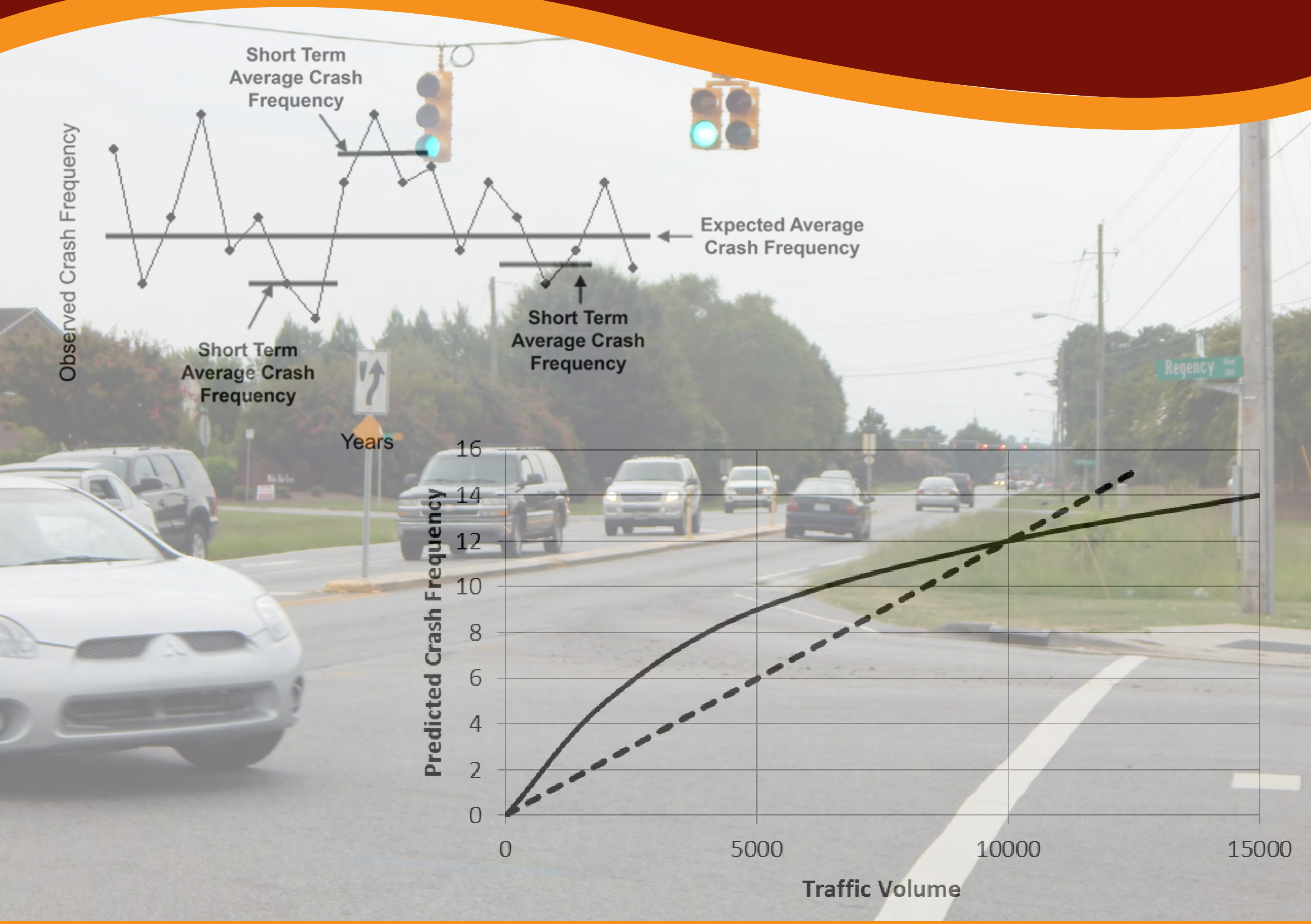
Reliability of Safety Management Methods

Systemic Safety Programs



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16. Abstract

High quality data and reliable analytical methods are the foundation of data-driven decision-making. The Reliability of Safety Management Methods series includes five information guides that identify opportunities to employ more reliable methods to support decisions throughout the roadway safety management process. Four of the guides focus on specific components of the roadway safety management process: network screening, diagnosis, countermeasure selection, and safety effectiveness evaluation. The fifth guide focuses on the systemic approach to safety management, which describes a complementary approach to the methods described in the network screening, diagnosis, and countermeasure selection guides. The purpose of the Reliability of Safety Management Methods series is to demonstrate the value of more reliable methods in these activities, and demonstrate limitations of traditional (less reliable) methods.

The Reliability of Safety Management Methods: Systemic Safety Programs guide describes the state-of-the-practice and the latest tools to support systemic safety analysis. The target audience includes program managers, project managers, and data analysts involved in projects that impact highway safety. The objectives of this guide are to: 1) raise awareness of the systemic approach to safety management, 2) characterize typical projects identified and implemented through a comprehensive safety management program, 3) demonstrate the value of integrating systemic approaches as part of a comprehensive safety management program, and 4) provide information on allocating funding to systemic projects within a comprehensive safety management program.

This guide includes six sections and an appendix. The first section introduces roadway safety management and the purpose of safety programs. The second section provides an overview of two general approaches that support a comprehensive safety program, including a discussion of the high-level strengths and limitations. The third section demonstrates the value of projects implemented through various safety programs. Empirical examples lead to cost-effectiveness estimates and information on integrating the systemic approach within a comprehensive safety program. The next sections summarize the data requirements to employ, and available tools and resources to support, a comprehensive approach to safety management. The final section describes future research needs to enhance the state of the knowledge on the systemic approach. An appendix provides detailed information related to the methods and examples presented throughout the guide.

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CMF	Crash Modification Factor
DOT	Department of Transportation
EB	Empirical Bayes
FHWA	Federal Highway Administration
HFST	High Friction Surface Treatment
HSIP	Highway Safety Improvement Program
MIRE FDE	Model Inventory Roadway Elements—Fundamental Data Elements
MUTCD	Manual on Uniform Traffic Control Devices
SHSP	Strategic Highway Safety Plan
SPF	Safety Performance Function
TRID	Transport Research International Documentation

PREFACE

High quality data and reliable analytical methods are the foundation of data-driven decision-making. The Reliability of Safety Management Methods series includes five information guides that identify opportunities to employ more reliable methods to support decisions throughout the roadway safety management process. Four of the guides focus on specific components of the roadway safety management process: network screening, diagnosis, countermeasure selection, and safety effectiveness evaluation. The fifth guide focuses on the systemic approach to safety management, which describes a complementary approach to the methods described in the network screening, diagnosis, and countermeasure selection guides. The purpose of the Reliability of Safety Management Methods series is to demonstrate the value of more reliable methods in these activities, and demonstrate limitations of traditional (less reliable) methods.

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1. INTRODUCTION TO ROADWAY SAFETY MANAGEMENT

At the most basic level, the roadway safety management process is a three-step process as shown in Figure 1 and outlined in the Highway Safety Improvement Program (HSIP) Manual.(1) The intent of this process is to identify and improve sites expected to benefit the most from targeted, cost-effective treatments. This aligns with the purpose of the Federal HSIP, which is to achieve a significant reduction in fatalities and serious injuries on all public roads.(2) To achieve this goal, the safety management process should maximize the opportunity to improve safety; otherwise, agencies may allocate resources inefficiently to sites with less potential for improvement while locations with a higher potential for cost-effective safety improvement remain untreated.

There are two general approaches to safety management: 1) selecting and treating sites based on site-specific crashes (referred to as the crash-based approach for this guide), and 2) selecting and treating sites based on site-specific geometric and operational attributes known to increase crash risk (referred to as the systemic approach for this guide). These two approaches are complementary and support a comprehensive approach to safety management. The primary difference is the way in which analysts identify issues and develop projects in the planning stage.

In either case, it is important to use reliable, data-driven methods to inform decisions. The Highway Safety Manual presents a predictive method to relate crash frequency to roadway design and operational characteristics through statistical models or safety performance functions (SPFs). A predictive approach based on a combination of historical crash, exposure, and roadway data is more reliable than approaches based on crash frequency alone or ad hoc analysis of geometric and operational attributes that may increase risk.

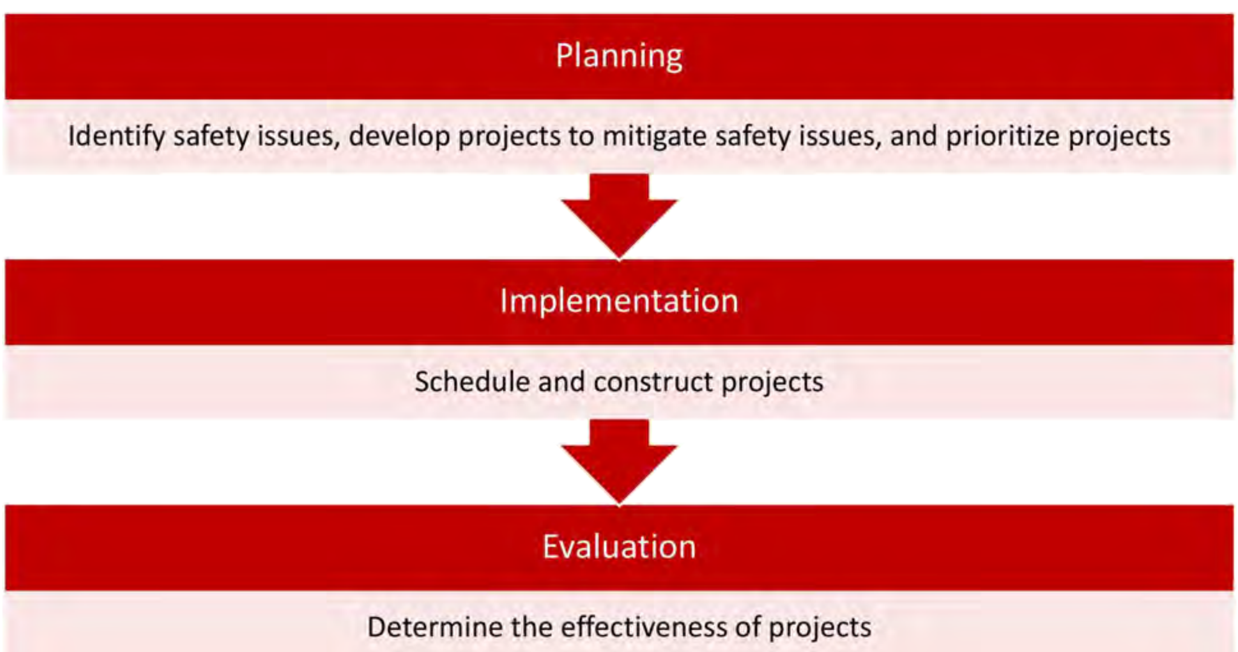

Figure 1. Chart. High-level overview of roadway safety management process.

2. OVERVIEW OF SAFETY MANAGEMENT APPROACHES

This section describes three approaches to safety management: crash-based, systemic, and policy-based.

CRASH-BASED APPROACH

The crash-based approach to roadway safety management is represented by the six-step process shown in Figure 2 and outlined in the Highway Safety Manual.[3] Most agencies employ at least the first three steps of this process: 1) network screening, 2) diagnosis, and 3) countermeasure selection. These three steps differentiate the crash-based approach from the systemic approach. The following is an overview of the crash-based approach.

1. **Network screening**: In the crash-based approach, analysts first identify sites based on site-specific, crash-based performance measures. For example, analysts may conduct crash-based network screening to identify candidate locations for safety projects with the highest frequency of crashes, highest potential for safety improvement, or worst safety performance. Refer to the *Reliability of Safety Management Methods: Network Screening* for further discussion of network screening.[4]
2. **Diagnosis**: Once an agency identifies a list of sites, diagnostic analyses serve to hone in on safety concerns at each site. The analyst (preferably a multidisciplinary analysis team) reviews the site-specific crash history and site characteristics (e.g., geometry, traffic operations, road users, and adjacent land use) in detail to understand and identify collision patterns and crash contributing factors. This provides the foundation for the identification and selection of appropriate countermeasures to mitigate the specific safety issues (e.g., crash patterns and contributing factors) at each site. Refer to the *Reliability of Safety Management Methods: Diagnosis* for further discussion of diagnosis.[5]
3. **Countermeasure selection**: Given a list of specific safety issues based on diagnosis, an agency can identify, assess, and select appropriate countermeasures. Appropriate countermeasures should directly target the underlying crash contributing factors, and may include engineering, education, enforcement, and EMS-related measures (i.e., the 4E approach). Refer to the *Reliability of Safety Management Methods: Countermeasure Selection* for further information and considerations related to countermeasure selection.[6]

The following points provide a general characterization of the crash-based approach:

- Agencies use the crash-based approach as an effective means to identify sites and implement treatments at those sites with the highest potential for site-specific safety improvement. Agencies may refer to these locations as hotspots, blackspots, or sites with potential for improvement.
- The underlying safety issue typically varies at each site (i.e., agencies are not focused on addressing a specific issue unless the screening is carried out for a specific crash type).
- Projects can range from relatively simple and low-cost improvements (e.g., enhancing signing or striping, trimming vegetation, or modifying signal phasing) to substantial capital improvement projects (e.g., constructing a roundabout, modifying the skew angle of an intersection, or realigning a horizontal curve).
- There is an opportunity to achieve reductions in crash frequency and severity at treated locations given the focus on site-specific issues and targeted treatments.

Potential limitations of the crash-based approach include the need for site-specific data, the inability to efficiently address highly-dispersed crashes, and the potential for high-cost improvements at spot locations.

- **Site-specific data:** The crash-based approach uses site-specific crash data to identify sites with potential for improvement. Other site-specific data such as geometric and operational characteristics can enhance the reliability of crash-based network screening.
- **Highly-dispersed crashes:** It is difficult to address a high percentage of highly-dispersed crashes with the crash-based approach because this would require projects at many sites. Using the crash-based approach, it is difficult for an agency to objectively establish priorities for treatment among the many locations that have few, if any, crashes each but which cumulatively account for a large percentage of crashes in a jurisdiction.
- **Potential for high-cost improvements:** High-cost projects represent a higher financial risk in terms of contributing to the effectiveness of an agency's safety program. Dedicating large amounts of funds to a safety project at one location represents the identification of a problem and a commitment to fix it; however, if the project does not adequately address the problem, revisiting the location with another project within a few years can be difficult to justify from funding and public relations perspectives. Further, agencies can only treat a limited number of sites with high-cost improvements given a fixed budget. These projects may have a notable safety benefit at the improved locations, and on the system as a whole when the majority of crashes occur at relatively few locations. For crashes more distributed across the network, such as fatal and severe injury crashes or crashes on rural and local roads, high-cost projects have limited capacity to impact the safety performance of the system as a whole.

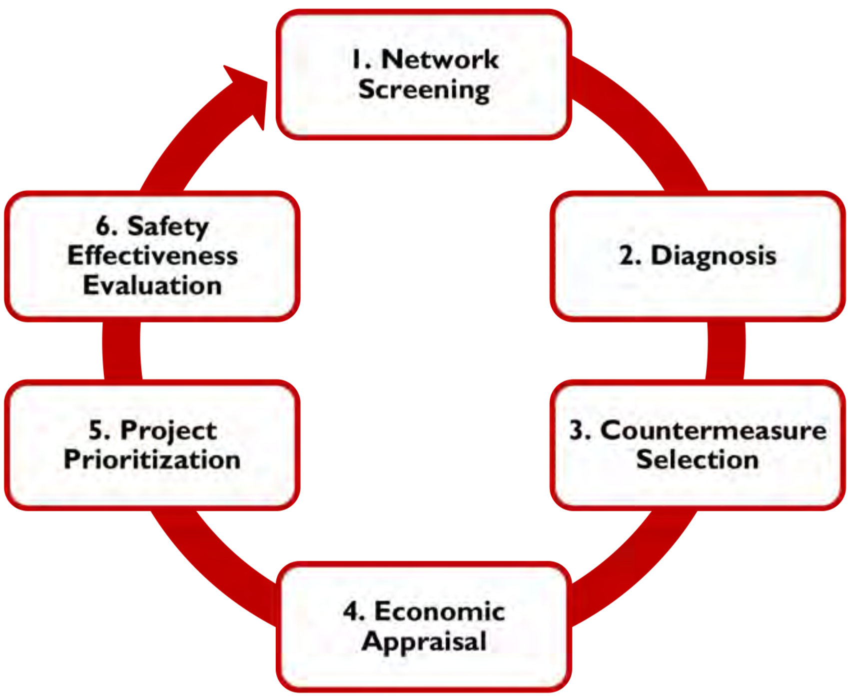

Figure 2. Chart. Schematic of crash-based roadway safety management process.

SYSTEMIC APPROACH

In the systemic approach, analysts identify sites based on site-specific geometric and operational attributes rather than observed crashes. The first three steps involved in the planning component of the systemic approach are: 1) identify focus crash types, facility types, and risk factors, 2) screen and prioritize candidate locations, and 3) select countermeasures. These steps are similar to the first three steps of the crash-based approach shown in Figure 2, but in a different order. The following is an overview of these three general steps:

1. **Identify focus crash types, facility types, and risk factors**: The first step in the systemic approach is to select focus crash type(s), facility types, and risk factors. This is similar to the second step in the crash-based approach (diagnosis). Focus crash types typically reflect prevalent severe crash types for a given jurisdiction. As noted in the Federal Highway Administration (FHWA) *Systemic Safety Project Selection Tool*, State and regional strategic highway safety plans (SHSPs) are a good starting point to identify focus crash types.(7) Focus facility types typically include the locations where the target crash types are most prevalent (e.g., rural, two-lane, undivided segments or urban, four-leg, signalized intersections). Risk factors are site-specific attributes common across locations with the focus crash type(s), and associated with an increased risk of the focus crashes. Risk factors may include site-specific crash history (if available) and geometric and operational attributes. For example, sharp horizontal curves are a common feature associated with roadway departure crashes. Analysts identify risk factors and the relative risk by analyzing crash data associated with the focus crash type and facility type from their jurisdiction or by reviewing previous research studies. Refer to the *Systemic Safety Project Selection Tool* for further information on the identification of focus crash types, focus facility types, and risk factors.(7)
2. **Screen and prioritize candidate locations**: The second step of this approach is to develop a prioritized list of potential locations for systemic improvement. This is similar to step one in the crash-based approach (network screening). Using risk factors as a guide, analysts identify sites on the focus facility types with these specific geometric and operational characteristics as candidate locations. To prioritize candidate locations, analysts assign a level of risk to each site based on the site-specific geometric and operational characteristics and crash history. Analysts can also apply thresholds or weights to each risk factor to reduce the list of sites based on available resources and program objectives. Refer to the *Systemic Safety Project Selection Tool* for further information related to the screening and prioritization of candidate locations.(7)
3. **Select countermeasures**: Given the list of risk factors for the focus crash type(s), an agency can develop targeted treatments to address or mitigate the specific risk factors at the specific locations across the network. This is similar to the third step in the crash-based approach (countermeasure selection). Refer to the *Systemic Safety Project Selection Tool* for further information related to the selection of countermeasures.(7) Analysts can refer to the CMF Clearinghouse for estimates of the effectiveness of countermeasures.

The following points provide a general characterization of the systemic approach:

- Agencies can use the systemic approach to target specific emphasis areas from their SHSP. Targeting common underlying safety issues across sites, agencies can implement similar projects across a network to address high priority crash types and risk factors.
- Agencies use the systemic approach as an effective means to identify sites and implement treatments at those sites with the highest risk across a road network.
- Agencies typically aim to make modest site-specific safety improvements with proven countermeasures on relatively high-risk sites identified by the presence of risk factors rather than site-specific crash history.
- Agencies can apply the systemic approach without site-level crash and exposure data or when the average crash frequency at individual sites is relatively low (i.e., highly-dispersed crashes).
- Given the typical extent of improvements (i.e., many improved sites), systemic projects are generally low-cost improvements (e.g., enhancing signing or striping, installing rumble strips, or upgrading signal heads). Higher-cost improvements are also candidates for the systemic approach, but the improvement should be highly effective to justify the increased cost.
- Agencies may begin with the intent to implement proven, low-cost countermeasures, and then continue to identify appropriate treatment locations based on risk factors. In general, the use of proven, low-cost countermeasures for systemic improvements will result in a positive return on investment; however, a benefit-cost analysis is useful to determine the most effective (i.e., greatest expected reduction in severe crashes) and most cost-effective (i.e., greatest return on investment) alternatives.
- There is an opportunity to achieve reductions in crash frequency and severity across a large portion of the system given the focus on priority crash types and risk factors rather than site-specific crash history. For example, consider a $3M safety program and the opportunity to implement one of two options. The first option is to install three roundabouts at an average cost of $1M per site with an average crash history of 20 crashes per year and assuming a 40 percent reduction in crashes as the average treatment effect. The second option is to install intersection improvement packages at 500 sites at an average cost of $6000 per site with an average crash history of 3 crashes per year and assuming a 5 percent reduction in crashes as the average treatment effect. The system benefit for the first option is a reduction of 24 crashes per year and the system benefit for the second option is a reduction of 75 crashes per year. Even with a modest crash reduction per site, targeted systemic improvements can have a large impact on the system as a whole. Chapter 3 provides examples of such comparisons, including a method to allocate funding between crash-based and systemic approaches.

Agencies can use the systemic approach in the absence of high quality historical site-level crash data. Rather than analyzing crashes at specific locations, analysts investigate prevalent severe crash types across the focus facility type to correlate risk factors (e.g., geometric and operational roadway characteristics) with the crash type of interest. Agencies then use those high-risk roadway characteristics as a basis for implementing countermeasures to address the focus crash types. Beyond the presence of risk factors, analysts may identify thresholds at which the characteristic becomes problematic. For example, rather than simply identifying sites with horizontal curves, the analyst may specify the degree of curve or radius at which risk increases. Analysts can also apply weights to these risk factors to prioritize sites for countermeasure implementation. For example, risk factors for roadway departure crashes may include lane width, shoulder width, and horizontal curvature; however, sharper horizontal curves may increase crash risk more than narrow lanes. If this is the case, the analyst may place more weight on the curve-related risk factor and less weight on the lane width factor.

The systemic approach is a preventative approach because it applies countermeasures to locations with features correlated with crashes, but the sites are not required to have a history of crashes to receive treatment. This is important because the types of crashes occurring on a system remain relatively consistent from year to year while the locations of crashes tend to fluctuate, particularly on lower volume and rural roads. In many States, these roads exhibit a high proportion of severe crashes, sparsely distributed across many segments and intersections. It is difficult to address these sites with the crash-based approach due to the low density of crashes and typical data limitations associated with local and rural roads. The systemic approach helps to overcome these limitations by focusing on the underlying risk factors across the network as opposed to crash history at individual locations. In Minnesota, hotspot locations represent approximately 10 percent of severe crashes statewide. As such, managing safety with the crash-based approach alone would overlook approximately 90 percent of severe crashes. Minnesota employs the crash-based approach to address select high-crash locations, and uses the systemic approach to address the remaining 90 percent of severe crashes.

Example: Consider a scenario where an agency identified head-on crashes as a focus crash type based on the number of fatal and severe injury crashes. They noted these crashes were most prevalent on rural, two-lane roads and selected this as the focus facility type for head-on crashes (i.e., the focus crash type). The agency reviewed the data for all head-on crashes on rural, two-lane roads and determined that common roadway features (potential risk factors) include narrow cross-section, narrow or no median, and no median barrier. Alternatives to address the underlying risk factors include installing centerline rumble strips, widening the cross-section, widening the median, or installing a median barrier. The agency deemed the latter three options cost prohibitive for wide-scale deployment. As such, they selected centerline rumble strips as an appropriate measure to address the underlying risk factors. At this point, the agency would consider installing centerline rumble strips on all rural, two-lane, undivided roads. If the agency does not have available funds to install centerline rumble strips on all rural, two-lane, undivided roads, then it becomes necessary to establish a threshold for implementation.

A primary challenge related to systemic improvements is justifying the cost of improving sites, specifically those with no recent crash history. In some cases, there is limited information on the safety effectiveness of improvements that are well-suited to systemic implementation. While there are more than 5,000 crash modification factors (CMFs) available in the CMF Clearinghouse, many of these CMFs reflect the safety effect of projects implemented based on the crash-based approach or countermeasures that require substantial engineering work prior to implementation at each site. It is generally unknown if the systemic application will result in the same level of benefit as the crash-based application for the same countermeasure. As such, it can be difficult to analyze the expected benefit and cost-effectiveness of some systemic projects. Project and maintenance costs can also range from negligible to relatively high depending on the treatment and level of implementation. Although the unit cost per site is often relatively low, the service life for low-cost countermeasures is typically less than the service life for higher-cost countermeasures. As such, it is important to consider the life-cycle costs prior to implementation.

Systemic Variations in Practice

Based on a review of agency practices, there are several variations of the systemic approach. The following are two variations of the systemic approach in practice, identified during this research effort. These variations are not completely consistent with the FHWA *Systemic Safety Project Selection Tool*, but each variation serves a specific purpose, using different levels of data and analysis. As a result, the variations are associated with varying levels of reliability and may produce different countermeasures and overall benefits from the approach described in the *Systemic Safety Project Selection Tool*. Table 1 provides a high-level summary of the variations, and the remainder of this section describes each in detail with examples.

Table 1. Summary of variations to the systemic approach.

Method	Approach	Benefits
Benefit-Cost Threshold	Begins with crash-based or systemic approach, but adds site-based crash threshold to achieve minimum desired benefit-cost ratio.	Helps to maintain a minimum benefit-cost ratio. Potential for a higher return on investment.
Hybrid Systemic and Crash-Based	Combines the crash-based and systemic approach to identify candidate locations based on safety performance.	Identifies sites with potential for improvement based on observed or expected safety performance.

Benefit-Cost Threshold Variation

It is common for agencies to specify minimum benefit-cost ratios for crash-based projects. For example, an agency may not fund any projects that do not result in an estimated benefit-cost ratio of at least 2.0. Agencies can apply similar thresholds to the systemic approach based on site-specific crash or exposure data. As described in the *Systemic Safety Project Selection Tool*, applying minimum thresholds can help to prioritize and select locations for treatment.[7] Minimum thresholds can also help to maintain a minimum benefit-cost ratio, considering all sites treated with the countermeasure(s), to ensure a higher return on investment. For example, using the average implementation cost, CMF, and average crash cost reduction for the countermeasure of interest, the analyst can establish a minimum crash threshold to improve the chance of a positive return on investment. See the appendix for details on estimating benefits.

Example: Consider the same scenario as described previously in the systemic approach. Using the risk factor-based method, an agency selected centerline rumble strips to address head-on crashes on rural, two-lane, undivided roads. The agency did not have sufficient funds to install centerline rumble strips on all candidate roads, so they applied a traffic volume and corridor-level crash threshold to prioritize sites. Further analysis of the crash data suggested sites with higher traffic volumes have an increased risk of head-on crashes, and the statewide average is 0.01 head-on crashes per mile for rural, two-lane, undivided roads. Using this information, the agency prioritized sites with more than 5,000 vehicles per day and more than 0.01 head-on crashes per mile for installing centerline rumble strips. To compete for funding with other safety improvement projects, the agency also required a minimum benefit-cost ratio of 2.0. Assuming an average installation cost of $2,500 per mile, a CMF of 0.70, an average crash cost of $400,000 per head-on crash reduced, a service life of 10 years, and a discount rate of 3.0 percent, the agency estimated the benefit-cost ratio. With these assumptions, and a minimum corridor-level crash threshold of 0.01 head-on crashes per mile, the benefit-cost ratio for installing centerline rumble strips is at least 4.0, which exceeds the agencies minimum threshold. Had the benefit-cost ratio been less than 2.0, then the agency could increase the crash threshold to achieve the desired minimum.

The benefit of this method is establishing a threshold to improve the chance of a positive return on investment. The difficulty in applying this method is determining an appropriate threshold. To apply crash-based thresholds, there is a need for crash data by site or at least by corridor. Further, there are multiple options for establishing crash-based thresholds (e.g., crash frequency, crash rate, predicted crashes, and expected crashes), and some measures are more reliable than others. Predicted and expected crashes are more reliable than crash frequency and crash rate for estimating the long-term safety performance of a site. Refer to the *Reliability of Safety Management Methods: Network Screening* for further discussion on the strengths and limitations of these measures.

While a positive return on investment is desirable, it does not guarantee the most effective use of funds. For example, allocating the funds to another project may result in a more cost-effective use of funding and resources. Refer to chapter 3, *Demonstrating the Value of Integrating Systemic Approaches in a Comprehensive Safety Program*, for further discussion of estimating benefit-cost ratios and allocating funds among different project types.

Hybrid Systemic and Crash-Based Variation

The hybrid method begins by identifying a focus crash type, similar to the systemic approach. Then, the analyst screens sites similar to crash-based network screening, using performance measures such as excess expected crash frequency of the focus crash type to prioritize sites for improvement. Again, some performance measures (predicted and expected crashes) are more reliable than others (crash frequency and crash rate) for screening sites. Refer to the *Reliability of Safety Management Methods: Network Screening* for further discussion on performance measures for screening.

The next step is to diagnose underlying safety issues and select appropriate countermeasures to mitigate the specific issues. One option is to analyze crash patterns, contributing factors, and distributions for the list of top sites from the screening. This is similar to the crash-based approach, but diagnosis focuses on a group of sites simultaneously to identify commonalities rather than focusing on individual locations in isolation. In essence, the analyst applies the systemic approach to the list of sites with potential for improvement rather than all sites.

Example: Consider a scenario where an agency identified roadway departure crashes as the focus crash type. Using excess expected roadway departure crashes as the performance measure for network screening, the agency identified potential locations for treatment. Upon further investigation of the candidate sites, the agency determined common characteristics among these sites: horizontal curvature and lack of advance and in-curve warning signs. Based on this information, the agency selected a countermeasure package to include the installation of advance warning signs (i.e., curve or turn ahead) and in-curve warning signs (i.e., chevrons or large arrow boards) as appropriate.

Another option is to select a proven countermeasure to target the focus crash type, and then determine where it would be most cost-effective. In this method, an analyst selects a countermeasure for implementation based on the focus crash type, and then uses the crash-based method to identify candidate locations. Agencies commonly use this option to employ proven countermeasures when the countermeasure addresses an emphasis area in its SHSP and past research shows the countermeasure to be universally cost-effective.

Example: An agency recently learned of the potential safety benefits of installing a high-friction surface treatment (HFST) on horizontal curves to address roadway departure crashes. Based on the literature, many agencies identify candidate curves based on crash frequency (e.g., greater than expected number of severe roadway departure crashes or greater than expected wet-weather crashes), low pavement friction, large speed differential between tangent and curve, small curve radii, and deficient superelevation. In an effort to address the roadway departure emphasis area of its SHSP, the agency identified curves throughout the State for implementation of HFST. The agency applied the following factors to screen and prioritize candidate locations: excess expected severe roadway departure crashes, pavement friction, and differential between posted and advisory speed.

A strength of this method is identifying sites with potential for improvement based at least in part on past crash experience and safety performance, as opposed to relying solely on geometric and operational risk factors. Countermeasures deployed in these projects can range from low to medium unit cost, with the higher crash risk serving as a justification for more expensive countermeasures that may produce greater benefits. Both low-cost and high-cost countermeasures can fit within projects identified and selected by the hybrid method. For example, the consideration of safety performance measures is popular among States developing systemic intersection safety improvement plans. Through these plans, States implement a number of countermeasures at a wide range of sites where the treatments are appropriate. To use this method, there is a need for detailed crash data (and possibly exposure data) at the site level. This method has similar limitations to the crash-based method, such as when there is a small sample of crashes. In these cases, it will be difficult to control for the random fluctuation in crashes from site to site over time. If there is an issue with small sample size or no crash data available at the site level, then it is more appropriate to employ the systemic approach.

POLICY-BASED METHOD

The policy-based method serves to bring design or operational features up to a standard or policy. Agencies often implement policy-based countermeasures aiming to reduce liability as well as crash risk. In some cases, policies reflect national standards such as improving the retroreflectivity of all curve warning signs to meet the Manual on Uniform Traffic Control Devices (MUTCD) criteria. In other cases, agencies create new policies based on past success.

New safety policies generally stem from successful crash-based and systemic improvements. As new safety concepts arise, agencies may try these improvements to address issues at a few site-specific locations. If a new safety concept proves effective at reducing crashes at these locations, agencies may implement the concept more widely through the systemic approach. The agency may then conduct an analysis to understand the countermeasure effectiveness. Finally, if the research proves the concept is effective, agencies may develop a policy to implement the proven countermeasure as part of their regular design, construction, operations, and maintenance practices.

For example, analyzing risk factors, an agency may identify an elevated risk of head-on crashes on divided highways with a given median width and traffic volume. Based on prior research, the agency understands the potential safety benefits of cable median barrier on divided highways with unprotected medians. As a result, the agency may develop a policy to install cable median barrier on all divided highways with a specific median width and traffic volume. This example reflects the use of the systemic approach to develop a policy for cable median barrier.

Using the policy-based approach, agencies upgrade features or install countermeasures at all applicable locations regardless of substantive risk. This includes all new construction and may include installation or upgrades on existing facilities to the extent possible. For example, an agency may create a new policy to install retroreflective backplates on all new signal installations as well as signal upgrades.

While many standards help to reduce risk and protect against liability, a standard is not a guarantee of safety. When developing standards, an agency should consider the costs and benefits of alternatives, including conditions without the treatment of interest. Continuing with the example of retroreflective backplates, an agency would consider the cost of installing backplates on all new signals and signal upgrades compared to the expected benefits (i.e., safety performance with and without backplates).

Given the need for cost-effective measures, policy-based safety improvements typically include proven countermeasures that are highly effective or relatively low cost to justify the installation on a large scale. Refer to FHWA's Proven Safety Countermeasures for opportunities to create policy-based safety improvements. The following are examples of policy-based safety projects that are also included in FHWA's Proven Safety Countermeasures:

- Install retroreflective backplates on all new signal installations and signal upgrades.
- Improve the retroreflectivity of curve warning signs to enhance delineation on horizontal curves.
- Install longitudinal rumble strips and stripes on two-lane roads.
- Install SafetyEdge$_{SM}$ for all asphalt paving projects without curbs.

SUMMARY OF CRASH-BASED AND SYSTEMIC APPROACHES

The crash-based and systemic approaches are complementary and support a comprehensive approach to safety management. The primary difference is the way in which analysts identify issues and develop projects. In the crash-based approach, analysts select sites and develop projects based on site-specific crashes. In the systemic approach, analysts focus on site-specific geometric and operational attributes known to increase crash risk.

While there are differences in the application of the approaches, both approaches focus on preventing future crashes and reducing fatalities and injuries. Another commonality is focusing on sites with the greatest potential for safety improvement. In either case, it is important to use reliable, data-driven methods to inform these decisions. A predictive approach based on a combination of historical crash, exposure, and roadway data is more reliable than an approach based on crash frequency alone or ad hoc analysis of geometric and operational attributes that may increase risk.

Finally, there is not an intrinsic link between the project cost and analysis approach. While systemic projects are generally low-cost and widely implemented, no countermeasures are exclusive to the systemic approach. For example, agencies may install lower unit cost countermeasures at a single site as a standalone low-cost project.

3. DEMONSTRATING THE VALUE OF INTEGRATING SYSTEMIC APPROACHES IN A COMPREHENSIVE SAFETY PROGRAM

This section presents a framework for characterizing the cost-effectiveness of and allocating funds to crash-based and systemic projects. In an attempt to characterize typical crash-based and systemic projects, the research team identified a sample of projects to represent both project types. Separate sections present the characteristics of the sample of crash-based and systemic projects, including average project costs and benefits, average benefit-cost ratios, and net benefits given a fixed program budget.

Table 2 shows the crash cost values used in this guide based on the Highway Safety Manual and expressed in 2016 dollars.[3] This guide uses weighted crash costs and average total crashes for the examples. Agencies should consider the potential impact of fatal crashes in estimating project benefits. Even one fatal crash can skew the estimated project benefits. Consider using expected crashes as the basis for estimating the long-term safety performance and weighted crash costs in estimating project benefits.

Table 2. Comprehensive crash costs by maximum reported severity.

Maximum Crash Severity	Cost
Fatal	$5,715,100
Incapacitating Injury	$302,400
Non-incapacitating Injury	$110,400
Possible Injury	$62,200
Property Damage Only	$10,000

While agencies implement some countermeasures such as median barrier, signal retiming, or sight distance improvements with either the crash-based or systemic approach depending on the project, a review of the 2014 HSIP annual reports indicated some projects are more common to one approach or the other. This guide includes six sample countermeasures representing the crash-based approach: left turn lanes, high friction surface treatments, intersection reconfigurations, reduction of intersection skew, road diets, and roundabouts. It also includes six sample countermeasures representing the systemic approach: cable median barriers, centerline and shoulder rumble strips, ramp curve signage, chevron curve warning signs, and low-cost intersection improvements at signalized and stop-controlled intersections.

The following sections present the potential value of crash-based and systemic projects. Note the results reflect a sample of safety projects and a hypothetical safety program budget of $10,000,000. While all States receive more than $10,000,000 annually for safety programs, this value is for illustrative purposes and is easily scalable to larger values. Agencies could replicate the process to customize the results based on local experience. They could also generalize these results to an available portion of a larger budget. Following the cost-effectiveness analyses is a discussion of several noted strengths, limitations, and key considerations for the crash-based and systemic approaches. There is also information for program managers on how to incorporate both types of projects (crash-based and systemic) and allocate funding within a comprehensive safety improvement program.

VALUE OF CRASH-BASED PROJECTS

Crash-based projects deploy countermeasures with the potential to yield reductions in crash frequency and severity at the specific site. Table 3 presents data for six countermeasures representing crash-based projects, including the service life, average crashes before treatment, CMF, and average cost. The numbers in the table represent data from various research reports and from State DOTs. The countermeasures represent the primary treatment implemented in the project; however, minor improvements may have accompanied the primary treatments in some cases. The following is a brief summary of the data elements in Table 3.

- **Countermeasure:** The table presents data for six countermeasures selected to represent projects associated with a crash-based approach. For road diets, the table includes two versions; one assuming resurfacing and restriping, and the other assuming milling old pavement markings and restriping as a new configuration.
- **State(s):** The table includes data from California, Iowa, Rhode Island, South Carolina, and Washington. The table indicates the State(s) represented for each countermeasure.
- **Service life:** The table presents the assumed service life (in years) for each countermeasure based on research reports and State documentation. The service life ranges from 10 years (high friction surface treatment) to 20 years (add left turn lanes, reconfigure intersection, reduce intersection skew and add left turn lanes, road diets, and roundabouts).
- **Average crash frequency before treatment:** The table presents the average crash frequency before treatment based on research reports and State documentation. While the average crash frequency is one measure of the opportunity for improvement, the expected crashes from the Empirical Bayes (EB) method provides a more reliable measure of the potential for improvement in the long-term.
- **CMF:** The table presents the total crash CMF for each countermeasure based on existing documentation or data provided by the States. The appendix provides detailed information on project effectiveness by crash severity.
- **Study method:** The table presents the method used to develop the CMF for each countermeasure. For road diets, the CMF is from an EB before-after analysis documented in an existing report. For the other countermeasures, the CMF is from a simple before-after analysis of projects provided by the States.
- **Similar CMFs from the CMF Clearinghouse:** The table presents the existing CMF (or range of CMFs) from the CMF Clearinghouse. This provides a point of reference for comparing the CMFs based on limited project data directly from the States. In general, the CMFs assumed for this study are comparable to those from the CMF Clearinghouse.
- **Average cost per mile or per site:** The table presents the average countermeasure cost based on research reports and State documentation. The costs range from $100,000 per mile (road diets without resurfacing) to $1,106,000 per intersection (reduce intersection skew and add left turn lanes).

Table 3. Crash-based countermeasure data.

Countermeasure	State(s)	Service Life (years)	Average Crash Frequency Before Treatment[1]	CMF	Study Method[2]	Similar CMFs from the CMF Clearinghouse (CMF ID#)	Average Cost Per Mile or Per Site
Add Left Turn Lanes	SC	20	5.0 per intersection	0.59	Simple Before-After	0.69 (7853)	$706,000
High Friction Surface Treatment	RI	10	5.4 per site	0.85	Simple Before-After	0.76 (194)	$100,000
Reconfigure Intersection[3]	SC	20	4.2 per intersection	0.66	Simple Before-After	N/A	$822,000
Reduce Intersection Skew and Add Left Turn Lanes	SC	20	3.8 per intersection	0.48	Simple Before-After	N/A	$1,106,000
Road Diet Without Resurfacing[4]	IA, CA, WA	20	26.2 per mile	0.71	EB Before-After	0.63 (874)	$100,000
Road Diet Including Resurfacing Costs[4]	IA, CA, WA	20	26.2 per mile	0.71	EB Before-After	0.63 (874)	$1,000,000
Roundabout	SC	20	4.6 per intersection	0.28	Simple Before-After	0.21-0.32 (2122, 2123)	$739,000

1. All crash frequencies expressed as crashes per mile-year or crashes per site-year.
2. CMFs from simple before-after studies are generally less reliable than CMFs from EB before-after studies. As such, there is more uncertainty in the estimates from simple before-after studies.
3. Includes various treatments such as reducing skew, removing slip ramps, and teeing up a scissors-type intersection.
4. Information for road diets is from the following sources:
    a. Incorporating On-Road Bicycle Networks into Resurfacing Projects
    b. Florida District 3 Preliminary Estimates Section Transportation Costs
    c. Evaluation of Lane Reduction "Road Diet" Measures on Crashes

Given the countermeasure data in Table 3 and the appendix, Table 4 presents the benefit-cost ratio of theoretical projects, representing the potential coverage and benefits of implementing each countermeasure within a budget of $10,000,000. The table presents project costs and net safety benefits in terms of present dollar value for each countermeasure as well as the average of all countermeasures. For road diets, the table includes two analyses using the same crash data; one includes reconstruction and resurfacing costs, and the other assumes milling old pavement markings and restriping as a new configuration. The appendix provides further details.

Table 4. Crash-based project cost-effectiveness.

Countermeasure	Coverage[1]	Project Costs	Net Safety Benefits	Benefit Cost Ratio
Add Left Turn Lanes	14 intersections	$9,884,000	$62,386,011	6.3
High Friction Surface Treatment	100 sites	$10,000,000	$498,263,771	49.8
Reconfigure Intersection	12 intersections	$9,864,000	$134,293,525	13.6
Reduce Intersection Skew and Add Left Turn Lanes	9 intersections	$9,954,000	$83,931,637	8.4
Road Diet Without Resurfacing	100 miles	$10,000,000	$631,888,312	63.2
Road Diet Including Reconstruction and Resurfacing Costs	10 miles	$10,000,000	$63,188,831	6.3
Roundabout	13 intersections	$9,607,000	$111,682,769	11.6
Average	37 sites	$9,901,286	$226,519,265	23.0

1. Assumes one mile, one curve, and one intersection are equivalent to a single site.

Benefit-cost ratios greater than 1.0 represent a positive return on investment. While benefit-cost ratios in Table 3 are all well above 1.0 and are economically justifiable projects, this sample of projects is associated with relatively high costs and high investment risks in the context of the overall safety program. With high-cost projects, agencies can address relatively few sites annually given a fixed budget. While this sample of projects developed through a crash-based approach has relatively high costs, there is not an intrinsic link between the project cost and analysis approach. With respect to investment risk, if a high-cost project does not yield the expected benefits, and results in a benefit-cost ratio less than 1.0, then the agency could have allocated this portion of the safety budget more effectively elsewhere. This is a particular concern when the estimated benefit-cost ratio prior to treatment is close to 1.0 because slight overruns in project costs can result in a benefit-cost ratio less than 1.0. High-cost projects may also include additional costs related to resurfacing, drainage, and other elements required to implement the safety-related aspects of a more substantial project. These costs are required to facilitate the overall project construction, but do not necessarily contribute to the expected safety benefit. To mitigate this issue, there is an opportunity to integrate efforts from 3R/4R condition management with high-cost safety improvements.

VALUE OF SYSTEMIC PROJECTS

Agencies commonly install systemic projects at many sites or along longer corridors within a single project. As such, there are economies of scale and systemic projects are often associated with lower unit costs and low economic risk compared to high-cost projects. While systemic projects are generally low-cost and widely implemented, no countermeasures are exclusive to the systemic approach. For example, agencies may install lower unit cost countermeasures at a single site as a standalone project. Agencies are less likely to program high-cost projects with the systemic approach for a number of reasons, including budget limitations, but this does not preclude higher cost countermeasures from systemic implementation.

Table 5 presents data for a six countermeasures representing systemic projects, including the service life, average crashes before treatment, CMF, and average cost. The numbers in the table represent data from various research reports and from State DOTs. The following is a brief summary of the data elements in Table 5.

- **Countermeasure:** The table presents data for six countermeasures selected to represent projects associated with a systemic approach.
- **State(s):** The table includes data from Connecticut, Kentucky, Michigan, Missouri, Pennsylvania, Rhode Island, South Carolina, and Washington. The table indicates the State(s) represented for each countermeasure.
- **Service life:** The table presents the assumed service life for each countermeasure based on research reports and State documentation. The service life ranges from five years for general signing improvements to 13 years for cable median barrier.
- **Average crash frequency before treatment:** The table presents the average crash frequency before treatment based on research reports and State documentation. While the average crash frequency is one measure of the opportunity for improvement, the expected crashes from the Empirical Bayes (EB) method provides a more reliable measure of the potential for improvement in the long-term.
- **CMF:** The table presents the total crash CMF for each countermeasure based on existing documentation or data provided by the States. The appendix provides detailed information on project effectiveness by crash severity.
- **Study method:** The table presents the method used to estimate the safety effect for each countermeasure. For most countermeasures, the CMF is from an EB before-after analysis documented in an existing report. For ramp curve signage, the CMF is from a simple before-after analysis of projects provided by Rhode Island.
- **Similar CMFs from the CMF Clearinghouse:** The table presents the existing CMF (or range of CMFs) from the CMF Clearinghouse. This provides a point of reference for comparing the CMFs based on limited project data directly from the States. In general, the CMFs assumed for this study are comparable to those from the CMF Clearinghouse.
- **Average cost per mile or per site:** The table presents the average countermeasure cost based on research reports and State documentation. The costs range from $1,600 per site for curve warning signs to $196,000 per mile for cable median barrier. The research team included maintenance cost for cable median barrier at a three percent discount rate; otherwise, maintenance costs are negligible over the service life.

Table 5. Systemic countermeasure data.

Countermeasure	State(s)	Service Life (years)	Average Crash Frequency Before Treatment[1]	CMF	Study Method[2]	Similar CMFs from the CMF Clearinghouse (CMF ID#)	Average Cost Per Mile or Per Site
Cable Median Barrier[3]	MI	13	1.97	2.14 0.95 for KABC crashes	EB Before-After	1.91 (5442) 0.79 for KABC crashes (6129)	$196,000
Centerline and Shoulder Rumble Strips[4]	KY, MO, PA	7	0.91	0.80	EB Before-After	0.80 (6850)	$5,000
Ramp Curve Signage	RI	5	15.2	0.74	Simple Before- After	0.59-0.69 (1905, 1907, 1909)	$10,000
Curve Warning Signage (Chevrons)[5]	WA, CT	5	6.2	0.94	EB Before-After	0.63-0.72 (1898, 7268)	$1,600
Low Cost Intersection Improvements – Signal[6]	SC	7	12.5	0.96	EB Before-After	N/A	$7,000
Low Cost Intersection Improvements –Stop[7]	SC	7	3.5	0.92	EB Before-After	N/A	$6,000

1. All crash frequencies are expressed as crashes per mile-year or crashes per site-year.
2. CMFs from simple before-after studies are generally less reliable than CMFs from EB before-after studies. As such, there is more uncertainty in the estimates from simple before-after studies.
3. Guidance on the application of cable median barrier: tradeoffs between crash frequency, crash severity, and agency costs
4. Safety Evaluation of Centerline Plus Shoulder Rumble Strips
5. Safety Evaluation of Improved Curve Delineation
6. Includes doubling and oversizing advance warning signs, fluorescent yellow sheeting for warning signs, retroreflective sign posts, refreshing existing pavement markings, one signal per lane, retroreflective backplates, and 12-inch LED lenses, with each installed only where appropriate.
7. Includes doubling and oversizing advance warning signs, fluorescent yellow sheeting for warning signs, retroreflective sign posts, refreshing existing pavement markings, and stop bar markings on cross streets, with each installed only where appropriate.

Given the countermeasure data in Table 5 and the appendix, Table 6 presents the benefit-cost ratio of theoretical projects, representing the potential coverage and benefits of implementing each countermeasure within a budget of $10,000,000. The table presents project costs and net safety benefits in terms of present dollar value for each countermeasure as well as the average of all countermeasures. The appendix provides further details on these calculations.

Table 6. Systemic project cost-effectiveness.

Countermeasure	Coverage[1]	Project Cost	Net Safety Benefits	Benefit Cost Ratio
Cable Median Barrier	51 miles	$9,996,000	$58,006,096	5.8
Centerline and Shoulder Rumble Strips	2,000 miles	$10,000,000	$126,771,305	12.7
Ramp Curve Signage	1,000 curves	$10,000,000	$2,928,925,502	292.9
Curve Warning Signage (Chevrons)	6,250 curves	$10,000,000	$640,014,079	64.0
Low Cost Intersection Improvements - Signal	1,428 intersections	$9,996,000	$279,526,340	28.0
Low Cost Intersection Improvements - Stop	1,666 intersections	$9,996,000	$168,073,055	16.8
Average	2,066 sites	$9,998,000	$700,219,396	70.0

1. Assumes one mile, one curve, and one intersection are equivalent to a single site.

The benefit-cost ratios of the systemic projects in Table 5 are all well above 1.0 and are economically justifiable projects. While the systemic approach appears to hold great promise, the approach also has specific limitations. First, many agencies are not as familiar or experienced with the project delivery and analysis methods to identify and plan systemic projects. Second, some jurisdictions have found difficulties in managing and administering systemic projects when there is a requirement for detailed plans or surveys for construction, which can add considerable costs to otherwise low-cost projects. Additionally, there are limitations to address some crash types with systemic projects because proven, low-cost countermeasures are not available for targeting all severe crash types. For example, roundabouts are effective at reducing severe, right-angle crashes, but roundabouts are not a viable systemic improvement. Finally, although systemic projects may yield high net benefits, agencies still have an obligation to address the highest risk sites, which include those with a history of severe crashes.

COMPARISON OF CRASH-BASED AND SYSTEMIC PROJECTS

Table 4 and Table 6 present the results of simulated safety programs for crash-based and systemic projects, respectively. Table 7 lists the average results for the crash-based and systemic countermeasure programs. Note there are seven crash-based programs and six systemic programs represented in Table 7. While each hypothetical program is $10M, the research team assumed an agency can only install whole projects. For example, it is not possible to install 3.5 roundabouts.

Table 7. Comparison of crash-based and systemic economic measures.

Economic Measure	Crash Based	Systemic
Total Cost	$9,901,286	$9,998,000
Total Benefit	$226,519,265	$700,219,396
Overall Benefit-Cost Ratio	23.0	70.0

The results for the crash-based countermeasure program show an average cost of $9,901,286, average benefit of $226,519,265, and average benefit-cost ratio of 23.0 based on seven projects. The results for the systemic countermeasure program shows an average cost of $9,998,000, average benefit of $700,219,396, and average benefit-cost ratio of 70.0 based on six projects.

There are a number of considerations for interpreting these results. The research team selected studies for this analysis with available data for at least before period crashes, project cost and coverage, and the countermeasure effectiveness (CMF). There may be a level of bias associated with this limitation. For example, agencies tend to implement proven (i.e., effective) countermeasures, and research tends to focus on the most prevalent countermeasures. As such, those countermeasures with available CMFs may reflect more effective measures. Further, there is limited availability of crash-based evaluations of systemic projects, and there is limited information on, and variability in, the methods used to plan systemic projects, identify sites for implementation, and evaluate the results. Agencies should use caution in applying these results.

The analysis in this guide reflects the average effectiveness of a countermeasure. There is a standard error associated with each estimate. While many agencies use the average CMF in benefit calculations, the recommended practice is to consider the standard error and confidence interval associated with the estimates. However, given the relatively high benefit-cost ratios in Table 4 and Table 6, there is a low probability these hypothetical projects would result in benefit-cost ratios less than 1.0. The research team did not analyze whether there are significant differences, accounting for the confidence interval, between crash-based and systemic projects. For more information on CMFs and confidence intervals, refer to the *Reliability of Safety Management Methods: Countermeasure Selection*.[6]

The FHWA Office of Safety identifies all but two of the crash-based countermeasures in this analysis as proven countermeasures (exceptions are reconfiguring intersections and reducing intersection skew).[8] While the proven countermeasures are associated with a demonstrated capability to provide cost-effective safety benefits, agencies should still confirm that a proven countermeasure will not trigger other crashes due to specific conditions not considered by CMFs associated with total crashes.

While the benefit-cost ratios and net benefits in Table 4 are relatively high, the coverage within a budget of $10,000,000 is limited given the relatively high cost of the countermeasures. High friction surface treatment and road diets without resurfacing are relatively lower cost crash-based projects, resulting in higher coverage and higher net benefit than other crash-based countermeasures. This guide uses a $10,000,000 budget for comparison, and the results represent average projects based on available information. See the appendix for details related to the individual projects represented in these averages. It is safe to assume the sites used as a basis for this analysis were some of the better candidates in a State for implementing these treatments. As agencies address locations with the highest potential for improvement, they may realize diminishing returns and relatively smaller benefits from additional implementation of the same measure. However, it takes many years to address all notable concerns and other sites may emerge as safety concerns due to new developments or changes in the nature of the site.

The sample of systemic projects show a higher ceiling of net benefit and higher coverage overall (i.e., ability to treat more sites with the same budget as shown in Table 6) than the crash-based projects (see Table 4). The FHWA Office of Safety identifies all but two of the systemic countermeasures in this analysis as proven countermeasures (exceptions are the low-cost intersection improvements at signalized and stop-controlled intersections).[8] The systemic or systematic implementation of countermeasures helps to streamline or forego the site-specific diagnostic considerations in a crash-based safety management process. The systemic process can start with the selection of a countermeasure based on the focus crash type, which precludes the opportunity to improve a site beyond the implementation of the systemic countermeasure. However, it is necessary for agencies to consider the potential for sites to exhibit other safety concerns not addressed during the implementation of a single systemic project due to the limited diagnosis.

By nature of the approach, agencies implement systemic projects at multiple sites. When implemented at many sites as part of a single contract, this helps to distribute engineering and construction costs. As such, these countermeasures are associated with lower unit costs and potentially higher system benefits. Similar to the crash-based projects, there is potential for diminishing returns of implementing additional systemic projects as agencies address locations with the highest potential for improvement.

CRASH-BASED AND SYSTEMIC PROJECTS WITHIN A COMPREHENSIVE SAFETY PROGRAM

The ultimate purpose of the HSIP is to achieve a significant reduction in traffic fatalities and serious injuries on all public roads. Safety program managers administer funds to maximize the reduction in fatal and serious crashes, which could be expressed in terms of maximizing the net economic benefits of projects. This task requires selecting projects with the best chance to achieve these goals while ensuring that funds do not lapse and programs are not over-committed (i.e., planning sufficient projects, but not planning excessive financial commitments relative to the estimated budget).

The analysis and discussion in the previous sections demonstrate the value of both crash-based and systemic projects. Sites with the highest potential for improvement are often high profile locations with a notable history of severe crashes. The public expects agencies to address such problematic sites, and it is often beneficial to do so with the right countermeasures. Systemic projects may not adequately address crash problems at the highest crash sites, but show the potential to address targeted issues across a larger portion of the network, particularly highly-dispersed crashes across a network.

The number of sites representing high quality candidates for crash-based safety projects is small relative to the entire network of sites. Additionally, crash-based projects usually represent solutions requiring more effort to plan, program, and design, and may require right-of-way acquisition. These projects are generally not flexible within programs due to larger construction efforts and are not as scalable as systemic projects. Given these factors, and considering the average return on investment may be lower than systemic projects as suggested in Table 7, a program built entirely of crash-based projects is likely not optimal.

A logical conclusion is that crash-based and systemic safety projects are complementary, serving different purposes within an overall safety management program. Figure 3 illustrates a typical distribution of expected fatal and injury crash frequency at approximately 1,400 intersections across a network. These sites represent those three-legged and four-legged, stop-controlled and signalized intersections in New Hampshire with available traffic volume for all approaches. Based on the screening measures employed, these sites represent relatively larger intersections. A distribution including all intersections will skew further toward lower frequency sites.

The few sites with the highest expected crash frequency (e.g., the top 0.5 percentile) are sparse outliers, and the top five percent of sites have substantially higher frequencies than the rest of the sites on average. This is typical of most road networks. There is a need to implement crash-based projects to address the sites with the highest potential for improvement. Beyond the sites representing the steep slope of the distribution (e.g., top five percent), the potential return is fairly constant and relatively low. As such, diagnosing and treating the lower frequency sites one by one is not feasible within safety budgets and resource constraints.

Systemic projects can provide an effective way to address the safety concerns at the majority of sites with countermeasures representing generally lower risk, potentially more cost-effective, and scalable projects. Widespread implementation of similar countermeasures within a single systemic project can also save costs during design and construction, and the low-cost, low-impact nature of systemic countermeasures often does not trigger right-of-way and environmental impacts that can increase project costs. However, preliminary engineering can constitute a greater proportion of systemic projects due to the planning and coordination involved in developing the project. Additionally, systemic projects do not realize the potential for greater improvements at the highest crash sites.

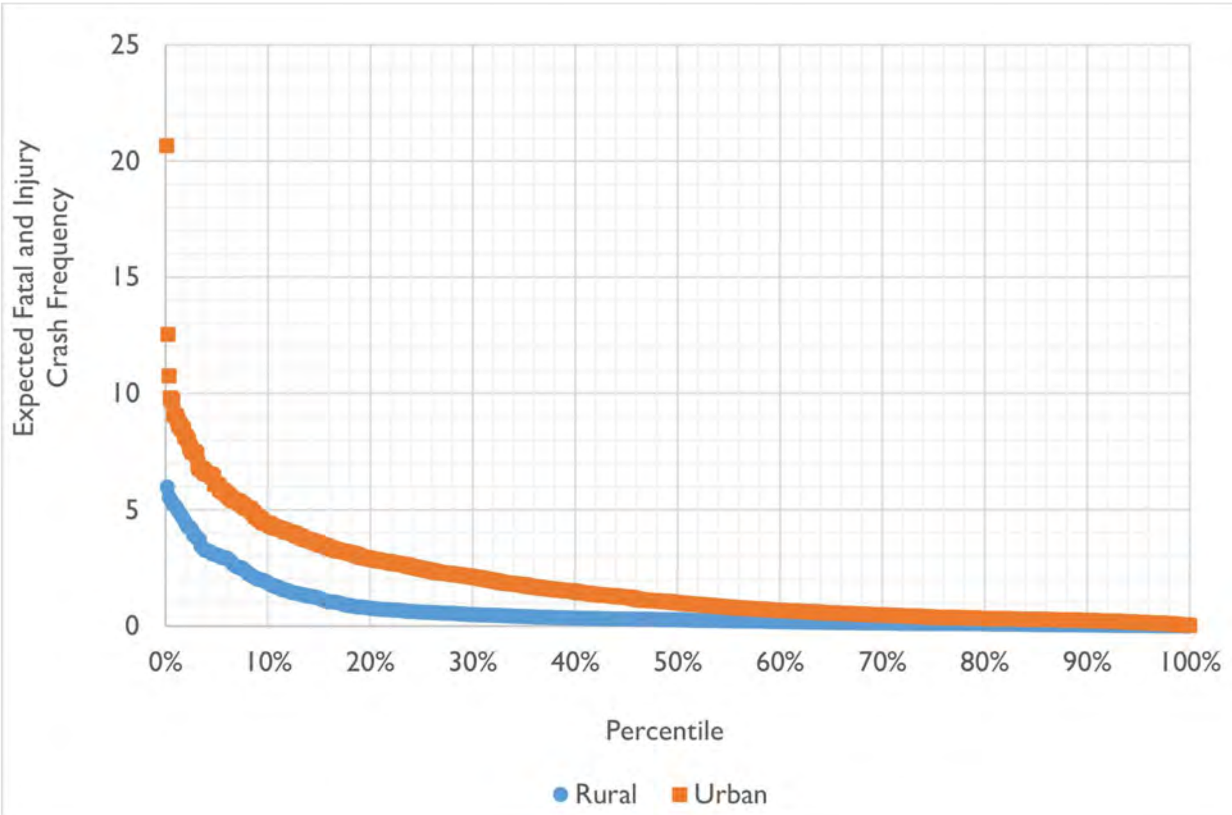

Figure 3. Graph. Statewide distribution of intersection safety performance.

ALLOCATING FUNDS TO CRASH-BASED AND SYSTEMIC PROJECTS

The question of how to allocate funds in a safety program for crash-based and systemic projects is not necessarily a question of complementing the two safety management approaches. A more applicable question for program managers is how to balance the implementation of high-cost and low-cost countermeasures.

Based on the sample analysis in this study, the results in Table 7 show the potential cost-effectiveness of both crash-based and systemic projects. In this guide, the sample of projects seem to reflect an association between the project cost and approach: the sample of crash-based projects are relatively high-cost and the sample of systemic projects are relatively low-cost. Again, there is not an intrinsic link between the project cost and analysis approach. As such, the remainder of this guide discusses high-cost and low-cost projects in addition to crash-based and systemic projects.

Safety programs are like an investment portfolio in the sense that it is helpful to diversify risk and optimize return on investment. Consider the crash frequency distribution in Figure 3 in this context. The goal of a program is to reduce the area under the curve. High-cost projects may be a sound investment in the highest crash sites when there is a clear opportunity for a large crash reduction. High-cost investments in sites with lower crash frequencies do not present the same potential return, and a lower level of investment with modest return may be appropriate.

Agencies can address the wide-ranging, but lower magnitude, safety concerns across the network with relatively low-cost, low-risk countermeasures. These types of countermeasures typically offer lower potential return on investment at individual sites, but represent a large potential benefit considering the widespread implementation. An optimization function can demonstrate the breakeven points along the crash frequency distribution using the information from the cost-effectiveness analysis presented earlier.

The following section describes a process for determining the optimal allocation of funds between two types of projects or two countermeasures.

Development of a Breakeven Crash Frequency Equation

Figure 4 presents the equation for calculating the net benefits of some safety improvement.

$$NB = AVB - AVC$$

Figure 4. Equation. General equation for net benefits of a project.

Where:

NB = net annual safety benefits.

AVB = annualized value of project safety benefits.

AVC = annualized value of project costs.

The economic benefits of a safety project are the product of multiplying the estimated crash reduction by average crash costs. If the estimated crash reduction is the difference between the estimated crash frequency with and without the treatment, then the previous equation can be rewritten as shown in Figure 5.

$$NB = (ACF_{without} - ACF_{with}) * CC - AVC$$

Figure 5. Equation. Net benefits in terms of crash frequency, crash cost, and project cost.

Where:

$ACF_{without}$ = average annual crash frequency without treatment.

ACF_{with} = average annual crash frequency with treatment.

CC = average estimated economic cost per crash.

The average crash frequency before treatment is an approximation of the average annual crash frequency without treatment. The Highway Safety Manual presents a predictive method to estimate average annual crash frequency without treatment. Note a predictive approach based on a combination of historical crash, exposure, and roadway data is more reliable than approaches based on crash frequency alone. The annual crash frequency with treatment is the annual crash frequency without treatment multiplied by a CMF for the treatment. The crash costs, crash frequency, and CMF must all be in terms of the same crash types and severities. Figure 6 reflects the expanded equation, and simplifies to the equation shown in Figure 7. Note analysts can calculate the net benefits of multiple crash types and severities separately, and then sum the results.

$$NB = [ACF_{without} - (ACF_{without} * CMF)] * CC - AVC$$

Figure 6. Equation. Net benefits in terms of before-period crashes, project effectiveness, crash cost, and project cost.

$$NB = ACF_{without} * (1 - CMF) * CC - AVC$$

Figure 7. Equation. Simplified equation for net benefits of a project.

Where:

CMF = crash modification factor for a given safety treatment.

A general goal of safety improvement programs is to maximize the net safety benefits of the overall program of safety projects. A common tradeoff in project planning and countermeasure selection is whether it is more appropriate to select a more expensive treatment that is more likely to reduce a relatively greater number of crashes per site, or to select a less expensive treatment that may reduce a relatively lower number of crashes per site. Given that some sites experience a much higher crash frequency than others, it is usually more appropriate and beneficial to implement higher cost and more effective treatments at sites with higher crash frequency, and lower cost treatments at sites with relatively lower crash frequency. There is then a certain crash frequency where the benefits of these two types of projects are equivalent, yielding a breakeven point where either approach is warranted. In other words, there is a minimum crash frequency below which a high-cost investment is no longer worth the expenditure. Above the minimum threshold, it is possible to realize a return on investment from a high-cost strategy. Figure 8 illustrates this optimization problem where the dashed line represents the breakeven threshold.

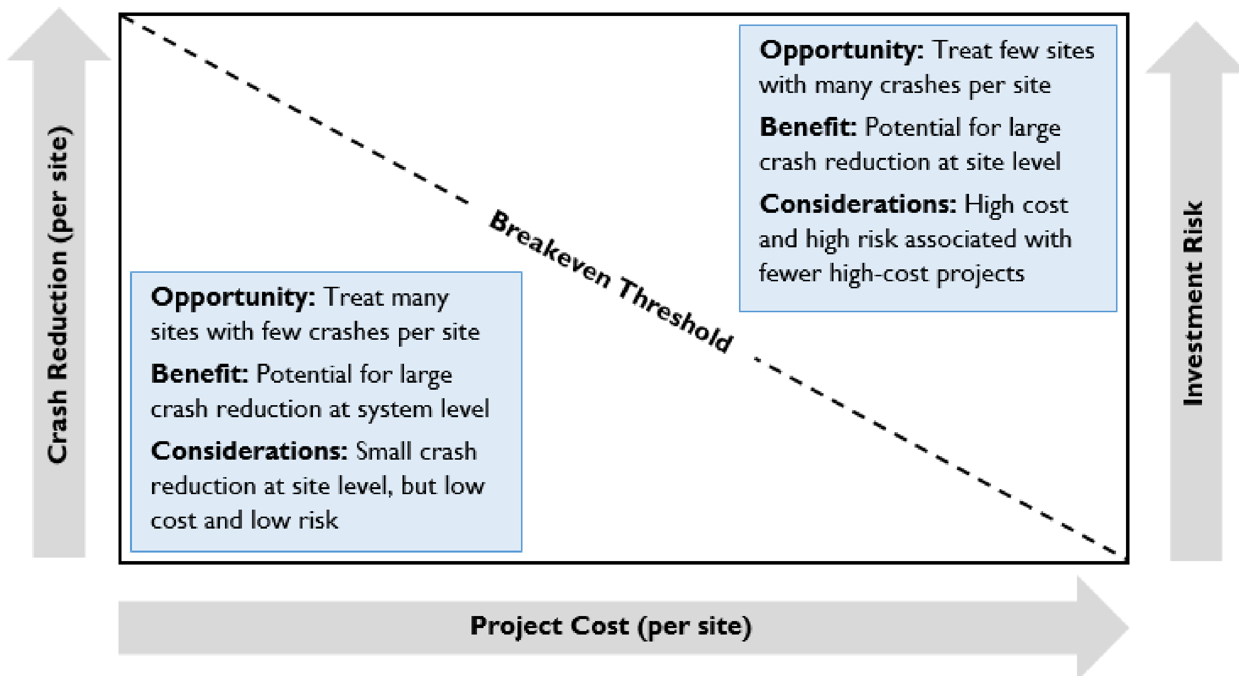

Figure 8. Chart. Optimizing investments in high-cost and low-cost improvements.

By determining the breakeven crash frequency ($ACF_{without}$), program managers can determine the sites within a roadway network that warrant higher investments and similarly those that warrant lower cost improvements. Analysts can determine the breakeven crash frequency by setting the net benefits equal for crash-based and systemic projects, using Figure 9, and characterizing the net benefits and crash frequency for the two approaches by representative project costs and CMFs.

$$NB_C = NB_S$$

Figure 9. Equation. Equality criterion for calculation of breakeven of net benefits.

Where:

NB_C = net safety benefits of a crash-based treatment.

NB_S = net safety benefits of a systemic treatment.

Substituting the net benefit notation from Figure 7 into the equality in Figure 9, and using algebra to solve for $ACF_{without}$, Figure 10 shows the equation to calculate the breakeven crash frequency.

$$ACF_{without} = \frac{AVC_C - AVC_S}{CC * (CMF_S - CMF_C)}$$

Figure 10. Equation. Breakeven crash frequency equation.

Where:

$ACF_{without}$ = crash frequency before treatment representing a breakeven between hotspot and systemic treatments.

AVC_C = annualized value of project costs for a crash-based treatment.

AVC_S = annualized value of project costs for a systemic treatment.

CC = average estimated economic cost per crash.

CMF_S = crash modification factor for a systemic treatment.

CMF_C = crash modification factor for a crash-based treatment.

Assuming:

$CMF_S > CMF_C$

$AVC_C > AVC_S$

Crash cost, crash frequency, and CMF are determined for same crash type and severity.

Using the equation in Figure 10 and substituting the average costs and CMFs for each type of project, analysts can solve for the breakeven crash frequency for crash-based and systemic projects across the roadway network. The application of this equation is to determine the breakeven threshold, and then assess whether the crash frequency for a given site is above or below that threshold. Crash-based projects are likely more appropriate at sites with a crash frequency higher than the breakeven threshold, and systemic projects are likely more appropriate at sites with a crash frequency below the threshold. The crash frequency, $ACF_{without}$, should represent the average observed crash frequency or the expected crash frequency with EB adjustment for the entire area of the project.

If such a situation arises where $CMF_C > CMF_S$ and $AVC_C > AVC_S$ (or vice versa), it is not necessary to undertake this analysis of tradeoffs. In this case, the treatment with lower cost and greater effectiveness (i.e., lower CMF) will result in the optimal solution.

Example Application of the Breakeven Equation

Analysts can use the equation to calculate the breakeven crash frequency for applying the results of crash-based and systemic projects in Table 4 and Table 6. Table 8 presents the weighted average CMF and annualized cost for the crash-based and systemic projects over the service life. The average data for systemic projects excludes cable median barrier due to the large increase in total crashes and maintenance cost that limited the application in this simple analysis of total crashes. Note cable median barrier is highly-effective at reducing severe head-on crashes, but can increase total crashes.

Table 8. Weighted average CMF and costs by project type.

Economic Measure	Crash Based	Systemic
Average CMF	0.73	0.90
Average Project Cost Per Site (Intersection, Curve, or Mile) Per Year	$20,000	$750

This analysis used an average crash cost for total crashes of $55,900. This value is from the average crash costs presented in Table 2 and an assumed crash severity distribution. See the appendix for further discussion of the assumed crash severity distribution and calculation of the average crash cost of $55,900. With these inputs, the breakeven equation in Figure 10 yields a breakeven crash frequency threshold of 2.0 as shown in Figure 11.

$$ACF_{without} = \frac{\$20{,}000 - \$750}{\$55{,}900 * (0.90 - 0.73)} = 2.0$$

Figure 11. Equation. Application of the breakeven equation.

The resulting breakeven crash frequency for the average crash-based and systemic projects in this example is 2.0 total crashes per site per year. For intersection-related improvements, a site represents one intersection. For segment-related improvements, a site represents one mile. As discussed previously, higher-cost projects may be more appropriate at sites with an average crash frequency higher than the breakeven threshold, and lower-cost projects may be more appropriate at sites with an average crash frequency below the threshold. In this case, sites with estimated total crashes higher than 2.0 crashes per site per year are more fitting locations for a crash-based approach and countermeasures, and sites with estimated total crashes lower than 2.0 crashes per site per year are more appropriate for systemic countermeasures. If applied to the distribution in Figure 3, the top 15 percent of sites are potentially more appropriate for some type of crash-based countermeasure, and the remaining 85 percent of sites are more fitting for systemic countermeasures.

Figure 12 illustrates the results of the breakeven analysis. Again, the hypothetical program budget is $10M. The average cost per site and average benefit reflect the numbers in Table 8 based on the sample of projects included in this study. Based on these results, the higher-cost projects and lower-cost projects produce similar benefits when assigned to sites with more than 2.0 and less than 2.0 crashes per year, respectively.

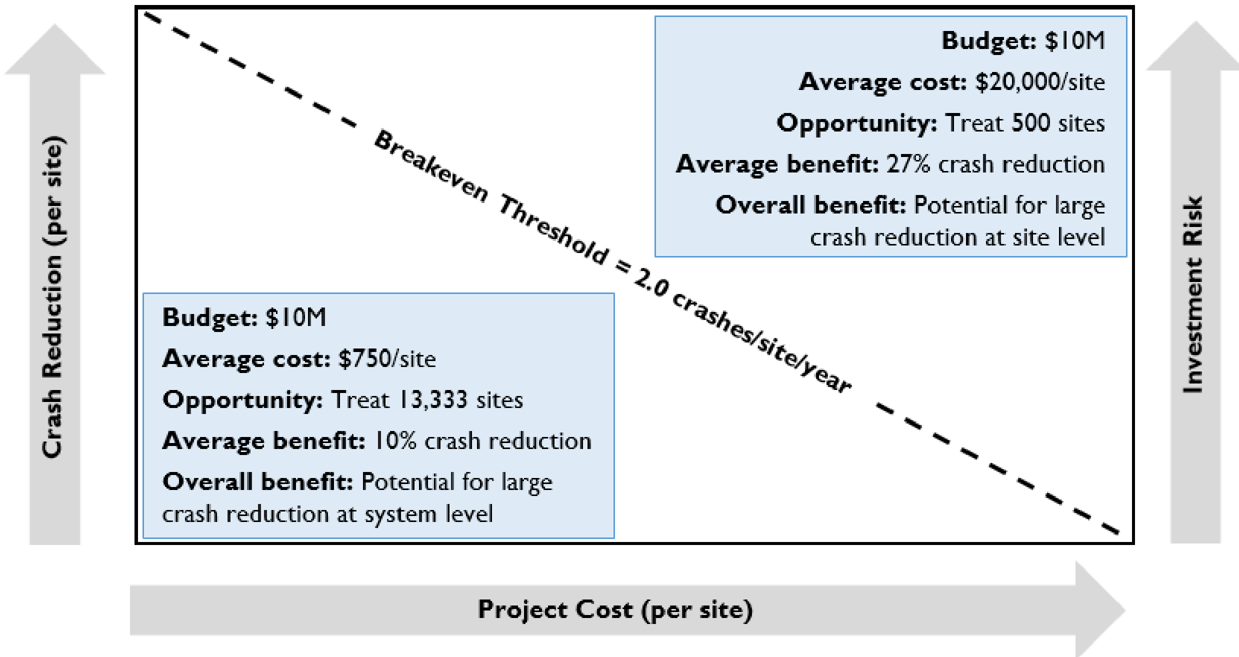

Figure 12. Chart. Optimizing investments in high-cost and low-cost improvements.

Note this is a basic example of how practitioners can apply the equation in Figure 10. Analysts should consider the applicability of the average projects included in this research before applying the results of this example to actual safety programs. It is desirable to generate agency-specific estimates for the average cost and CMF of crash-based and systemic-based projects.

Considerations for Applying the Breakeven Equation

Analysts should consider a number of factors to appropriately apply the breakeven equation. First, it is desirable to apply the equation to fatal and injury or fatal and severe injury crashes rather than total crashes as shown in the example. In either case, analysts should use the weighted average crash cost for crashes of that severity level and the CMF for crashes of that severity level. The resulting breakeven crash frequency reflects those conditions (e.g., the breakeven fatal and injury crashes or breakeven total crashes). Similarly, analysts could input a crash cost and CMF for a specific crash type. Note the analysis should focus on a single crash type or severity using corresponding crash costs and CMFs as inputs.

Another consideration is the mix of projects considered in the analysis. Ideally, analysts would consider segment and intersection projects separately. The previous example application mixes projects along segments, intersections, and curves to estimate the average project cost and effectiveness. It may be more appropriate to consider segments, intersections, and curves separately, particularly when allocating funds within a targeted program such as a roadway departure program or an intersection improvement program.

Practitioners could apply this equation in a number of ways to help inform project planning and programming decisions. For example, analysts could apply the equation to assess the tradeoff and selection of specific treatments for a certain site, rather than average project costs and effectiveness estimates for typical projects within a program.

Given these additional considerations, the remainder of this section presents an example of how an agency could apply the equation to an intersection improvement program. Let's assume an agency is developing an intersection improvement program, focusing on fatal and injury crashes. They have narrowed the focus to stop-controlled intersections, and are considering how to allocate funding between crash-based and systemic improvements. The proposed crash-based projects include the conversion of stop-controlled intersections to roundabouts. The proposed systemic projects include enhanced signing and marking packages.

Table 9 presents the assumed CMF and average annualized cost for the two improvements over the assumed service life. The CMFs apply to fatal and injury crashes, and reflect the average effectiveness over rural and urban areas. The average project cost for roundabouts and signs and markings are from Table 3 and Table 5, respectively. The assumed service life is 20 years for roundabouts and seven years for signing and marking packages. The average crash cost for fatal and injury crashes is approximately $160,000.[9]

Table 9. CMFs and project costs for intersection improvement example.

Economic Measure	Crash Based (Roundabout)	Systemic (Signs and Markings)
CMF (fatal and injury crashes)	0.15[1]	0.90[2]
Average Project Cost Per Intersection Per Year	$739,000	$6,000

1. The CMF for roundabouts is an average of the CMF for fatal and injury crashes in urban areas (CMF = 0.12; http://cmfclearinghouse.org/detail.cfm?facid=210) and the CMF for fatal and injury crashes in rural areas (CMF = 0.18; http://cmfclearinghouse.org/detail.cfm?facid=211).

2. The CMF for signing and marking packages is from the following paper: Le, T., F. Gross, and T. Harmon. Safety Effects of Low-Cost Systemic Safety Improvements at Signalized and Stop-Controlled Intersections. 96th Annual Meeting of the Transportation Research Board Compendium of Papers, January 8 – 12, 2017.

With these inputs, the breakeven equation in Figure 10 yields a breakeven crash frequency threshold of 6.1 fatal and injury crashes per intersection per year as shown in Figure 13. In this case, stop-controlled intersections with more than 6.1 fatal and injury crashes per year are more fitting locations for roundabouts, and stop-controlled intersections with less than 6.1 fatal and injury crashes per year are more appropriate for the signing and marking package.

$$ACF_{without} = \frac{\$739{,}000 - \$6000}{\$160{,}000 * (0.90 - 0.15)} = 6.1$$

Figure 13. Equation. Application of the breakeven equation.

SUMMARY

These analyses and other considerations demonstrate the value of complementing crash-based and systemic approaches to safety management within a comprehensive safety program. While States currently allocate approximately 75 percent of HSIP funds to crash-based projects, the analysis results and breakeven crash frequency threshold calculation provide evidence of the potential to improve the cost-effectiveness of safety improvements through increased systemic projects. Incorporating more systemic projects into a safety program has the potential to address safety problems on a broader scale and enhance the overall effectiveness of a program.

In complementing crash-based projects with systemic projects, it is important to understand the strengths and limitations of each approach. The crash-based approach is useful to identify and mitigate safety issues at sites with high potential for improvement. While projects implemented under the crash-based approach have an opportunity to produce great local benefits, the associated project costs are typically high. As such, there are limited system benefits because agencies can treat only a limited number of sites. Further, the projects are higher risk in terms of contributing to the effectiveness of an agency's safety program.

The systemic approach is useful to identify and address widespread safety issues distributed across many segments and intersections. It is difficult to address these sites with the crash-based approach due to the low density of crashes. The systemic approach overcomes these limitations by focusing on the underlying risk factors across the network as opposed to crash history at individual locations. While systemic projects typically represent lower-cost and lower-risk countermeasures, the site-specific benefits are typically not as attractive as crash-based projects, and it may be difficult for agencies to justify the allocation of resources to sites without a history of crashes.

In either case, it is important to use reliable, data-driven methods to inform decisions. The Highway Safety Manual presents a predictive method to relate crash frequency to roadway design and operational characteristics through statistical models or SPFs. A predictive approach based on the combination of historical crash, exposure, and roadway data is more reliable than approaches based on crash frequency alone or ad hoc analysis of geometric and operational characteristics to approximate risk. The following is a brief summary of using the predictive method in crash-based and systemic approaches to safety management.

- **Crash-based approach:** Agencies can employ predictive models to estimate the average safety performance given specific site conditions (e.g., traffic volume, geometric, and operational attributes). They can also incorporate the observed crash history with the average crash predictions to estimate the long-term crash propensity for a given site. Sites with higher expected crashes over the long-term (compared to the average safety performance for those conditions) indicate a higher potential for improvement.
- **Systemic approach:** Agencies can use the results from predictive models to identify the most critical risk factors or combination of features that increase risk for a given crash type. They can use these risk factors to identify high risk locations with or without a history of crashes. While the systemic approach is still useful when data are limited, agencies should use crash and traffic volume data when it is available throughout

network screening, diagnosis, and countermeasure selection to the extent possible. The use of low-cost countermeasures in systemic projects helps to limit the uncertainty of using site-based geometric and operational data (i.e., risk factors) for site selection in the absence of site-specific observed crash or traffic volume data.

Crash-based performance measures and exposure are eligible, appropriate, and possibly preferred risk factors that analysts can employ in the systemic approach. This is not common practice at this time and was not mentioned in any reports reviewed during the data collection effort for the analysis in this guide. However, AASHTOWare Safety Analyst™ employs crash-based screening performance measures in the systemic approach and usRAP employs a systemic approach in which exposure is a risk factor. Other tools may have similar capabilities.

It is clear through the development of the current state of the art in SPFs, and specifically in several papers and in the Highway Safety Manual, that crash-based performance measures and exposure are superior predictors of risk compared to other geometric and operational factors. When crash and exposure data are adequate and available, analysts should incorporate these data in the systemic approach. Doing so will help to improve the reliability of the results and potentially improve the benefits of the approach compared to the crash-based approach.

4. DATA REQUIREMENTS FOR CRASH-BASED AND SYSTEMIC APPROACHES

The following is a brief overview of the data requirements for crash-based and systemic approaches to safety management.

CRASH-BASED APPROACH

The crash-based approach comprises a safety management process with six steps: network screening, diagnosis, countermeasure selection, economic appraisal, project prioritization, and safety effectiveness evaluation. Table 10 provides a summary description of the data needs for various components of the crash-based approach to safety management, excluding project prioritization as this is an internal process that can include many different factors. While the table presents the data elements separately, there is a need to link crash, roadway, and traffic volume data geospatially to use the predictive crash-based approaches. Refer to the Model Inventory Roadway Elements—Fundamental Data Elements (MIRE FDE) for further discussion of basic data elements required for crash-based network screening and beyond.

Table 10. Data needs for the crash-based approach to safety management.

Component	Crash	Exposure	Roadway	Other
Network screening	Crash counts by severity at the site level (intersections and segments)	Traffic volume and segment length	Area type (rural or urban), number of lanes, median type, intersection control, and number of legs	Safety performance functions (SPFs) or other thresholds by facility type
Diagnosis	Three to five years of police crash reports and details for each location	Traffic volume and turning movement counts	Traffic operations, roadway design, and roadside design features	Adjacent land use, road user behavior, and road user demographics
Counter-measure selection	Three to five years of police crash reports and details for each location	Traffic volume and turning movement counts	Traffic operations, roadway design, and roadside design features	List of crash contributing factors and countermeasure details
Economic appraisal	Expected change in crashes due to treatment	Current and future traffic volume	Site characteristics to identify suitable crash modification factors (CMFs)	Applicable CMFs, average crash costs, and service life of treatment
Safety effectiveness evaluation	Crash counts by severity before and after treatment for each site	Traffic volume before and after treatment for each site	Site characteristics to define a suitable reference group or comparison group	Treatment details, including location and implementation date; SPFs

SYSTEMIC APPROACH

The systemic approach begins with the identification of focus crash types based on crashes at the network level. For example, an agency may identify roadway departure crashes as a focus crash type because these crashes present the majority of fatal and injury crashes across their network. Given a focus crash type, the next step is to determine risk factors related to the focus crash type. Once an agency determines the risk factors associated with a focus crash type, the next step is to determine appropriate countermeasures to target the underlying issue(s). Next, the agency must identify sites to implement the treatment. Finally, there is a need to evaluate the safety effectiveness of the treatment.

The following is a brief summary of the data requirements for each step of the systemic safety management process. Note many of the data requirements are similar to the crash-based approach; however, agencies can apply the systemic approach without site-level crash and exposure data or when the average crash frequency at individual sites is relatively low. Both of these conditions present issues in applying the crash-based approach.

- **Identify focus crash types and facility types:** The data requirements include a summary of crashes by facility type, often by severity, at the network level. There is no need to match crashes with individual locations.
- **Determine risk factors:** This requires statistical modeling or cross-tabulations, and the association of specific roadway data with each crash type. If an agency lacks the data or expertise to determine risk factors for the focus crash type, then they may search for related results from national or state research reports to inform the analysis. Refer to the National Cooperative Highway Research Program Report 500 to identify risk factors related to specific crash types. Refer to the CMF Clearinghouse and review CMFs to understand the level of risk associated with specific roadway features. The following are common segment and intersection features to define risk factors.
    - Segment features: number of lanes, lane width, shoulder type and width, median type and width, road edge features and quality, number and type of access points, radius and superelevation of horizontal curves, speed limit, speed differential between curves and tangents, roadside hazards, and pavement condition and friction.
    - Intersection features: number of approaches, number of approach lanes, traffic control devices, skew, proximity to horizontal and vertical curves, signal timing, proximity to railroad crossing, presence of street lighting, proximity to nearby access points, and presence of commercial developments.
- **Select countermeasures:** This step requires information related to the applicability, cost, and effectiveness of potential countermeasures. It is important to select measures that directly target the underlying risk factor(s). The Highway Safety Manual and CMF Clearinghouse provide CMFs and associated standard errors for various measures. If available from the underlying study, these sources indicate the applicability of the CMFs with respect to site conditions (e.g., area type, number of lanes, median type, and traffic volume), crash type, and crash severity.

- **Screen network for suitable locations:** This step requires roadway data for the network of interest. For example, if the agency is focusing on angle crashes at rural, four-legged, two-way stop-controlled intersections, then they would need data for this facility type. Specific data needs will vary, but there is a need for at least basic information to identify the presence of risk factors at those locations. Refer to the MIRE FDE for further discussion of basic data elements required for network screening. If there is incomplete data for a portion of the network or for specific risk factors, then the agency may choose to collect the required data, screen the portion of the network with complete data, or screen the entire network with incomplete risk factor data.
- **Evaluate safety effects:** The data requirements to evaluate the safety effectiveness of systemic treatments are identical to the data requirements to evaluate treatments implemented though the crash-based approach. Refer to Table 10 for details. There are several potential methods for evaluating the safety effects of both crash-based and systemic projects, and the Empirical Bayes before-after method is generally preferred. Refer to A Guide to Developing Quality CMFs for further details related to appropriate evaluation methods. Potential issues related to the evaluation of systemic improvements include small sample sizes, many treated sites with no recent crashes, and the lack of site-specific crash data. If the sample size is relatively small, it may not be possible to detect changes in safety performance at the desired level of statistical significance. Further, if there are many sites with few or no crashes in the before period, then even one or two crashes at these sites in the after period can indicate an increase in crashes. As such, it is important to evaluate systemic projects as a system rather than as individual sites. For example, if an agency installs shoulder rumble strips on all two-lane, rural roads with a minimum shoulder width of five feet, then it is appropriate to evaluate the safety effectiveness of shoulder rumble strips at the system level (i.e., all treated two-lane, rural roads) rather than evaluating individual sites or corridors. Finally, if the average crash frequency per site is relatively small (i.e., low sample mean), then it may be necessary to rely on more sophisticated methods (e.g., Full Bayes before-after) to evaluate the impact of these countermeasures.

5. TOOLS AND RESOURCES FOR SYSTEMIC APPROACHES

Tools and resources are available to support systemic approaches, including guides and software. Some guides provide a discussion of the systemic approach, while other tools relate to specific components of the systemic process. For example, selecting targeted countermeasures to address systemic safety issues requires information related to potential countermeasures. Tools such as the National Cooperative Highway Research Program Report 500 series can help users identify risk factors and appropriate countermeasures for a given safety issue or focus crash type. The CMF Clearinghouse can help users identify and apply CMFs to estimate the expected benefits of countermeasures.

The FHWA Roadway Safety Data and Analysis Toolbox is a web-based repository of safety data and analysis tools. Use the Toolbox to identify an appropriate tool for your systemic safety management needs. A Primer is available to understand the overall scope and functionality of the Toolbox as well as the roles, responsibilities, and tasks supported by tools in the Toolbox.

USING THE ROADWAY SAFETY DATA AND ANALYSIS TOOLBOX

There are two primary options for searching the Toolbox. The first is a predefined query using the four large icons in the upper right of Figure 14 (Manage, Analyze, Collect, and Research). The second is an advanced search option where users can search keywords and apply filters to customize their search as shown in the lower left of Figure 14.

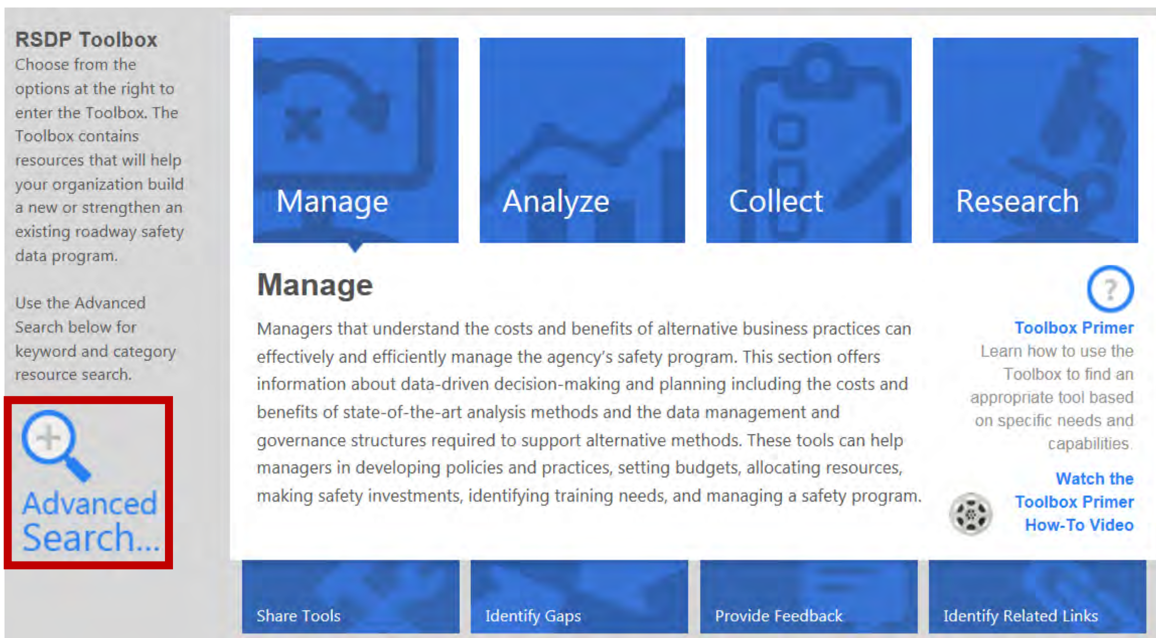

Figure 14. Screenshot. Roadway Safety Data and Analysis Toolbox.

The following is a brief demonstration of the stepwise process to identify an appropriate tool to support the systemic approach.

1. Click the 'Advanced Search' icon, highlighted in the lower left of Figure 14.
2. From the advanced search page (Figure 15), enter the word 'systemic' in the keyword search and click the search button. This returns a list of tools related to systemic safety management.

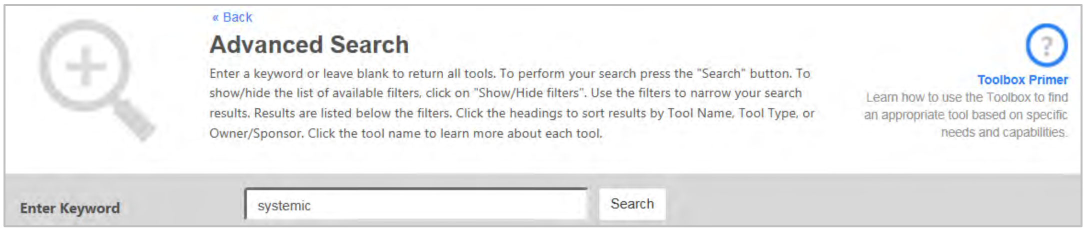

Figure 15. Screenshot. Advanced search feature.

Using the advanced search, the Toolbox returns guides such as the Systemic Safety Project Selection Tool, Manual for Selecting Safety Improvements on High Risk Rural Roads, and Integrating Safety in the Rural Transportation Planning Process. Related software tools include AASHTOWare Safety Analyst™ and usRAP.

To identify appropriate tools to support specific aspects of the systemic approach (e.g., countermeasure selection or economic appraisal), use the following stepwise process.

1. From the advanced search page (Figure 15), leave the keyword blank and click the search button. This returns a list of all tools in the Toolbox.
2. Click the 'Show/Hide Filters' button, highlighted in the upper left of Figure 16. This reveals a list of filters to refine the general search.
3. Use the 'Safety Management Process' filter to select 'Countermeasure Selection' or other primary area of interest as shown in Figure 16. Apply additional filters as needed to refine the results. For example, apply the 'Tool Type' filter to narrow the list of tools to application guides, information guides, software, information sources, or databases.

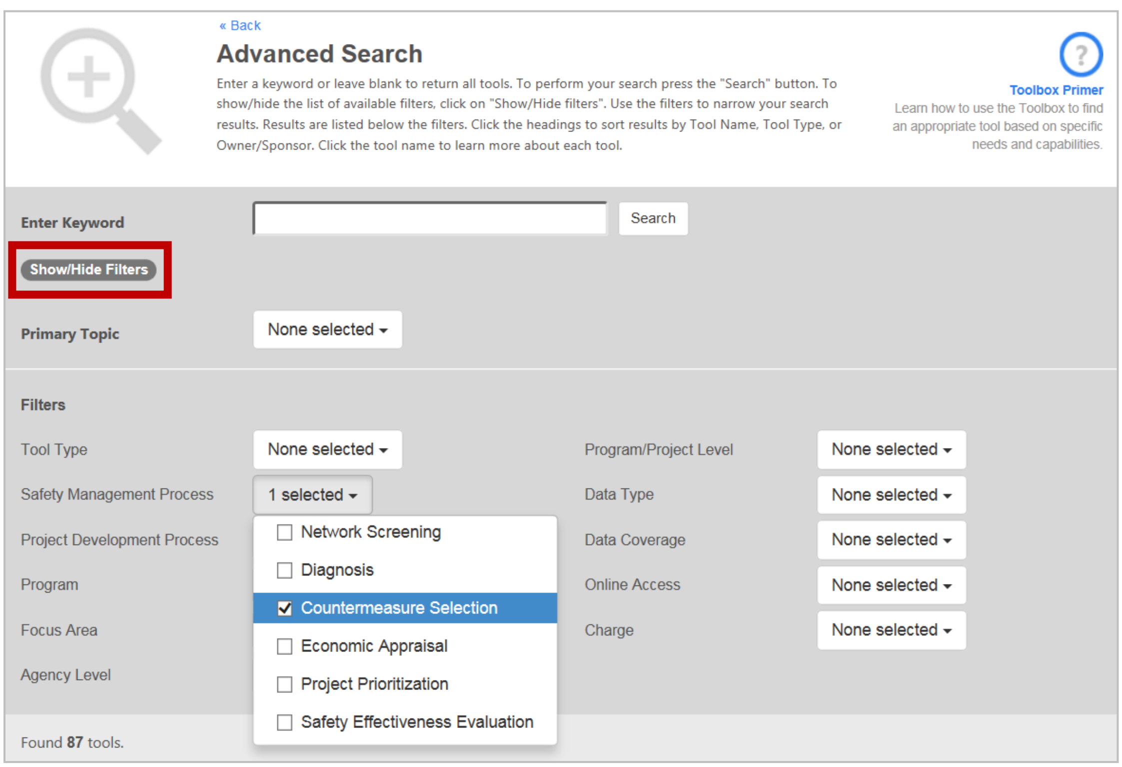

Figure 16. Screenshot. Filter options from advanced search page.

6. FUTURE RESEARCH NEEDS

This guide presents an initial framework for estimating the value of and allocating funds between two complementary approaches to safety management: crash-based and systemic. While this work represents one potential method for comparing crash-based and systemic approaches, there is considerable research needed to test and validate the method and underlying assumptions. The following is a list of opportunities to enhance the information presented in this guide:

- There is limited information on the prevalence of systemic countermeasures. As such, there is a need for agencies to track, and specifically identify, systemic projects.
- There is limited information on the safety effectiveness of systemic countermeasures. Many CMFs to date reflect the safety effectiveness of crash-based projects. It is unknown if these countermeasures will have the same level of effectiveness when applied systemically. It is assumed that the Empirical Bayes before-after method is appropriate to evaluate the safety effects of systemic improvements, but future research should validate this approach.
- Many of the estimates presented in this guide reflect the safety effectiveness of a limited number of projects based on simple before-after studies. It is necessary to increase the sample size and employ more reliable methods to obtain more reliable estimates of the average safety effectiveness of various project types.
- The results presented in this guide reflect the safety benefits in terms of all crash types and severities. A similar analysis should focus on fatal and serious injury crash reductions for the calculation of benefits.
- There is a need to expand the analysis to include more types of crash-based and systemic projects as more information becomes available on the cost and effectiveness.
- There is a need to test the application of the framework for allocating funds to crash-based and systemic projects. This framework should be tested in real-world scenarios and under various conditions (e.g., HSIP program level, subprogram level, and project level to identify potential strengths, limitations, challenges, and opportunities).

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APPENDIX: CRASH-BASED AND SYSTEMIC PROJECT DETAILS

Table 11 through Table 14 present crashes per site-year for improvements associated with the crash-based and systemic approaches. The tables present crashes by severity where available and for separate periods before and after treatment. When possible, the benefits included in this guide reflect the change in crashes by severity, accounting for situations where crashes may increase for certain severities (e.g., PDO crashes) and decrease for other severities. For cases when crashes by severity are unavailable, the research team used applicable CMFs to estimate the change in crashes for all severities. For treatments with data from multiple States or studies, the research team weighted the average crashes using the proportion of mile-years or site-years contributed by each State or study.

Table 11. Crash-based crashes per site-year before treatment.

Treatment	State(s)	CMF	Total	K	A	B	C	PDO
Add Left Turns	SC	0.59	5.02	0.03	0.28	0.49	1.21	3.01
High Friction Surface Treatment	RI	0.85	5.37	0.09	0.11	0.14	1.46	3.57
Reconfigure Intersection	SC	0.66	4.22	0.12	0.15	0.50	0.84	2.61
Reduce Intersection Skew and Add Left Turn Lanes	SC	0.48	3.76	0.13	0.17	0.29	1.04	2.14
Road Diet Without Resurfacing	IA, CA, WA	0.71	26.20	-	-	-	-	-
Road Diet With Reconstruction and Resurfacing	IA, CA, WA	0.71	26.20	-	-	-	-	-
Roundabout	SC	0.28	4.61	0.07	0.13	0.74	1.15	2.52

Table 12. Crash-based crashes per site-year after treatment.

Treatment	State(s)	CMF	Total	K	A	B	C	PDO
Add Left Turns	SC	0.59	2.95	0.00	0.06	0.10	0.83	1.97
High Friction Surface Treatment	RI	0.85	4.57	0.00	0.00	0.14	0.43	4.00
Reconfigure Intersection	SC	0.66	2.78	0.00	0.06	0.26	0.81	1.65
Reduce Intersection Skew and Add Left Turn Lanes	SC	0.48	1.80	0.03	0.06	0.17	0.34	1.19
Road Diet Without Resurfacing	IA, CA, WA	0.71	18.60*	-	-	-	-	-
Road Diet With Reconstruction and Resurfacing	IA, CA, WA	0.71	18.60*	-	-	-	-	-
Roundabout	SC	0.28	1.27	0.00	0.00	0.19	0.29	0.79

*After-period crash data not given and estimated using the CMF from the report.

Table 13. Systemic crashes per site-year before treatment.

Treatment	State(s)	CMF	Total	K	A	B	C	PDO
Cable Median Barrier	MI	2.14 (0.95)	1.97	0.03	0.12	0.22	0.34	1.26
Centerline and Shoulder Rumble Strips	KY, MO, PA	0.80	0.91	-	-	-	-	-
Ramp Curve Signage	RI	0.74	15.21	0.08	0.50	1.12	3.13	10.38
Curve Warning Signs (Chevrons)	WA, CT	0.94	6.19	-	-	-	-	-
Low Cost Intersection Improvements –Signal	SC	0.96	12.49	-	-	-	-	-
Low Cost Intersection Improvements –Stop	SC	0.92	3.49	-	-	-	-	-

Table 14. Systemic crashes per site-year after treatment.

Treatment	State(s)	CMF	Total	K	A	B	C	PDO
Cable Median Barrier	MI	2.14 (0.95)	4.38	0.01	0.06	0.18	0.44	3.69
Centerline and Shoulder Rumble Strips	KY, MO, PA	0.80	0.73*	-	-	-	-	-
Ramp Curve Signage	RI	0.74	11.18	0.00	0.27	1.18	2.03	7.70
Curve Warning Signs (Chevrons)	WA, CT	0.94	5.79	-	-	-	-	-
Low Cost Intersection Improvements –Signal	SC	0.96	11.93 *	-	-	-	-	-
Low Cost Intersection Improvements –Stop	SC	0.92	3.20*	-	-	-	-	-

* After-period crash data not given and estimated using the CMF from the report.

Table 15 and Table 16 present the costs and benefits associated with crash-based and systemic improvements. Maintenance for all countermeasures over the service life was considered negligible with the exception of cable median barrier. Benefits reflect the economic impact of the difference in crashes (by severity, when applicable) before and after treatment. When crashes by severity were unavailable, the benefits reflect the difference in total crashes.

Table 15. Crash-based project benefits.

Treatment	Average Construction Cost (per mile/site)	Average Maintenance Cost (per mile/site)	Project Coverage (miles/sites)	Service Life (years)	Net Benefits per Site	Net Benefits for Program	Benefit Cost Ratio
Add Left Turns	$706,000	-	14	20	$4,456,144	$62,386,011	6.3
High Friction Surface Treatment	$100,000	-	100	10	$4,982,638	$498,263,771	49.8
Reconfigure Intersection	$822,000	-	12	20	$11,191,127	$134,293,525	13.6
Reduce Intersection Skew and Add Left Turn Lanes	$1,106,000	-	9	20	$9,325,737	$83,931,637	8.4
Road Diet Without Resurfacing	$100,000	-	100	20	$6,318,883	$631,888,312	63.2
Road Diet With Reconstruction and Resurfacing	$1,000,000	-	10	20	$6,318,883	$63,188,831	6.3
Roundabout	$739,000	-	13	20	$8,590,982	$111,682,769	11.6

Table 16. Systemic project benefits.

Treatment	Average Construction Cost (per mile/site)	Average Maintenance Cost (per mile/site)	Project Coverage (miles/sites)	Service Life (years)	Net Benefits per Site	Net Benefits for Program	Benefit Cost Ratio
Cable Median Barrier	$156,000	$40,000*	51	13	$1,137,374	$58,006,096	5.8
Centerline and Shoulder Rumble Strips	$5,000	-	2,000	7	$63,386	$126,771,305	12.7
Ramp Curve Signage	$10,000	-	1,000	5	$2,928,926	$2,928,925,502	292.9
Curve Warning Signs (Chevrons)	$1,600	-	6,250	5	$102,402	$640,014,079	64.0
Low Cost Intersection Improvements –Signal	$7,000	-	1,428	7	$195,747	$279,526,340	28.0
Low Cost Intersection Improvements –Stop	$6,000	-	1,666	7	$100,884	$168,073,055	16.8

*Assumes $848.58 repair cost per crash, 4.38 crashes per mile per year, and a 13-year service life at a discount rate of 3 percent.

Table 17 presents the crash severity distribution and associated average crash costs used in the benefit-cost analysis. When information was available for crashes by severity, the benefits reflect the crash costs by severity. When information was not available for crashes by severity, the benefits reflect the total crash cost ($55,900).

Table 17. Typical crash cost matrix.

Injury	Percent of Total	Cost per Crash
K-Killed	0.38%	$5,715,100
A-Incapacitating	1.69%	$302,400
B-Non-Incapacitating	13.50%	$110,400
C-Possible Injury	10.89%	$62,200
PDO-No Apparent Injury	73.54%	$10,000
Total	100%	$55,900

Figure 17 through Figure 23 present the equations used to estimate the project benefits and compare them to estimated project costs. Each equation is accompanied by two examples, one for a road diet with resurfacing (crash-based) and one for cable median barrier (systemic). The examples show the differences in calculations for projects with and without annual maintenance costs and for projects with and without information by crash severity.

Figure 17 presents the equation to estimate the average project cost per site.

$$\mathrm{PVC_{site}} = \mathrm{PVC_{construction}} + \left[\mathrm{AVC_{maintenance}} * \left(\frac{(1+\mathrm{r})^{\mathrm{y}} - 1}{\mathrm{r} * (1+\mathrm{r})^{\mathrm{y}}}\right)\right]$$

Figure 17. Equation. Average project cost per site.

Where:

PVC_{site} = present value of project costs per site.

$PVC_{construction}$ = present value construction cost per site.

$AVCm_{aintenance}$ = average annual maintenance cost per site.

y = service life.

r = discount rate (assumed as 3 percent for this guide).

Example: The present value construction cost of the road diet (with resurfacing) is $1,000,000 per mile with no annual maintenance costs. The following shows the calculation of the present value cost for the road diet.

$$\mathrm{PVC_{road\ diet}} = \$1{,}000{,}000 + 0 = \$1{,}000{,}000 \text{ per mile}$$

The present value construction cost of the cable median barrier is $156,000 per mile with an annual maintenance cost of $3,720, assuming a discount rate of three percent (r = 0.03) and service life of 13 years (y = 13). The following shows the calculation of the present value cost for the cable median barrier. Note this is rounded to $196,000 for the purpose of this report.

$$\mathrm{PVC_{cable\ median\ barrier}} = \$156{,}000 + \left[\$3{,}720 * \left(\frac{(1+0.03)^{13} - 1}{0.03 * (1+0.03)^{13}}\right)\right] = 195{,}562 \text{ per mile}$$

Figure 18 presents the equation to estimate project coverage, which is the number of projects an agency could implement given a fixed budget. The research team assumed a $10,000,000 budget for each countermeasure. The team did not scale projects up to the exact limitations of the budget; rather, only whole projects were considered within the budget. The research team calculated the number of sites within the budget using the formula in Figure 18, rounded down to the nearest whole number of sites.

$$\mathrm{N_{sites}} = \frac{\$10{,}000{,}000}{\mathrm{PVC_{site}}}$$

Figure 18. Equation. Project coverage.

Where:

N_{sites} = number of sites within budget (i.e., project coverage).

Example: The following shows the calculation of the project coverage for the road diet, assuming a present value cost of $1,000,000 per mile as previously shown.

$$\mathrm{N_{road\ diet}} = \frac{\$10{,}000{,}000}{\$1{,}000{,}000} = 10\ \text{miles}$$

The following shows the calculation of the project coverage for the cable median barrier, assuming a present value cost of $196,000 per mile as previously shown. Note the value is rounded down to the nearest whole project (51 miles) for the purpose of this report.

$$\mathrm{N_{cable\ median\ barrier}} = \frac{\$10{,}000{,}000}{\$196{,}000} = 51.02\ \text{miles}$$

Figure 19 presents the equation to estimate average cost per crash using the crash severity distribution and associated crash costs presented in Table 17.

$$\mathrm{CC} = 0.0038 * \mathrm{K_{cost}} + 0.0169 * \mathrm{A_{cost}} + 0.135 * \mathrm{B_{cost}} + 0.1089 * \mathrm{C_{cost}} + 0.7354 * \mathrm{PDO_{cost}}$$

Figure 19. Equation. Average cost per crash.

Where:

CC = average total cost per crash.

K_{cost} = average cost per fatal crash.

A_{cost} = average cost per incapacitating crash.

B_{cost} = average cost per non-incapacitating crash.

C_{cost} = average cost per possible injury crash.

PDO_{cost} = average cost per no apparent injury crash.

Example: The following shows the calculation of the average cost per crash using the crash severity distribution and associated crash costs presented in Table 17. Note the value is rounded to $55,900 for the purpose of this report.

$$\mathrm{CC} = 0.0038 * \$5{,}715{,}100 + 0.0169 * \$302{,}400 + 0.135 * \$110{,}400 + 0.1089 * \$62{,}200 + 0.7354 * \$10{,}000 = \$55{,}860$$

Figure 20 presents the equation to estimate the net benefit for a single site based on crashes reduced and crash costs by severity. For this analysis, the research team assumed a discount rate of three percent.

$$NB_{site} = (K_{reduced} * K_{cost} + A_{reduced} * A_{cost} + B_{reduced} * B_{cost} + C_{reduced} * C_{cost} + PDO_{reduced} * PDO_{cost}) * \left(\frac{(1+r)^y - 1}{r * (1+r)^y}\right)$$

Figure 20. Equation. Net benefit per site for crashes by severity.

Where:

NB_{site} = net benefits per site.

$K_{reduced}$ = average fatal crashes reduced per site-year.

$A_{reduced}$ = average incapacitating crashes reduced per site-year.

$B_{reduced}$ = average non-incapacitating crashes reduced per site-year.

$C_{reduced}$ = average possible injury crashes reduced per site-year.

$PDO_{reduced}$ = average no apparent injury crashes reduced per site-year.

Example: The following shows the calculation of the net benefit per site for the cable median barrier, assuming a discount rate of three percent (r = 0.03) and service life of 13 years (y = 13). Note the benefit is based on the change in crashes by severity from Table 13 and Table 14 and crash costs by severity from Table 17. For example, the average fatal crashes reduced per site-year ($K_{reduced}$) is 0.03 – 0.01 = 0.02 from Table 13 and Table 14.

$$NB_{site} = (0.02 * \$5{,}715{,}100 + 0.06 * \$302{,}400 + 0.04 * \$110{,}400 + (-0.1) * \$62{,}200 + (-2.43) * \$10{,}000) * \left(\frac{(1+0.03)^{13} - 1}{0.03 * (1+0.03)^{13}}\right)$$
$$= \$1{,}130{,}942$$

Figure 21 presents the equation to estimate the net benefit for a single site based on total crashes reduced and average total crash costs.

$$NB_{site} = T * \left(\frac{(1+r)^y - 1}{r * (1+r)^y}\right) * CC$$

Figure 21. Equation. Net benefit per site for total crashes.

Where:

T = total average crashes reduced.

Example: The following shows the calculation of the net benefit for the road diet, assuming a discount rate of three percent (r = 0.03) and service life of 20 years (y = 20). Note the change in crashes by severity was not available, so the benefit is based on the change in total crashes from Table 11 and Table 12 and total crash cost from Table 17.

$$NB_{site} = (26.2 - 18.6) * \left(\frac{(1+0.03)^{13} - 1}{0.03 * (1+0.03)^{13}}\right) * \$55{,}900 = \$6{,}320{,}546$$

Figure 22 presents the equation to estimate the total net benefits assuming full implementation given a fixed budget.

$$\mathrm{NB}_{\mathrm{program}} = \mathrm{NB}_{\mathrm{site}} * \mathrm{N}_{\mathrm{sites}}$$

Figure 22. Equation. Net benefit for whole program.

Where:

$NB_{program}$ = total net benefits for program (i.e., all projects within $10,000,000 budget).

Example: The following shows the calculation of the net benefit for a $10,000,000 budget spent entirely on road diets (with resurfacing), assuming a present value cost of $1,000,000 per mile and coverage of 10 miles. Note the result is slightly different than the program benefit presented in Table 4 due to rounding in Table 11 and Table 12.

$$\mathrm{NB}_{\text{road diet program}} = \$6{,}320{,}546 * 10 = \$63{,}205{,}460$$

The following shows the calculation of the net benefit for a $10,000,000 budget spent entirely on cable median barrier, assuming a present value cost of $196,000 per mile and coverage of 51 miles. Note the result is slightly different than the net safety benefit presented in Table 6 due to rounding in Table 13 and Table 14.

$$\mathrm{NB}_{\text{cable median barrier program}} = \$1{,}130{,}942 * 51 = \$57{,}678{,}042$$

Figure 23 presents the equation to estimate the benefit-cost ratio.

$$\mathrm{BCR} = \frac{\mathrm{NB}_{\mathrm{site}}}{\mathrm{PVC}_{\mathrm{site}}}$$

Figure 23. Equation. Net benefits per site.

Where:

BCR = benefit-cost ratio.

Example: The following shows the calculation of the benefit-cost ratio for road diets (with resurfacing), assuming a present value cost of $1,000,000 per mile and present value benefit of $6,320,546.

$$\mathrm{BCR}_{\text{road diet program}} = \frac{\$6{,}320{,}546}{\$1{,}000{,}000} = 6.3$$

The following shows the calculation of the benefit-cost ratio for cable median barrier, assuming a present value cost of $196,000 per mile and present value benefit of $1,130,942.

$$\mathrm{BCR}_{\text{cable median barrier program}} = \frac{\$1{,}130{,}942}{\$196{,}000} = 5.8$$

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