the cost-effectiveness and overall benefits with respect to the targeted risk factors. In these cases, it is useful to identify peer agencies that have demonstrated successful implementation of the countermeasure and include that as part of the project justification (Atlanta Regional Commission 2022).
- Long-term maintenance: While maintenance costs should be built into the quantitative benefit-cost analysis, agencies may prioritize countermeasures with longer-lasting effects and lower long-term maintenance needs. For instance, while it may take months or years to establish new policies or operational procedures, these types of strategies can have long-lasting effects with little to no long-term maintenance.

For further information on countermeasure selection, refer to FHWA's guide, *Selecting Projects and Strategies to Maximize Highway Safety Improvement Program Performance* (Gross et al. 2021).

CHAPTER 5

Post-Implementation Evaluation Process

The final step of the roadway safety management process is evaluation. There are three basic levels of post-implementation evaluations: project, countermeasure, and program level. In general, the objective of evaluations is to determine how a particular project, group of projects, or policy has affected one or more performance measures. Agencies use evaluation results to inform future funding and policy decisions. For instance, if evaluations show that certain programs or strategies are consistently effective, then agencies may choose to continue those programs and implement similar strategies at additional locations. If an evaluation shows that a project is not meeting expectations, then an agency may address the situation accordingly (e.g., remove the countermeasure or install supplemental countermeasures) (Atlanta Regional Commission 2022).

Project-level evaluations become the foundation for countermeasure- and program-level analysis. Countermeasure evaluations provide updated values of countermeasure effectiveness (e.g., crash modification factors) and help identify situations where the countermeasure is more (or less) effective (e.g., bridges or tunnels, rural or urban areas, high- or low-volume roads). Program evaluations can include an entire portfolio of projects or specific subprograms that focus on specific emphasis areas (e.g., bridges or tunnels, trucks and buses, oversize loads) (Atlanta Regional Commission 2022).

The following subsections describe project tracking and the fundamental concepts for evaluating projects, countermeasures, and programs, including measures of effectiveness, methods, and data to track before, during, and after implementation. Refer to FHWA's *Highway Safety Improvement Program Evaluation Guide* for further details on countermeasure and program evaluations and the related templates to support evaluations (Gross 2017).

5.1 Project Tracking

Project tracking is the basis of all evaluations. For each project, agencies should document the specific countermeasure(s) implemented, specific locations treated, implementation period (begin and end dates), and final project costs. Documented project costs should include preliminary engineering, right-of-way, and construction costs as applicable based on the final cost to complete the project (Atlanta Regional Commission 2022).

Tracking individual projects supports project-level evaluations and subsequently countermeasure- and program-level evaluations (Atlanta Regional Commission 2022). As such, there is a need to link each project with specific countermeasures, programs, and subprograms. As part of project tracking, the agency should note the applicable program(s) that funded the project as well as any emphasis areas targeted by the project (e.g., on-bridge strikes, under-bridge strikes with overhead structure, under-bridge strikes with pier or support, tunnel strikes).

5.2 Project-Level Evaluations

Project-level evaluations focus on individual projects and serve as the basis for more aggregate evaluations (countermeasure- and program-level). The following are general considerations related to performance measures, methodology, and data requirements for project evaluations.

Performance Measures

Safety effectiveness evaluations typically focus on crash-based performance measures, focusing on the localized safety impacts at the project location. Crash-based performance measures typically include site-specific changes in crashes, injuries, and fatalities. In addition, it is useful to evaluate target and correctable crashes (e.g., BrTS crashes as opposed to total crashes), particularly if the project targets specific crash types or crash contributing factors. For instance, roadway weather information systems target weather-related crashes, so it would be useful to evaluate the change in rain-, ice-, and snow-related crashes in addition to other common safety performance measures (e.g., total and fatal plus injury crashes) (Atlanta Regional Commission 2022).

While crash-based measures are preferred for safety-focused evaluations, there is the potential to use other performance measures to assess the operational effectiveness of completed projects. Operational performance measures may include operating speed, driver compliance, and driver response. Further, it may be useful to assess the economic performance of a project through measures such as the observed benefit-cost ratio; however, economic measures are susceptible to influence from a few severe crashes, particularly when using simple before-after methods to evaluate the change in crashes. For example, just one fatal crash in the before or after period can have a substantial impact on the estimated benefit.

Methodology

At the project level, the intent is to determine whether the project achieved its objective and addressed the crashes and/or risk factors that were the impetus of the project (Atlanta Regional Commission 2022). This section focuses on crash-based performance measures, but the same methods can generally be applied using other noncrash-based performance measures. For crash-based project-level evaluations, the simple before-after method and test of proportions are appropriate. While more rigorous methods can produce more reliable results, this is generally not necessary at the project level (Atlanta Regional Commission 2022).

The simple before-after method compares the performance measure before and after the implementation of the project, typically excluding the year(s) of construction. Project-level evaluations should include 12-month increments to avoid seasonal impacts, and it is preferred to use the same duration for the before-after period (e.g., 3 years before and 3 years after). If the duration of the before-and-after periods is different, it is important to normalize the analysis on a per-year basis. Note this method does not account for changes in traffic volume or other factors from the before to the after period, which can impact the results (Gross 2017).

Table 14 provides an example of a crash-based project-level evaluation using the simple before-after method. In this example, the study period is 7 years, which includes 3 years before and after implementation and excludes the one year of implementation. For this example, the sample data indicates a 6.7% increase in total crashes and a 60% reduction in target crashes (Gross 2017).

The test-of-proportions method compares the proportion of target crashes to total crashes before and after implementation (Gross 2017). For example, an agency may compare the proportion of weather-related crashes before and after installation of a roadway weather information system at a bridge. This method is particularly useful and generally more appropriate than the

Table 14. Example crash-based project-level evaluation using simple before-after method.

Crash Category	Crashes Before Implementation (3-year period)	Crashes During Implementation (1-year period)	Crashes After Implementation (3-year period)	Change (before-after)	% Change
Total crashes	15	Excluded	16	−1	6.7% increase
Target crashes	5	Excluded	2	3	60.0% reduction

Table 15. Example crash-based project-level evaluation using test-of-proportions method.

Total Crashes Before (3-year period)	Target Crashes Before (3-year period)	Proportion of Target to Total Crashes Before	Crashes During Implementation (1-year period)	Total Crashes After (3-year period)	Target Crashes After (3-year period)	Proportion of Target to Total Crashes After
18	12	0.67	Excluded	9	3	0.33

simple before-after method, when the traffic volume changes from the before to the after period. Similar to the simple before-after method, evaluations should include 12-month increments to avoid seasonal impacts, and it is preferable to include at least 3 years before and after implementation in the study period. Unlike the simple before-after method, the test-of-proportions method is not affected by different durations of before-and-after periods.

Table 15 provides an example of a crash-based project-level evaluation using the test-of-proportions method. Similar to the prior example, the study period is 7 years, including 3 years before implementation, 3 years after implementation, and excluding the implementation year (Gross 2017). The target crashes will depend on the project of interest. In this example, the proportion of target to total crashes is 0.67 before implementation and 0.33 after implementation. The result is a difference of −0.33 from the before to the after period, indicating a 50% reduction in the proportion of target crashes.

Data Requirements

For simple before-after, crash-based project-level evaluations, it is desirable to use a minimum of 3 full years of before-data and 3 full years of after-data (Atlanta Regional Commission 2022). There may be a need for more years of data to better understand the long-term averages. This is particularly true for projects that target rare or seemingly random crash types (e.g., a BrTS). While a longer study period generally provides a larger sample of crashes for analysis, it also increases the chances for other changes over time (e.g., roadway or operational changes, driver behavior, or vehicle fleet) (Gross 2017). As such, agencies should balance the study period with the potential for other changes over time.

5.3 Countermeasure-Level Evaluation

Countermeasure-level evaluations focus on the effectiveness of similar projects, often with the intent to develop a crash modification factor (CMF). Countermeasure-level evaluations inform future decisions, particularly when estimating the expected benefits of other similar proposed projects. As evaluations demonstrate the effectiveness of countermeasures, there is an opportunity for agencies to integrate those measures in planning and design policies rather than implementing them on an as-needed basis. The following are general considerations related to performance measures, methodology, and data requirements for countermeasure evaluations.

Performance Measures

If the intent is to develop a CMF, agencies should use crash-based measures for countermeasure-level evaluations. Crash-based measures include the frequency and severity of crashes. It is often useful to evaluate the countermeasure effects separately for fatal and injury (FI) crashes and property damage only (PDO) crashes. This supports future benefit-cost analyses where the net benefits are based on CMFs by severity. There is also the option to evaluate the effect of countermeasures by crash type. This can be useful to assess programs or countermeasures that target specific crash types.

Methodology

Crash-based before-after studies are generally appropriate to evaluate countermeasures and develop CMFs. If the intent is to develop a CMF for use in future decisions, then agencies should use more reliable methods such as the Empirical Bayes before-after method or before-after with comparison group method for countermeasure-level evaluations. As shown in Table 16, the more reliable methods account for potential sources of bias, such as regression-to-the-mean, changes in traffic volume, the nonlinear relationship between crashes and traffic volume, and other changes over time (Gross 2017).

In before-after studies, some change occurs during the study period (i.e., projects are implemented). The simple methods focus on the safety performance at the treated locations over time. The more reliable methods incorporate information from a comparison or reference group (i.e., untreated locations) to adjust for other changes over time that affect safety performance. As shown in Table 16, the Empirical Bayes before-after method is the more reliable method for developing quality CMFs because it can properly account for potential sources of bias (Gross 2017). Refer to FHWA's *A Guide to Developing Quality CMFs* (Gross, Persaud, and Lyon 2010) and FHWA's *Highway Safety Improvement Program (HSIP) Evaluation Guide* (Gross 2017) for more information on the simple, comparison group, and Empirical Bayes before-after methods, including equations and templates to implement the methods.

Table 16. Overview of before-after methods.

Method	Accounts for Regression-to-the-Mean	Accounts for Changes in Traffic Volume	Accounts for Nonlinear Relationship Between Crashes and Traffic Volume	Accounts for Other Changes Over Time
Simple	—	—	—	—
Simple with linear traffic volume correction	—	•	—	—
Comparison group	—	•	—	•
Empirical Bayes	•	•	•	•

Note: – = Does not account for the given issue.

Data Requirements

The primary data requirements for countermeasure evaluations include the following:

- Treatment locations: Select the treatment sites for inclusion in the evaluation. This should include all sites that represent typical conditions and applications of the treatment of interest (no cherry-picking). It is not appropriate to exclude certain sites because the results are not favorable. This can bias the resulting CMF and lead to misinformed future investment decisions. It may, however, be appropriate to exclude a site from the analysis if the conditions (e.g., site characteristics or treatment application) are different from the other sites included.
- Crash data: It is recommended to use 3 to 5 years of crash data before and after implementation (Gross 2017).
- Traffic data: Traffic volume is used in three of the four methods shown in Table 16 to adjust for changes over time. It is acceptable to use a single value to represent the traffic volume in the before period and a single value to represent the traffic volume in the after period; however, it is important to use values that reflect any changes in traffic from one period to the next because changes in traffic are directly related to changes in crashes.
- Comparison group: For the comparison group before-after method, there is a need for data from an untreated group of similar sites to account for temporal effects and changes in traffic volume (Gross 2017). The sites should be similar to the treatment sites but without the treatment.
- Reference group: For the Empirical Bayes before-after method, there is a need for an applicable safety performance function (SPF) and dispersion parameter. Many states have developed or calibrated SPFs for use in safety analyses. If there is not an applicable SPF for the facility type of interest, then it would be necessary to develop or calibrate an SPF using data from a reference group.

To increase the reliability of countermeasure evaluations, there is a need to include multiple similar projects in the analysis rather than a single project (Gross 2017). While countermeasure-level evaluations could be based on a few sites, this will typically result in a large standard error and lower confidence in the result. When grouping multiple projects, there is a need to consider the consistency among projects (e.g., strategies and site characteristics) and the potential for different effects under different conditions. Different combinations of countermeasures and site characteristics along with variations in vehicles and driver behavior can result in different countermeasure effects.

Sample size is another consideration in data collection and countermeasure evaluation. The sample size necessary to obtain statistically significant results depends on the desired level of confidence and the magnitude of the countermeasure effect. As the desired level of confidence increases (e.g., from 90% to 95%), so does the minimum sample size. Similarly, a larger sample is necessary to detect smaller changes in safety (e.g., a larger sample is necessary to detect a 10% change in crashes compared to the sample needed to detect a 40% change in crashes).

Table 17 presents minimum sample sizes for a before-after with comparison group study that can serve as a conservative sample size estimate for an Empirical Bayes study. The table shows the minimum number of crashes to detect different levels of effectiveness (i.e., best guess at how effective the countermeasure will be) at common levels of significance. For example, if the expected level of effect is a 20% reduction in crashes and the desired level of significance is 0.10 (90% confidence), then the minimum number of crashes is 193 (Gross 2017). These estimates assume the number of comparison sites is equal to the number of treated sites, and the duration of the before-and-after periods are equal. This indicates a minimum sample of 193 crashes in both the before-and-after periods for both the treatment and comparison groups. For scenarios not listed in the table, refer to the spreadsheet template in FHWA's *Highway Safety Improvement Program (HSIP) Evaluation Guide* (Gross 2017). Do not use linear interpolation or extrapolation

Table 17. Minimum sample size (number of crashes) for before-after with comparison group method.

Expected Level of Effect (% Change)	0.10 Level of Significance (90% Confidence)	0.05 Level of Significance (95% Confidence)
10	1,155	1,858
20	193	279
30	67	95
40	29	41

to estimate sample sizes for other levels of significance or levels of effect from the numbers in the table because the trends are nonlinear (Gross 2017).

Once the minimum sample size is determined in terms of the number of crashes, it is possible to determine the number of years needed to accumulate the minimum crashes given the sample of projects available for countermeasure evaluation. In general, the study period should include at least 3 years before and after implementation and exclude the implementation period from the analysis. It is possible to use different durations for the before-and-after periods (e.g., 5 years before and 3 years after); however, the before-and-after periods should represent 12-month increments to avoid seasonal bias. For some countermeasures, it may be difficult to collect the minimum sample size due to a low number of crash occurrences. Increasing the duration of the study period is one option to increase the number of crashes for analysis; however, this can introduce bias if other changes occur over time as discussed previously. When other options to increase the sample size are unavailable or undesirable, an alternative is to accept a lower level of significance (e.g., 0.15 or 0.20) as opposed to the typical value of 0.05 or 0.10 as an interim step (Gross 2017).

5.4 Program-Level Evaluation

Program-level evaluations focus on the overall program and subprograms with the ultimate goal of improving the efficiency of projects, programs, and policies. These types of evaluations are particularly useful for strategies or programs that are not specific to a single location (e.g., statewide permitting policy on specialized loads). The following are general considerations related to performance measures, methodology, and data requirements for program evaluations.

Performance Measures

Crash-based program-level evaluations measure effectiveness by changes in the frequency, severity, and rate of crashes at the system level. This can occur at the national level, statewide level, program or subprogram level, or jurisdiction level (region or county). In general, it is appropriate to include all projects associated with a given program for the program-level evaluation. Similar to countermeasure-level evaluations, it is not appropriate to exclude certain sites or countermeasures because the results are not favorable. This can bias the program-level evaluation results and lead to misinformed future investment decisions.

Methodology

There are various methods to assess program effectiveness, including the number of BrTS crashes and the rate of BrTS crashes per 100 million truck-miles traveled. Agencies can compare

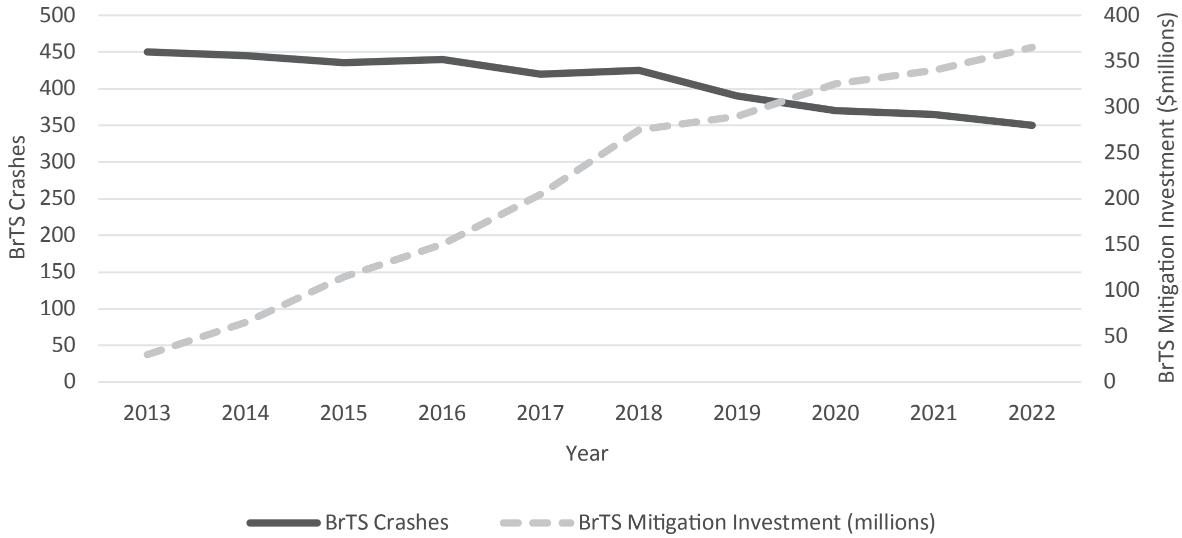

Figure 53. Hypothetical comparison of statewide BrTS crashes versus level of investment over time.

these basic measures over time and compare against factors such as the number of related projects and level of investment (i.e., dollars spent). Figure 53 shows an example comparison of statewide BrTS crashes over time versus the level of investment in BrTS mitigation strategies.

Data Requirements

The primary data requirements for program evaluations include the performance measure of interest (e.g., BrTS crashes by severity) and general information for each project or countermeasure within the program. Project- and countermeasure-level details could include the applicable program(s) that funded the activity, applicable focus areas (e.g., on-bridge strikes, under-bridge strikes with overhead structure, under-bridge strikes with pier or support, tunnel strikes), and final costs to complete the project.

CHAPTER 6

Conclusion

Bridge and tunnel strikes (BrTS) damage infrastructure, damage vehicles and cargo, create traffic delays, disrupt access to communities, and kill and injure people. For motor carriers, BrTS crashes have the potential to result in insurance increases, safety rating drops, operator termination, and direct responsibility to pay for the cost of repairs. While BrTS crashes can be catastrophic, there have been several challenges to addressing these crashes, including under-reporting of crashes, low crash density (crashes spread across the network), and data quality issues. Further, BrTS crashes are complex and may involve several diverse contributing factors, such as roadway characteristics, bridge or tunnel characteristics, driver or human factors, and vehicle and load factors. Some of these factors are location-specific (e.g., roadway and bridge characteristics), while others could occur randomly (e.g., unsecured load) or propagate throughout the system (e.g., inattentive driver). This guide provides a foundation for identifying priority (high-risk) locations; diagnosing BrTS risk factors; and planning, prioritizing, implementing, and evaluating multidisciplinary strategies to mitigate BrTS risk. By diagnosing BrTS risk and crash contributing factors, agencies can better target engineering, operational, education, outreach, and enforcement policies and strategies to address those specific underlying factors. By quantifying BrTS risk and considering safety alongside other performance measures (e.g., resilience), agencies will better understand the comprehensive costs and benefits of projects, which will lead to more informed decisions and impactful investments.

The following is a list and summary of opportunities to employ this guide in practice:

- Identify high-risk BrTS locations.
- Diagnose BrTS contributing factors.
- Select and prioritize countermeasures to mitigate BrTS risk.
- Evaluate the effectiveness of BrTS projects and programs.
- Enhance BrTS data and analysis capabilities.

Identify high-risk BrTS locations. The first step to addressing BrTS risk is to locate each crash to the respective bridge or tunnel. The guide describes various methods for locating crashes as well as the strengths and limitations of those methods. There are also various options for prioritizing bridges and tunnels, including crash-based and risk-based methods. The guide describes the challenges in using traditional crash-based methods and the value of using a risk-based approach to assess the vulnerability of the infrastructure and proactively mitigate BrTS risk.

Diagnose BrTS contributing factors. Before an agency identifies countermeasures, it is important to understand the factors contributing to and associated with BrTS risk. This guide provides an overview of risk-based assessments and a list of common factors that increase BrTS risk. It also includes data collection and analysis procedures that agencies could use to identify jurisdiction-specific risk factors and assess BrTS risk based on state, regional, or local data.

Select and prioritize countermeasures to mitigate BrTS risk. Once an agency identifies BrTS contributing factors, the next step is to identify appropriate countermeasures to target the underlying issue(s). This guide provides a list of common engineering, operational, education, outreach, and enforcement policies and strategies to address specific BrTS risk factors. The guide also includes detailed descriptions and information on the applicability, effectiveness, and cost of the various countermeasures. This will help practitioners identify appropriate options to address the issue at hand. The guide provides methods to pare down the initial list of options to the preferred alternative through the analysis of alternatives. This supports the development of agency-wide strategies and procedures to mitigate BrTS risk.

Evaluate the effectiveness of BrTS projects and programs. The final step is to evaluate projects and programs to understand their effectiveness and return on investment. This guide describes fundamental concepts for tracking and evaluating projects and programs, including measures of effectiveness, methods, and data needs. Agencies should then use the evaluation results to inform future funding and policy decisions.

Enhance BrTS data and analysis capabilities. Beyond the analysis of jurisdiction-specific issues, there is a need for agencies to provide accessible data and information for external users. This guide describes opportunities for agencies to contribute data to a national BrTS Clearinghouse to improve the completeness, accuracy, and accessibility of a comprehensive and up-to-date inventory of BrTS data. This will support national efforts, such as cross-jurisdiction truck routing, BrTS research, and BrTS tracking and reporting. Given complete and quality data, the national BrTS Clearinghouse can provide estimates of the risk (i.e., likelihood and consequences) of a BrTS crash based on bridge, tunnel, roadway, and operational characteristics. Transportation agencies can then use this information to identify roadway, bridge, and tunnel locations for potential infrastructure improvement projects. Commercial motor vehicle enforcement officials can use this information to identify risk factors and potential locations for implementing enforcement strategies. Motor carriers can use this information to identify routes that are higher risk and instruct their drivers to avoid such routes, and researchers can use the BrTS Clearinghouse to advance the state of the practice for identifying and addressing BrTS risk.

Glossary

Countermeasure – an infrastructure improvement, behavioral or enforcement program, or other treatment that is meant to reduce the frequency and or severity of crashes.

Crash-level data – a description of the overall characteristics of a crash event. Datasets may include time, date, location, first harmful event, most harmful event, manner of collision, light conditions, road surface conditions, number of vehicles involved, highest injury severity recorded, and direction of vehicles, among other elements for each crash event. Crash-level data may be further disaggregated into vehicle-level data.

Crash tree – a diagram that shows the breakdown of crashes occurring at an individual location or across a network by selected data elements and attributes. By disaggregating crash datasets in this manner, agencies can identify common characteristics (geometric or otherwise) associated with varying subsets of crashes to narrow the focus of the safety analysis and resulting countermeasure selection.

Evaluation – a post-implementation review of a project, countermeasure, or program to assess its effectiveness. This is the last step of a comprehensive roadway safety management process and can help to inform future policy decisions and target future funding allocations.

Exposure – a measure of the number of potential opportunities for a crash to occur. In the context of BrTS events, exposure generally equates to the traffic volume observed at the bridge or tunnel under consideration.

Focus crash-type – the crash type around which a systemic safety program is built and defined using crash, roadway, person, and other data elements as needed. In the context of this guide, the focus crash-type is a BrTS crash; however, this may be further refined based on elements such as crash severity, structural element struck, or other focus areas defined by the investigating agency.

Focus facility-type – the facility type around which a systemic safety program is built. Typically, this is the facility type on which the largest proportion of focus crashes occurs, on which focus crashes are overrepresented, or on which selection is derived from another program or safety plan. Within the context of this guide, examples of focus facility-types may include bridges, tunnels, over bridges, bridges carrying freeways, bridges with pedestrian facilities, or any other related definition selected for safety analysis.

On-bridge (or in tunnel) collision with superstructure – a crash that occurs while a vehicle is traveling over a bridge or within a tunnel and involves a component of the bridge superstructure (e.g., railing or truss) or tunnel walls.

Overheight vehicle – vehicles and loads beyond legal size limitations or standard-size vehicles beyond a local height limitation of a specific bridge or tunnel.

Overrepresentation – the comparison of the proportional distribution of a set of subject data to a set of comparison data with the goal of identifying attributes for which the subject data accounts for a notably larger proportion than the comparison group. For example, if one out of 30 bridges in a jurisdiction accounts for 20% of all reported over-bridge crashes, that bridge and crash type combination is overrepresented within the network.

Performance measure – a quantitative, qualitative, or hybrid indicator used to prioritize locations for further investigation or to assess the effectiveness or efficiency of projects, countermeasures, or programs. Crash-based performance measures may include the number of crashes by type and/or severity. Risk-based performance measures may include the risk score for a given location or the percentage of the system with a risk score exceeding a specified threshold. Operational performance measures may include operating speeds, driver compliance, and driver response.

Risk – made up of two elements: a qualitative or quantitative measure of the likelihood of a BrTS event and a quantitative or qualitative measure of the impacts (road closures, infrastructure repairs, crash consequences, crash costs, etc.) of such an event given that one occurs.

Risk score – a quantitative measure based on the presence and weight of risk factors for each element being considered in a safety analysis. Ranking potential project locations by their total risk score can help agencies identify and prioritize locations with the greatest opportunity for safety improvements.

Severe crash – the subjective definition in the context of this guide depending on the performance measure of interest. May be defined by a jurisdiction using an injury category (such as fatal and suspected serious injury), a threshold of resulting structural damage, or some combination of related elements.

Site-level data – summary of data for an individual location, such as a bridge or tunnel structure. This may include crash, roadway, traffic, and structure datasets among others.

Systemic safety – a proactive form of safety management in which agencies install proven safety countermeasures at locations that are prioritized based on their relative level of risk.

Target crashes – the subset of crashes for which analysis and countermeasure applications are focused. For example, an agency may select BrTS crashes as their target crash dataset for safety analysis, or they may choose to refine their definition further to target over-bridge crashes involving heavy vehicles striking outside barriers. Some countermeasures specifically target certain crash types, such as lighting improvements to reduce nighttime crashes.

Under-bridge (or entering tunnel) collision with substructure – a crash that occurs while a vehicle is traveling under a bridge or entering a tunnel and involves a component of the bridge substructure (e.g., supports) or tunnel entrance.

Under-bridge (or entering tunnel) collision with superstructure – a crash that occurs while a vehicle is traveling under a bridge or entering a tunnel and involves a component of the bridge superstructure (e.g., girder, truss) or tunnel entrance.

Vehicle-level data – the characteristics of each vehicle involved in a crash event. Datasets may include a description of damage, insurance company information, make and model of vehicles, registration, number of occupants, travel direction, and sequence of events before the crash, among other elements.

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Acronyms

AADT	Annual average daily traffic
ALPR	Automatic license plate reader
BrTS	Bridge and tunnel strikes
BTS	Bureau of Transportation Statistics
CB	Citizens band [Radio]
CDL	Commercial Driver's License
CMF	Crash modification factor
CMS	Changeable message sign
CSV	Comma-separated values
ETL	Extract, transform, and load
FI	Fatal and Injury
FMEA	Failure mode and effects analysis
GIS	Geographic information systems
GPS	Global positioning system
HSIP	Highway Safety Improvement Program
ID	Identification
LADAR	LAser Detection And Ranging [System]
MMUCC	Model Minimum Uniform Crash Criteria
MUTCD	*Manual on Uniform Traffic Control Devices for Streets and Highways*
NB	Negative binomial
NBI	National Bridge Inventory
NTI	National Tunnel Inventory
NYSDOT	New York State Department of Transportation
OHV	Overheight vehicle
OHVD	Overheight vehicle detection
OS/OW	Oversize/overweight
PDO	Property damage only
P/EVO	Pilot/escort vehicle operator
SPF	Safety performance function
UUID	Universal Unique Identifier
VTrans	Vermont Agency of Transportation

APPENDIX

Resources

This section includes a summary of other applicable guides and tools that may be of interest to the reader. These resources provide additional details on systemic safety and the Safe System Approach and support implementation of the methods described in this guide (e.g., benefit-cost analysis and post-implementation evaluation).

Crash Costs for Highway Safety Analysis **(FHWA)** (Harmon, Bahar, and Gross 2018): This guide describes the various sources of crash costs, current practices and crash costs used by states, critical considerations when modifying and applying crash unit costs, and the feasibility of establishing national crash unit cost values. It also proposes a new set of national crash unit costs and presents procedures to update the costs over time and among states (e.g., adjust national crash costs based on state-specific cost of living, injury-to-crash ratio, and vehicle-to-crash ratio).

Developing an Effective Evaluation Plan: Setting the Course for Effective Program Evaluation **(CDC)** (CDC 2011): This document provides information for developing a living "Evaluation Plan" for public health programs. In the case of highway safety, agencies may consider the knowledge and guidance in this document for the management, evaluation, and improvement of their BrTS safety program. The document helps program administrators identify answers to three questions about their program: what, how, and why it matters. The 6-step process presented in the document will help provide answers to these questions as well as assist program managers with improving their plan.

Highway Safety Benefit-Cost Analysis Guide **(FHWA)** (Lawrence et al. 2018): This guide provides methods to quantify the costs and direct and indirect safety-related benefits of project alternatives. Direct safety benefits include the expected change in crash frequency and severity. Indirect benefits include the operational and environmental benefits that result from a reduction in crashes (e.g., reduced delay, fuel use, and emissions). The guide also describes the data requirements and considerations associated with benefit-cost analysis. Examples demonstrate the application of the methods in various scenarios, including both site-specific and systemic projects with single or multiple countermeasures.

Highway Safety Improvement Program (HSIP) Evaluation Guide **(FHWA)** (Gross 2017): This guide provides direction on how to track critical project details in support of HSIP evaluation, perform three different levels of evaluation (i.e., project, countermeasure, and program level), and use the results of HSIP evaluations to improve decisions and processes. It describes the methods, data requirements, and considerations associated with the different levels of evaluation. Examples from various states highlight noteworthy practices and the benefits of evaluation.

Safe System Approach **(U.S. DOT, n.d.)**: The website "What Is a Safety System Approach" establishes the Safe System Approach as the guiding principles and elements for a safer road system.

Systemic Safety User Guide **(FHWA)** (Gooch et al. 2024): This document is a guide for a risk-based approach to identifying and addressing systemwide safety opportunities. It provides assistance for identifying and implementing countermeasures and methods for assessing their effectiveness.

The Art of Appropriate Evaluation—A Guide for Highway Safety Program Managers **(NHTSA)** (Pullen-Seufert and Hall 2008): This guide provides an overview of the traffic safety evaluation process, specifically for safety program managers. The guide helps the manager identify the appropriate evaluation method for a project as well as how to choose a well-qualified professional evaluator for a safety program.

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Abbreviations and acronyms used without definitions in TRB publications:

A4A	Airlines for America
AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FAST	Fixing America's Surface Transportation Act (2015)
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
GHSA	Governors Highway Safety Association
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S. DOT	United States Department of Transportation

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