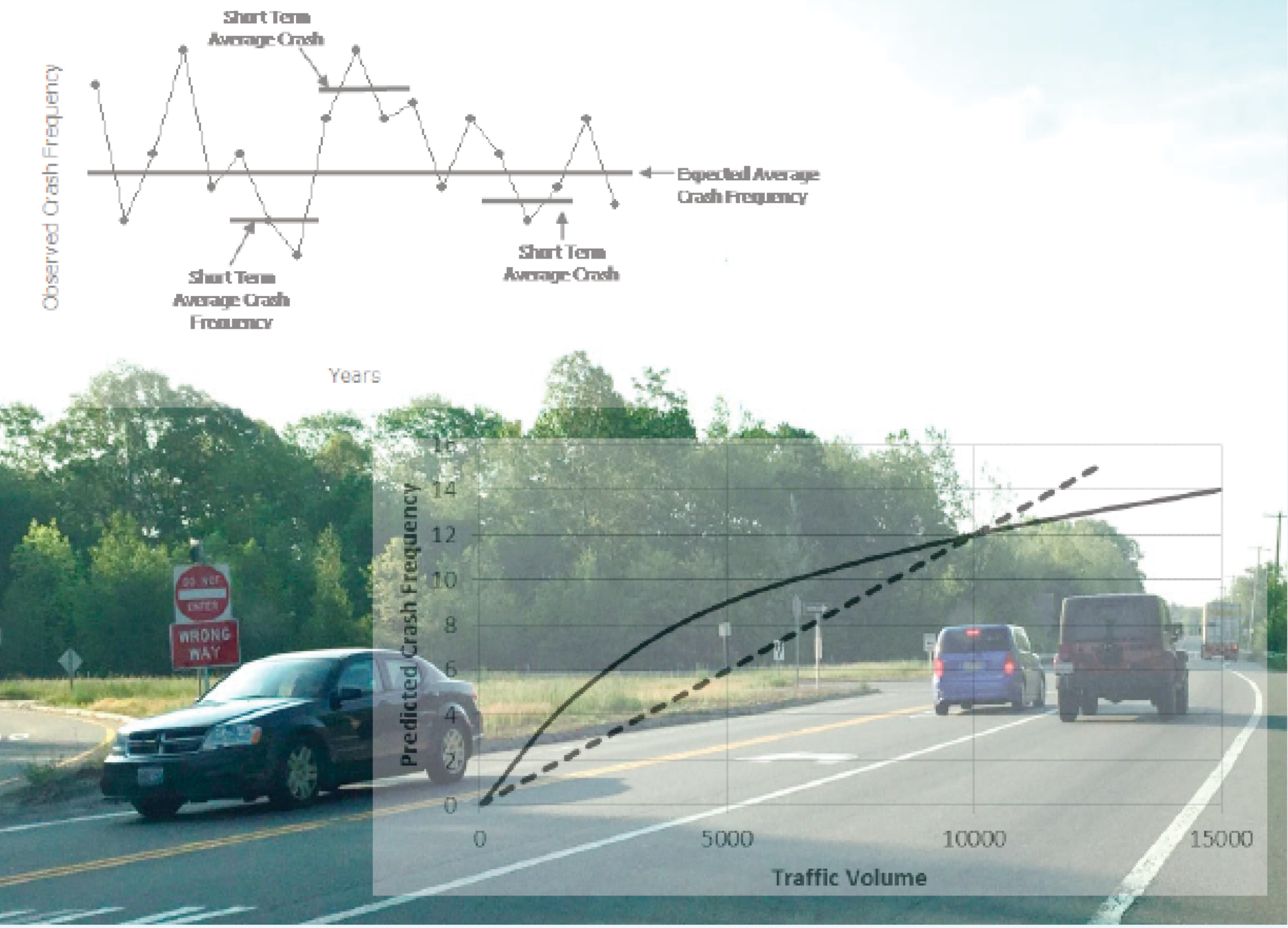
MassDOT Safety
Alternatives Analysis Guide



PREPARED FOR

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List of Acronyms

A	Suspected Serious Injury or Incapacitating Injury
AADT	Annual Average Daily Traffic
B	Suspected Minor Injury or Non-Incapacitating Injury
C	Possible Injury
CMF	Crash Modification Factor
CMFunction	Crash Modification Function
EB	Empirical Bayes
FAST	Fixing America's Surface Transportation
FHWA	Federal Highway Administration
FI	Fatal and Injury Crashes
HSIP	Highway Safety Improvement Program
HSM	Highway Safety Manual
ICE	Intersection Control Evaluation
K	Fatal Injury
MAP-2	Moving Ahead for Progress in the 21st Century
MassDOT	Massachusetts Department of Transportation
MMUCC	Model Minimum Uniform Crash Criteria
O	No Apparent Injury
PDO	Property Damage Only
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equality Act: A Legacy for Users
SPF	Safety Performance Function
SPICE	Safety Performance for Intersection Control Evaluation
vpd	Vehicles per Day

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Executive Summary

The Massachusetts Department of Transportation (MassDOT) administers Highway Safety Improvement Program (HSIP) funds to implement projects that address safety issues on Massachusetts roadways. To direct HSIP funding towards projects which meet this objective, MassDOT is implementing a data-driven approach to determine project eligibility and prioritization for HSIP funds. This guide is designed for use by engineers, planners, and analysts at the project level to assist with the data-driven approach. The methods and tools within this guide are meant to provide insight into the potential effects design and traffic decisions will have on the safety of Massachusetts roadways. The results of these procedures are intended to inform decisions at the project and program level, specifically the HSIP, which direct funding towards projects intended to reduce the frequency of fatal and serious injury crashes.

This report introduces and defines the principles of highway safety analysis, chronicles the required data, mathematically explains the steps of the analysis, and describes methods for interpreting and documenting the results. The report also includes descriptions of useful tools for these analyses and an example for readers to follow along as the procedure is implemented for an actual safety alternative analysis. Finally, two appendices are attached to this document. Appendix A is a list of links to relevant documentation which readers may find useful. Appendix B provides a short but detailed background on safety performance functions (SPFs) for interested readers.

The benefit-cost procedure described in the document follows three steps, and is summarized in Figure 1:

1. Estimate Future No-Build Safety Performance
    a. This is calculated using either expected, predicted, or observed crash frequency. Analysts select the performance metric based on the tools and data available for the study site. The safety performance under existing conditions is projected to the future design year based on the projected growth in traffic volume.
2. Calculate the Expected Change in Safety Performance
    a. This is calculated by applying a CMF to the future no-build safety performance calculated in Step 1. Relevant CMFs are available in the State-Preferred CMF List (available in the Massachusetts Safety Analysis Tools).
3. Perform an Economic Analysis
    a. This is done by converting the expected change in safety performance to a monetary value using average comprehensive crash costs, which are documented for common facility types in this guide.

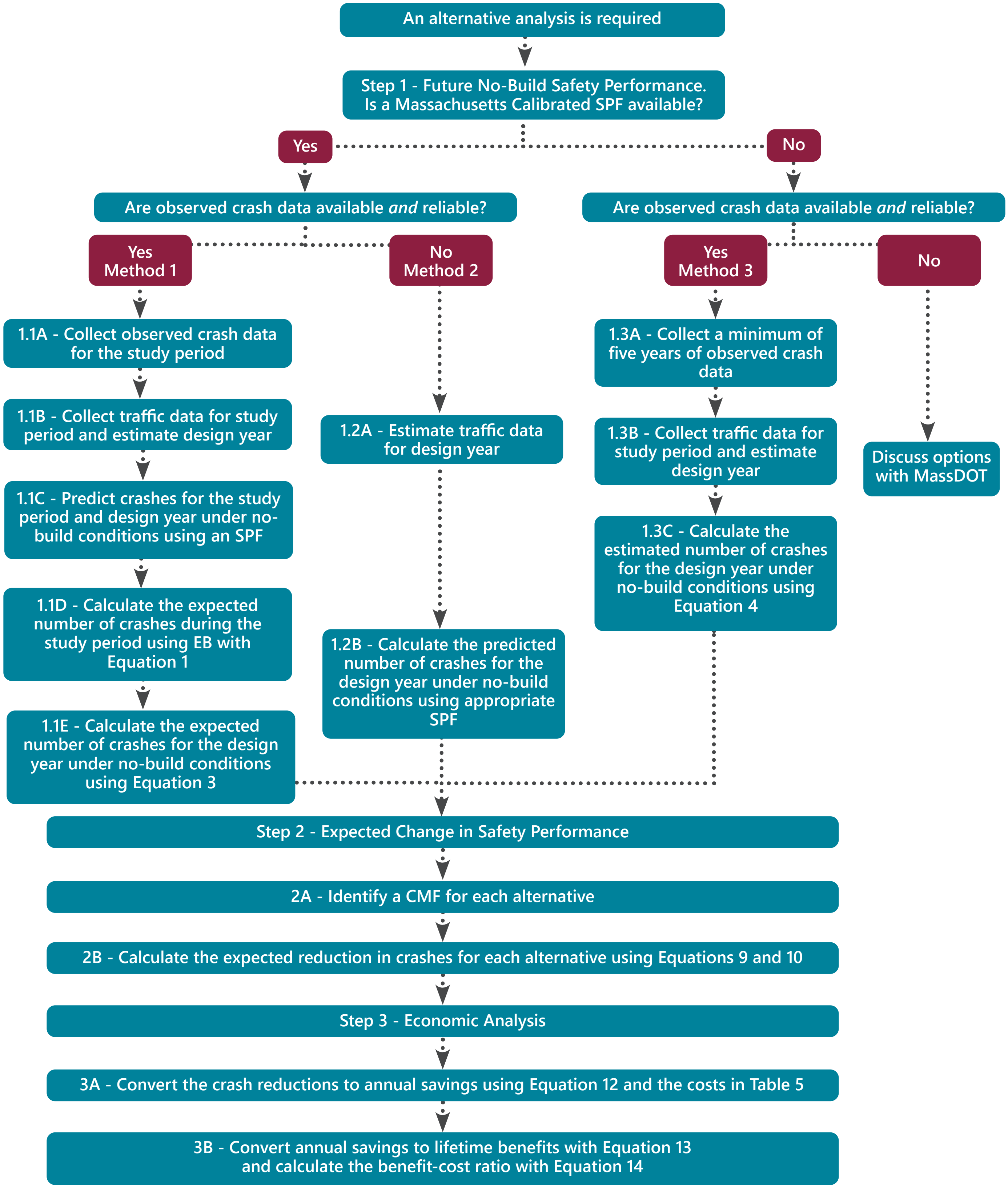


Figure 1 – Flowchart summarizing the safety alternatives analysis process for MassDOT.

Introduction

The Federal Highway Administration (FHWA) established the Highway Safety Improvement Program (HSIP) as a core Federal-aid program with the passing of Safe, Accountable, Flexible, Efficient Transportation Equality Act: A Legacy for Users (SAFETEA-LU) in 2005 and the program continued with the Moving Ahead for Progress in the 21st Century (MAP-21) Act and the Fixing America's Surface Transportation (FAST) Act (FHWA, 2018). The purpose of HSIP is to reduce the number of fatalities and serious injuries on all public roads in the United States. Every year, HSIP funding is apportioned to the Commonwealth of Massachusetts. The Massachusetts Department of Transportation (MassDOT) administers the funds to implement projects that address safety issues on Massachusetts roadways. To direct HSIP funding towards projects which meet this description, MassDOT is implementing a data-driven approach to determining HSIP hot spot project eligibility for HSIP funds. Specifically, the potential change in crash frequency and severity at a site must be quantified for most proposed infrastructure alternatives at HSIP Hot Spots to be considered for HSIP funding. The purpose of this guide is to standardize the methods used for quantifying these potential reductions. Presented below are the preferred methods for estimating future crash frequency and severity, quantifying the potential crash reduction for alternatives, monetizing these reductions for an economic evaluation, and comparing the effectiveness of the alternatives.

This guide is designed for use by engineers, planners, and analysts at the project level. The methods and tools within this guide are meant to provide insight into the potential effects design, traffic, and countermeasure decisions will have on the safety of Massachusetts roadways. The results of these procedures are intended to tie into decisions at the program level, specifically the HSIP, which direct funding towards projects intended to reduce the frequency of fatal and serious injury crashes.

The guide begins by defining safety, including classifying crash types and tools. Next is a discussion of data which are commonly used for safety analysis. This is followed by a section describing the steps necessary to perform an alternatives analysis, including three specific methods based on the available data. Then there is an introduction to tools available to analysts in Massachusetts. The guide concludes with an example that covers, in detail, an analysis of three alternatives, followed by conclusions and recommendations.

Defining Safety

Terms and methods presented in this guide are based on the *Highway Safety Manual* (HSM) (AASHTO, 2010). The HSM is a tool for evaluating safety in a quantitative and substantive way based on crash frequency and severity. The methods proposed in this guide follow procedures described in Parts B and C of the HSM. Part B provides guidelines for countermeasure selection, economic appraisal, and project prioritization, while Part C describes methods for calculating expected crashes. Using these tools, the safety performance of a given design can be considered based on expected crash frequency and severity rather than compliance with design standards.

Safety performance, both present and future, can be described using three measures (AASHTO, 2010):

- **Observed crashes** are the actual crashes reported to have occurred at the study site. The method for obtaining observed crash data is the MassDOT Crash Portal (IMPACT), which allows for relevant crashes to be identified using attribute and map filters as a first brush approach. Analysts should also request relevant crash records from police agencies to identify all crashes that occurred at the study site.

- **Predicted crashes** refers to the predicted crash frequency at a study site obtained from a safety performance function (SPF).
- **Expected crashes** refers to the expected crash frequency given existing conditions at a study site and the historical safety performance at many similar sites. This is a weighted average of observed and predicted crash frequency and is calculated using the Empirical Bayes (EB) method, which is described later in this document.

Observed, predicted, and expected crashes provide valuable insight into the safety performance of a given site. Observed crash data reflects the site-specific safety performance of an individual location. Predicted crash frequency, obtained from an SPF, reflects the average safety performance of similar sites. Expected crash frequency reflects a combination of the observed and predicted crashes, which provides a reliable estimate of the long-term safety performance of a given location. Predicted and expected crash frequency are calculated using the following tools described in the HSM (AASHTO, 2010):

- **Safety Performance Functions (SPFs)** are mathematical equations used to predict crash frequency for a given crash severity and crash type as a function of traffic volume and site characteristics.
- **Crash Modification Factors (CMFs)** are multiplicative factors used to quantify the expected change in crash frequency for a proposed countermeasure, such as changes in the geometric design, or operational characteristics of the facility. CMFs may apply to specific crash types and crash severities and can be reported as either a constant value or a function.
- **Empirical Bayes (EB)** is a statistical method for calculating expected crash frequency which is a weighted average of observed and predicted crash frequency.

Safety Performance Functions

SPFs are used to estimate the predicted crash frequency for a site (segment or intersection) of a specific facility type. Common inputs for SPFs include length and annual average daily traffic (AADT) for a segment and AADT on the major and minor roadway for intersections, all of which are measures of exposure. The result of an SPF is a predicted crash frequency for a given crash type and/or severity, which can be specific (e.g., angle crashes that resulted in no injury) or aggregated (e.g., total crashes). Additional details regarding SPFs are available in Appendix B.

For predicted crash frequency to be an effective measure, it is important to use SPFs which have been estimated or calibrated to local conditions. Addressing this issue for Massachusetts, MassDOT calibrated analysis-level SPFs from the HSM for four common urban intersection types. These are summarized in Table 1, which describes the facility types and shorthand code for each facility type (which is used for simplification throughout this document as well as in MassDOT analysis tools). They will be used, as directed in this guide, to predict crash frequency at subject intersections for alternatives analyses. This guide also provides procedures when no SPF is available. MassDOT will dictate which SPFs should be used based on the facility type. SPFs for additional facilities are expected to be calibrated or developed in the future to enhance safety analyses of additional facility types. HSM SPFs are calibrated to Massachusetts conditions and updated on a regular basis to account for annual changes in crash frequency. Current SPFs are available upon request from MassDOT’s Safety Group.

Table 1 – Summary of facility types for which MassDOT has calibrated HSM SPFs for analysis.

Segment or Intersection	Facility Type	Facility Type Code
Intersection	Urban Three-Leg Signalized Intersection	U3SG
Intersection	Urban Three-Leg Stop-Controlled Intersection	U3ST
Intersection	Urban Four-Leg Signalized Intersection	U4SG
Intersection	Urban Four-Leg Stop-Controlled Intersection	U4ST

Crash Modification Factors

Though there are many resources from which CMFs can be obtained, the most prominent is the FHWA CMF Clearinghouse (http://www.cmfclearinghouse.org/) (FHWA, 2019). The Clearinghouse is updated quarterly, incorporating new CMFs presented in reports, journal articles, and conference papers found in technical literature. Most CMFs in the Clearinghouse are given a star rating, ranging from zero to five stars, with five stars indicating the most reliable CMFs. Star ratings are assigned based on the study design, sample size, standard error, potential bias, and data sources used to estimate the CMF.

With the large quantity of CMFs in the Clearinghouse, single countermeasures frequently have numerous CMFs with different star-ratings, study designs, data sources, values, crash types, and crash severities. When there are multiple high-quality CMFs, it can be difficult to choose the most appropriate CMF for an analysis. To standardize this selection process, MassDOT developed a State-preferred list of CMFs.

MassDOT's State-Preferred CMF List, available in the Massachusetts Safety Analysis Tools, has CMFs at the "All Severity" (All) and "Fatal and Injury" (FI) severity levels for select countermeasures which can be used in Massachusetts. Reductions for property damage only (PDO) crashes will be based on the difference between All crashes and FI crashes. Proportional adjustments were made to determine All CMFs if only FI and PDO CMFs were available for a countermeasure.

The countermeasures are broken into five categories: bicycle and pedestrian, interchange, intersection, freeway segments, and non-freeway segments. Most of the CMFs in the list apply to all crash types with the exception of CMFs for single-vehicle crashes, multi-vehicle crashes, pedestrian crashes, and bicycle crashes –proportional adjustments were made where necessary to convert targeted CMFs to CMFs for all crash types. The purpose of the CMF list is to improve consistency and minimize confusion when estimating the potential crash reduction for a countermeasure. Though the list is extensive, alternatives may include countermeasures which are not on this list. In these cases, the analyst must provide documentation supporting any CMF proposed to the MassDOT Safety Group, who will review and work with the analyst to identify the correct, most applicable CMF to use. Guidelines for applying CMFs for an alternatives analysis are provided later in the document.

Empirical Bayes (EB)

Individually, observed and predicted crash frequency are biased predictors of the long-term expected future crash frequency of a specific site. Predicted crash frequency is only an average based on the safety performance at similar sites and does not take into consideration the actual safety performance of the study site as well as unobserved site-specific features. Observed crash frequency, typically summarized using three to five years of data, only provides analysts with a brief snapshot of safety performance at the study site. For example, the short-term averages for Period 1 and Period 2 in Figure 2 represent potential safety performance estimates obtained from short-term observed crashes. The short-term averages of observed crashes in each period do not accurately reflect the long-term expected crash frequency, denoted by the long, dashed line bisecting the plot. Failure to represent the long-term average introduces potential regression-to-the-mean bias.

Regression-to-the-mean is the tendency of crash frequency to return to a long-term average. As described in the HSM, "when a period with a comparatively high crash frequency is observed, it is statistically probable that the following period will be followed by a comparatively low crash frequency".

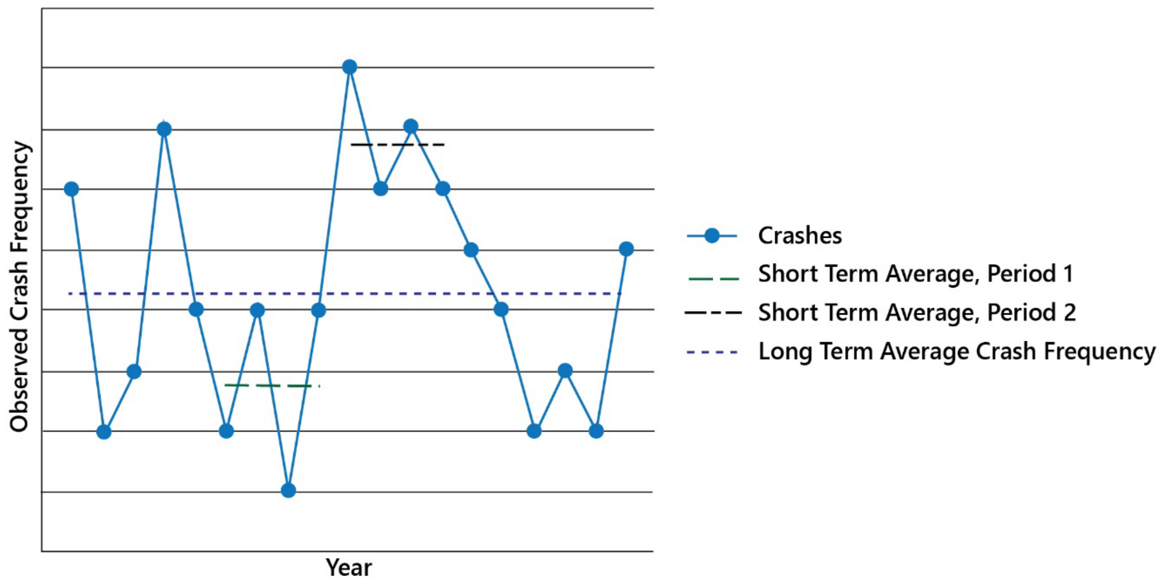


Figure 2 – Visual comparison of the differences between short-term and long-term averages.

Regression-to-the-mean can be corrected for using the EB method to estimate the expected crash frequency, which combines what is known about the study site over a study period (observed crashes) with what is known about the average safety performance of the site given the safety performance of many other similar sites (predicted crashes). As a result, expected crash frequency is a more reliable measure of the long-term average crash frequency.

EB cannot be used when:
Observed crash data are not available or reliable.
No SPF is available for the subject facility.

Data

The data necessary for alternative analysis are divided into three categories: crash, traffic, and roadway.

Crash Data

Analysts should obtain reported crash data for the entirety of the study period. Initially, the data are obtained from the MassDOT crash data portal, titled IMPACT, as a first brush approach. The actual crash data should be obtained by requesting crash reports from relevant law enforcement agencies. The crash data should be reviewed for location accuracy; verifying crashes used for the analysis occurred within the study area.

Traffic Volume Data

Traffic volume data, including pedestrian counts for signalized intersections, are collected by the designers. Ideally, analysts collect traffic volumes for every year in the study period. When this is not possible, the HSM provides guidance for interpolating and extrapolating traffic volumes (AASHTO, 2010):

- The AADT for the earliest year available should be used for any preceding years within the study period (e.g., for a study period of 2014 through 2016, if AADT is only available for 2016, then 2014 and 2015 is assumed to have the same AADT as 2016).
- The AADT for the latest year available should be used for any subsequent years within the study period (e.g., for a study period of 2014 through 2016, if AADT is only available for 2014, then 2015 and 2016 are be assumed to have the same AADT as 2014).
- Where two or more years of AADT are available, AADT can be interpolated for any intervening years (e.g., for a study period of 2014 through 2016, if AADT are only available for 2014 and 2016, then the AADT for 2015 is calculated using a linear interpolation of the AADT values in 2014 and 2016).

Roadway Data

Finally, roadway data are collected through a variety of resources, including satellite imagery, site visits, and photographs. The necessary data elements vary based on the SPF being used. For example, the required roadway data elements for an urban three-leg stop-controlled intersection are the presence of lighting and the number of major-road approaches with left-turn and right-turn lanes. Meanwhile, for an urban four-leg signalized intersection, the necessary roadway data elements include those previously mentioned for three-leg stop-controlled intersections, as well as the type of left-turn phasing for each approach, the number of approaches with right-turn-on-red prohibited, the presence of intersection red-light cameras, the maximum number of lanes crossed by a pedestrian on one intersection leg, and the number of bus stops, schools, and alcohol sales establishments within 1,000 feet of the intersection. Analysts should review the SPF to determine which roadway data should be collected. Table 2 shows which intersection characteristics are required for each Massachusetts SPF.

Table 2 – Features required for MassDOT-calibrated urban and suburban intersection HSM SPFs.

Variable	3ST	4ST	3SG	4SG
Presence of Lighting	✓	✓	✓	✓
Number of Approaches with Left-Turn Lanes			✓	✓
Number of Major Road Approaches with Left-Turn Lanes	✓	✓		
Number of Approaches with Right-Turn Lanes			✓	✓
Number of Major Road Approaches with Right-Turn Lanes	✓	✓		
Number of Approaches with Protected Left-Turn Phasing			✓	✓
Number of Approaches with Protected-Permitted or Permitted-Protected Left-Turn Phasing			✓	✓
Number of Approaches with Right-Turn-On-Red Prohibited			✓	✓
Presence of Intersection Red-Light Cameras			✓	✓
Total Pedestrian Crossing Volume			✓	✓
Maximum Number of Lanes Crossed by a Pedestrian			✓	✓
Number of Bus Stops within 1,000 Feet of the Intersection			✓	✓
Presence of a School within 1,000 Feet of the Intersection			✓	✓
Number of Alcohol Sales Establishments within 1,000 Feet of the Intersection			✓	✓

Alternatives Analysis

For MassDOT, the safety alternatives analysis is a three-step process:

1. Estimate the future no-build safety performance using one of three methods described later in this document.
2. Calculate the expected change in crash frequency and severity for each countermeasure by applying CMFs to the estimated safety performance in the design year under no-build conditions.
3. Monetize these potential reductions and comparing the benefits to expected costs for each alternative.

Steps 1 and 2 should be done separately for both fatal and injury (FI) and property damage only (PDO) crashes. The reductions are then monetized and combined in Step 3. To limit the sensitivity of the analyses to individual crash severities, crashes involving an injury should be combined into a single FI category. An FI crash is a crash in which the most severe injury in the crash is a fatality, incapacitating injury (suspected serious injury), non-incapacitating (suspected non-serious injury), or a possible injury. If there was no injury in the crash, it is classified as a PDO crash. These severity categories are also referred to using the KABCO scale:

- Fatal injury – K.
- Incapacitating injury / suspected serious injury– A.
- Non-incapacitating injury / suspected non-serious injury – B.
- Possible injury – C.
- PDO – O.

Crashes of K, A, B, and C severity are considered FI crashes. This process may also be broken out by crash type. For instance, an intersection analysis should focus on multi-vehicle, single-vehicle, pedestrian, and bicycle crashes separately for both FI and PDO, summing the associated change in crashes at the end of the analysis to compute the net benefits.

Table 3 includes a list of the variables used for alternatives analysis throughout this document. Engineers, designers, and analysts can use the results of this analysis to decide between alternatives.

Table 3 – A list of variables used throughout the document.

Variable	Description	Units
$N_{estimated,design,nobuild}$	The number of estimated crashes at the study site during the design year under no-build conditions.	Crashes
$N_{exp,study}$	The number of expected crashes during the study period.	Crashes
W	The weight assigned to the predicted number of crashes in the EB procedure.	Unitless
$N_{pr,study}$	The number of predicted crashes during the study period.	Crashes
$N_{obs,study}$	The number of observed crashes during the study period.	Crashes
k	The overdispersion parameter used for the SPF in the EB procedure.	Unitless
$N_{exp,design,nobuild}$	The number of expected crashes at the study site in the design year under no-build conditions.	Crashes
$N_{pr,design,nobuild}$	The number of predicted crashes at the study site in the design year under no-build conditions.	Crashes
$Y_{years,study}$	The number of years of data used in the study period.	Years
$N_{exp,obs,design}$	The number of expected crashes at the study site in the design year under no-build conditions based on observed crash history.	Crashes
$N_{exp,pr,design}$	The number of expected crashes at the study site in the design year under no-build conditions based on predicted crashes.	Crashes
$AADT_{study}$	AADT at the study site during the study period.	Vehicles per Day
$AADT_{Design}$	Estimated AADT at the study site during the design year.	Vehicles per Day
$N_{exp,design,alternative}$	The number of expected crashes in the design year for the alternative.	Crashes
$CMF_{alternative}$	The CMF used to estimate the change in crash frequency for the alternative.	Unitless
$N_{reduction,design,alternative}$	The expected crash reduction for the alternative compared to the no-build.	Crashes
$\$_{Average,FI}$	The average comprehensive cost for FI crashes for the subject facility type.	Dollars
$N_{Crashes,m}$	The number of reported crashes at KABCO severity level *m*.	Crashes
$\$_{Crashes,m}$	The comprehensive crash cost for KABCO severity level *m*.	Dollars
$\$_{savings,design,alternative}$	The reduction in comprehensive crash costs for the alternative.	Dollars
$N_{reduction,design,alternative,FI}$	The expected FI crash reduction for the alternative compared to the no-build.	Crashes
$\$_{comprehensive,facility,FI}$	The average comprehensive crash cost of an FI crash for the specific facility type.	Dollars
$N_{reduction,design,alternative,PDO}$	The expected PDO crash reduction for the alternative compared to the no-build.	Crashes
$\$_{comprehensive,facility,PDO}$	The average comprehensive crash cost of a PDO crash for the specific facility type.	Dollars
$\$_{savings,lifetime,alternative}$	Expected crash cost savings for the service life of the project.	Dollars
i	Discount factor for the economic analysis.	Unitless
t	Service life of the alternative.	Years
B/C	Benefit-cost ratio for the alternative.	Unitless
$\$_{project\ costs}$	Expected costs of the project, including design, construction, maintenance.	Dollars

If crash estimates for multiple future years are needed, such as the opening year and design year for an Intersection Control Evaluation (ICE) analysis, users should use this procedure for each traffic volume.

Step 1 – Future No-Build Safety Performance

The future safety performance of the study site, assuming no changes, is the baseline against which all alternatives are to be compared. There are three common methods used for estimating this future safety performance: 1) expected crash frequency calculated using the EB method, 2) predicted crash frequency calculated with an SPF, and 3) observed crash frequency.

Method 1 is the preferred method for alternatives analysis, followed by Method 2. Written justification must be provided when Method 2 or Method 3 are employed.

Figure 3 summarizes the process for selecting which method should be used based on tool and data availability. The outcome for each of these methods is the estimated number of crashes for the design year in a no-build scenario, shown in equations throughout this document as $N_{estimated,design,nobuild}$.

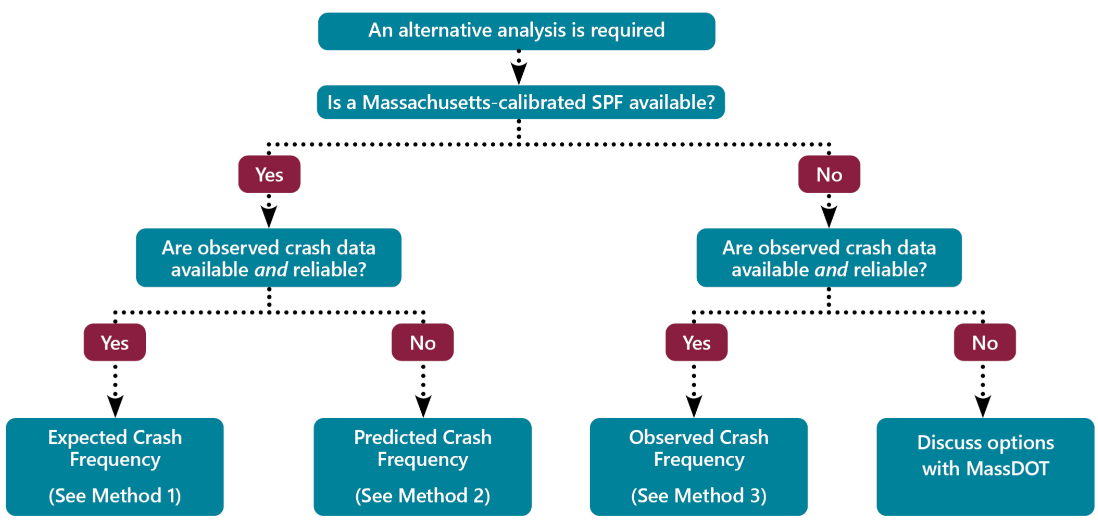


Figure 3 – Flow chart explaining when each method should be used.

Method 1 – Expected Crash Frequency via Empirical Bayes

Expected crash frequency, calculated using the EB method as documented by Hauer et al. (2002), is a statistically weighted average of predicted (N_{pr}) and observed (N_{obs}) crash frequency. This method is typically applied using a study period of three to five years of crash and traffic data for a study site. From these data, the number of observed crashes for the study period ($N_{obs,study}$) is obtained, and an SPF is used to predict the number of crashes for each year ($N_{pr,study}$). These are then combined to calculate an expected number of crashes during the design year under no-build conditions. An example scenario where Method 1 can be used is the analysis of a four-leg signalized intersection where observed crash data are available. The full procedure for Method 1 is summarized in Figure 4.

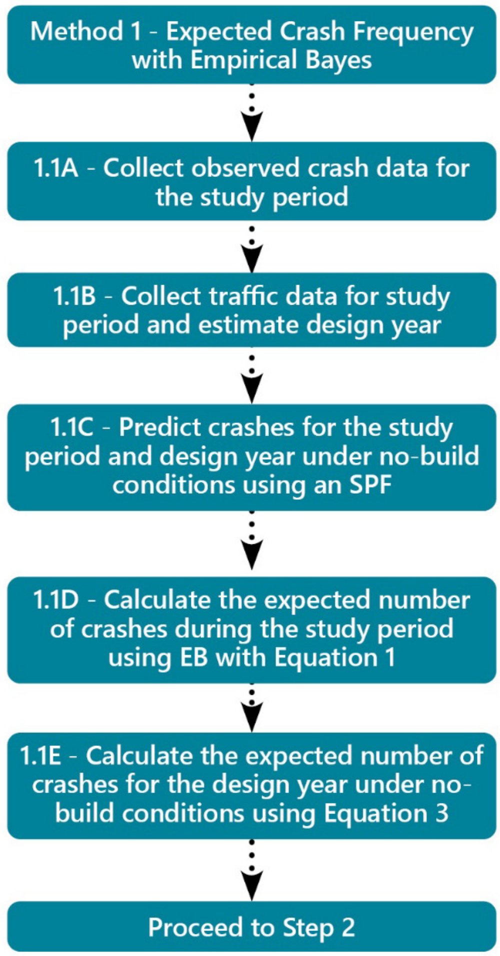


Figure 4 – Flowchart describing the alternatives analysis procedure using Method 1.

Step 1.1A: Collect Observed Crash Data for Study Period

Analysts should first query crash data for the study location via the MassDOT Crash Portal (IMPACT). Analysts should then supplement these data using crash records obtained from relevant policy agencies to capture crashes which are missing from the portal.

Step 1.1B: Collect Traffic Data for Study Period

Analysts need traffic volume for the study period to adjust for anticipated future changes in volume. For a segment analysis, volumes should be collected for the segment. For an intersection, analysts can use the highest AADT of the major approaches and the highest AADT of the minor approaches. When data are only available for certain years, analysts should follow the rules set out in the previous Data section (and repeated here):

- The AADT for the earliest year available should be used for any preceding years within the study period (e.g., for a study period of 2014 through 2016, if AADT is only available for 2016, then 2014 and 2015 is assumed to have the same AADT as 2016).
- The AADT for the latest year available should be used for any subsequent years within the study period (e.g., for a study period of 2014 through 2016, if AADT is only available for 2014, then 2015 and 2016 are be assumed to have the same AADT as 2014).

- Where two or more years of AADT are available, AADT can be interpolated for any intervening years (e.g., for a study period of 2014 through 2016, if AADT are only available for 2014 and 2016, then the AADT for 2015 is calculated using a linear interpolation of the AADT values in 2014 and 2016).

Typically, traffic analysis is done for a future opening year as well as a design year 10 or 20 years into the future for which traffic volumes are estimated, using background growth rates or a regional traffic model. These future traffic volumes, along with existing conditions at a site, are plugged into the SPF used previously to predict crash frequency at the study site during the design year ($N_{pr,design}$) assuming no changes other than traffic volume.

Step 1.1C: Predict Crashes for the Study Period and Design Year under No-Build Conditions using an SPF

SPFs are used to predict crash frequency for a given year. MassDOT developed SPF spreadsheet tools (Massachusetts Safety Analysis Tools) in which users select the SPF for the appropriate facility type and enter input values. The tool produces predicted numbers of crashes on an aggregate level and by type and severity. This guide includes additional details about these tools in a later section. Analysts should use SPFs to predict crashes during each year of the study period ($N_{pr,study}$) as well as the design year for the project.

Step 1.1D: Calculate Expected Number of Crashes During the Study Period

The expected number of crashes at the study site during the study period is calculated using Equation 1, which is a function of predicted crash frequency from the SPF, observed crash frequency, and a statistical weight calculated using Equation 2. Equation 2 shows the statistical weight used for EB as a function of the negative binomial overdispersion parameter of the SPF (k). This factor is a statistical output from the model used to estimate the SPF and describes the dispersion of the crash data. The overdispersion parameter is provided with each SPF; it is typically provided as a direct value (but can also be provided as a function of segment length for segment SPFs).

Equation 1 – EB calculation of expected crashes for the study period.

$$N_{exp,study} = w * N_{pr,study} + (1 - w) * N_{obs,study}$$

- $N_{exp,study}$ = the number of expected crashes during the study period.
- $N_{pr,study}$ = the number of predicted crashes during the study period.
- $N_{obs,study}$ = the number of observed crashes during the study period.
- w = weight used to calculate the average between observed and predicted crashes for EB.

Equation 2 – Weight used for EB calculation.

$$w = \frac{1}{1 + k * N_{pr,study}}$$

- k = the overdispersion parameter of the SPF used to calculate predicted crashes for the study period.
- All other terms as previously defined.

SPECIAL CASE: There is no SPF for single-vehicle fatal and injury (SV FI) for three-leg and four-leg stop controlled intersections. To calculate expected SV FI crashes, calculate the difference between all expected single-vehicle crashes (SV, All) and PDO expected single-vehicle crashes. This requires analysts to also predict the number of SV, All crashes with the relevant SPF.

Step 1.1E: Calculate Expected Number of Crashes for the Design Year

Next, this expected number of crashes must be projected to future conditions. Using the predicted study year and future safety performance (calculated in Step 1.1B), as well as the expected number of crashes during the study period (calculated in Step 1.1C), the expected number of crashes in the design year (or other future year) under no-build conditions ($N_{exp,design,nobuild}$)can be estimated using Equation 3.

Equation 3 – Calculating design year expected safety performance.

$$N_{estimated,design,nobuild} = N_{exp,design,nobuild} = \frac{N_{pr,design,nobuild}}{N_{pr,study}} * N_{exp,study}$$

- $N_{exp,design,nobuild}$ = the number of expected crashes in the design year under no-build conditions.
- $N_{pr,design,nobuild}$ = the number of predicted crashes in the design year under no-build conditions.
- All other terms as previously defined.

Under Method 1, the expected number of crashes for the design year ($N_{exp,design,nobuild}$) is the estimated number of crashes for the design year ($N_{estimated,design,nobuild}$) and becomes the baseline against which the alternatives will be measured. This process can also be used to estimate crashes for the opening year or any other future year.

Method 2 – Predicted Crash Frequency

In some cases, observed crash data are not available or do not represent the existing conditions at the site, meaning expected crash frequency cannot be used. For instance, a study intersection may have had a traffic control change in the previous year. As a replacement, predicted crash frequency calculated using an SPF should be used to represent future estimated safety performance. Inputs to the SPF include existing cross-section and geometric conditions for the study site with future no-build traffic volumes.

Step 1.2A: Collect traffic data for the study period

Analysts need traffic volume for the study period to adjust for anticipated future changes in volume. For a segment analysis, volumes should be collected for the segment. For an intersection, analysts can use the highest AADT of the major approaches and the highest AADT of the minor approaches. When data are only available for certain years, analysts should follow the rules set out in previous sections (and repeated here):

- The AADT for the earliest year available should be used for any preceding years within the study period (e.g., for a study period of 2014 through 2016, if AADT is only available for 2016, then 2014 and 2015 is assumed to have the same AADT as 2016).
- The AADT for the latest year available should be used for any subsequent years within the study period (e.g., for a study period of 2014 through 2016, if AADT is only available for 2014, then 2015 and 2016 are be assumed to have the same AADT as 2014).
- Where two or more years of AADT are available, AADT can be interpolated for any intervening years (e.g., for a study period of 2014 through 2016, if AADT are only available for 2014 and 2016, then the AADT for 2015 is calculated using a linear interpolation of the AADT values in 2014 and 2016).

Step 1.2B: Calculate the Predicted Number of Crashes for the Design Year under No-Build Conditions

The calculation is the same as the predicted crash frequency for the design year ($N_{pr,design}$) calculated in Method 1 using SPFs (see step 1.1B). An example scenario where Method 2 is applicable is the analysis of a four-leg signalized intersection which was only signalized in the previous year. The procedure for Method 2 is summarized in Figure 5.

Typically, traffic analysis is done for a future design year 10 or 20 years into the future for which traffic volumes are estimated, using background growth rates or a regional traffic model. These future traffic volumes, along with existing conditions at a site, are plugged into the SPF used previously to predict crash frequency at the study site during the design year ($N_{pr,design}$) assuming no changes other than traffic volume. This can also be done for another future year (such as an opening year).

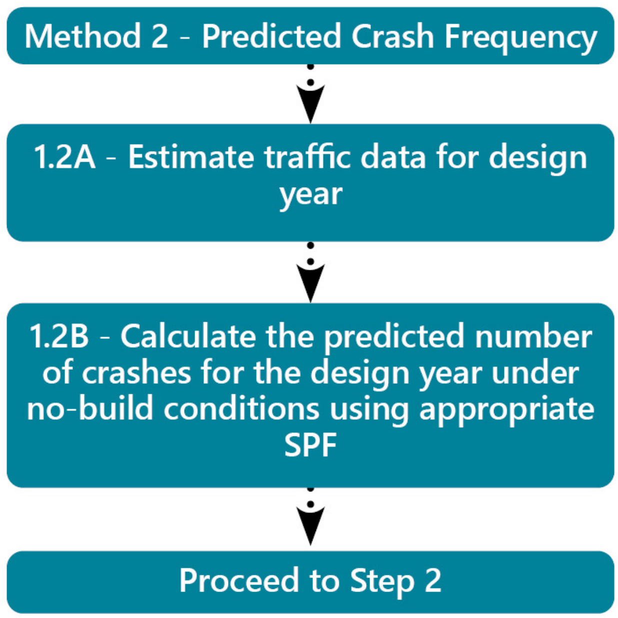


Figure 5 – Flowchart describing the procedure for Method 2.

Under Method 2, the predicted number of crashes for the design year ($N_{pr,design}$) is the estimated number of crashes for the design year ($N_{estimated,design,nobuild}$) and becomes the baseline against which the alternatives will be measured.

Method 3 – Observed Crash Frequency

SPFs require data from dozens of sites, meaning they are usually only estimated for common facility types, such as three-leg stop-controlled intersections. Since the Commonwealth has many unique roadways and intersections, there are numerous sites in Massachusetts for which there are no calibrated SPFs. Example sites where this may occur include one-way streets, rotaries, and five-leg intersections. In these scenarios, observed crash data are the only available crash metrics for estimating future safety performance. An example scenario for Method 3 is the evaluation of a roundabout, as MassDOT does not have a calibrated SPF for roundabouts.

The procedure for Method 3 is summarized in Figure 6.

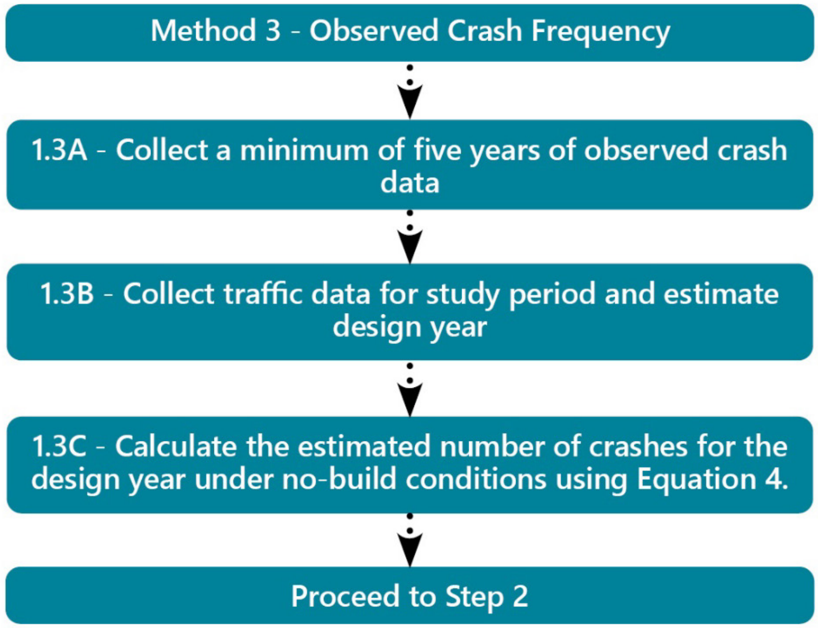


Figure 6 – Flowchart describing the procedure for Method 3.

Step 1.3A: Collect Observed Crash Data for Study Period

Analysts should first download crash data for the study location via the MassDOT Crash Portal (IMPACT). Analysts should then supplement these data using crash records obtained from relevant policy agencies to capture crashes which are missing from the portal. When using only observed crash data, analysts should use as many years as possible (preferably at least five) which are applicable to current site conditions.

Step 1.3B: Collect Traffic Data for Study Period

Analysts need traffic volume for the study period to adjust for anticipated future changes in volume. For a segment analysis, volumes should be collected for the segment. For an intersection, analysts can use total entering volume. When data are only available for certain years, analysts should follow the rules set out in previous sections (and repeated here):

- The AADT for the earliest year available should be used for any preceding years within the study period (e.g., for a study period of 2014 through 2016, if AADT is only available for 2016, then 2014 and 2015 is assumed to have the same AADT as 2016).
- The AADT for the latest year available should be used for any subsequent years within the study period (e.g., for a study period of 2014 through 2016, if AADT is only available for 2014, then 2015 and 2016 are be assumed to have the same AADT as 2014).
- Where two or more years of AADT are available, AADT can be interpolated for any intervening years (e.g., for a study period of 2014 through 2016, if AADT are only available for 2014 and 2016, then the AADT for 2015 is calculated using a linear interpolation of the AADT values in 2014 and 2016).

Analysts also need to estimate traffic volume for the design year, or any future year being used for this analysis, as is necessary for Methods 1 and 2.

Step 1.3C: Calculate Estimated Number of Crashes for the Design Year

Calculate the estimated number of crashes for the design year by multiplying the current observed crash rate by the future traffic volume at the site. The observed crash rate is estimated by dividing the number of observed crashes at the site during the study period by the AADT for the study period and the number of years in the study period ($Y_{years,study}$). For an intersection, the rate is estimated using the average daily entering volume and the number of years in the study period. The design year crash frequency is estimated by multiplying the current observed crash rate by the future traffic volume at the site. Mathematically, this is described in Equation 4.

Equation 4 – Calculating expected future crash frequency in Method 3.

$$N_{estimated,design,nobuild} = N_{obs,design} = \frac{N_{obs,study}}{AADT_{study} * Y_{years,study}} * AADT_{Design}$$

- $N_{obs,design}$ = the expected number of crashes in the design period based solely on observed crashes.
- $AADT_{study}$ = AADT representative of the study period, can be AADT of the roadway for a segment or entering AADT for an intersection.
- $Y_{years,study}$ = the duration of the study period in years.
- $AADT_{Design}$ = AADT representative of the design period.
- All other terms as previously defined.

Under Method 3, $N_{obs,design}$ is the estimated number of crashes for the design year ($N_{estimated,design,nobuild}$), the baseline against which the alternatives will be measured.

No Applicable Method

If neither observed nor predicted crashes can be obtained, the analysts should work with the MassDOT Safety Group to identify alternatives. Examples of scenarios where analysts may encounter this issue include a six-leg intersection, or a street which had a change in the number of lanes in the past year.

Step 2 – Expected Change in Safety Performance

The proposed alternatives are usually conceptualized as safety improvements, containing one or more countermeasures intended to reduce crash frequency and/or severity at the subject site. This change in expected safety performance is estimated using CMFs.

Step 2A: Identify CMF for each Alternative

CMFs should be obtained from the State-Preferred CMF List. In cases where a CMF for a treatment is not provided in this list, the analyst should work with MassDOT to identify an appropriate value for analysis. CMFs may be provided as constants or functions (sometimes referred to as crash modification functions, or CMFunctions). The State Preferred CMF List provides CMFs for crashes of all severities and FI severities. Additionally, the list notifies users if the CMF applies to all crash types or one of four categories: multi-vehicle, single-vehicle, vehicle-pedestrian, or vehicle-bicycle[1]. The CMF list is provided in the Massachusetts Safety Analysis Tools.

[1] When selecting a CMF for vehicle-pedestrian or vehicle-bicycle crashes (for use with Methods 1 and 2), use the CMF for all severities because the SPFs assume that all vehicle-pedestrian and vehicle-bicycle crashes result in a fatality or injury.

Application of Multiple CMFs

In some cases, an alternative can contain multiple safety countermeasures which should be accounted for in the analysis. Statistically, however, this presents a problem. Nearly all CMFs are estimated with the treatment in isolation, meaning installation of the countermeasure was the only difference at the study sites. As a result, interaction effects between different countermeasures are not commonly known. Analysts should limit their analysis to applying **NO MORE THAN TWO CMFs**[2]. When combining CMFs for two countermeasures where the CMFs apply to the same crash type(s) and severity, analysts need to consider a few factors, as described below.

Countermeasure Applicability

What type(s) and severity of crashes are the countermeasures targeting? In this context, "targeting" does not necessarily apply to the applicable crash type of the CMF. For instance, a roundabout may have a CMF that ***applies to total*** crashes; however, roundabouts are installed to ***target angle and left-turn*** crashes. Similarly, the CMF for shoulder rumble strips may ***apply to all fatal and injury crashes***, while shoulder rumble strips ***target roadway departures to the right***.

Countermeasure Overlap

Will the countermeasures target the same crash types and severities or completely different types and severities? Or will they both have some effect on a specific crash type or severity? Analysts can classify overlap using three general categories:

- **No Overlap** – An example of two countermeasures with no overlap are the installation of centerline rumble strips and a shared-use path along a roadway segment. In this scenario, centerline rumble strips target lane departure crashes to the left, while the shared-use path targets vehicle-bicycle and vehicle-pedestrian crashes.
- **Complete Overlap** – An example of two countermeasures that completely overlap are retroreflective backplates and larger signal bulbs on a traffic signal, which both target intersection crashes through increased visibility.
- **Some Overlap** – An example of countermeasures with some overlap are the installation of lighting along a roadway segment and a pedestrian hybrid beacon at a mid-block crossing on the segment; where the lighting targets all nighttime crashes and the pedestrian hybrid beacon targets vehicle-pedestrian crashes at the mid-block crossing. The lighting may provide a supplemental safety benefit to the mid-block crossing at night.

CMF Magnitude

Is each countermeasure expected to have a small impact (less than 10 percent), medium impact (10 to 25 percent), or large impact (greater than 25 percent) on the frequency of the target crashes? While this does not affect which method is used, analysts should be aware that mixing CMFs of different magnitudes produces different results. For instance, using the dominant common residuals approach for CMFs of small and medium impact may produce a CMF with a reduction larger than either of the original CMFs, while the same approach for CMFs of small and large impact may return a CMF with a reduction between the two CMF values.

CMF Value

Is at least one CMF greater than 1.0 or are both less than 1.0? If at least one CMF is greater than 1.0, then the CMFs can simply be **multiplied** together regardless of target, overlap, and magnitude. If both CMFs are less than

[2] If considering more than two countermeasures, determine which two countermeasures will have the largest safety impact and use those two for the analysis.

1.0, analysts can use one of the **additive**, **dominant effect**, or **dominant common residuals** approaches based on the overlap of the countermeasures. The specific conditions which dictate the method to use when there is overlap are described below.

CMF Combination Methods

There are four methods analysts use to calculate the combined CMF based on the considerations above. The methods are:

- **Multiplicative** – When at least one CMF is greater than 1.0, analysts should use the multiplicative approach, shown in Equation 5.

Equation 5 – Multiplicative approach to combining CMFs.

$$CMF_{Combined} = CMF_{Countermeasure\ 1} * CMF_{Countermeasure\ 2}$$

- **Additive** – When analysts determine there is no overlap between countermeasures, they should combine CMFs using the additive method shown in Equation 6.

Equation 6 – Additive approach to combining CMFs.

$$CMF_{Combined} = 1 – [(1 - CMF_{Countermeasure\ 1}) + (1 - CMF_{Countermeasure\ 2})]$$

- **Dominant Effect** – When there is complete overlap between the countermeasures, analysts should select the CMF with the dominant effect (i.e., the CMF with the largest predicted reduction in crashes); the logic is shown in Equation 7. When there is some overlap between the countermeasures, analysts should select the CMF from either the Dominant Effect or Dominant Common Residuals method; whichever provides the greatest reduction.

Equation 7 – Dominant effect approach to combining CMFs.

$$If\ (1 - CMF_{Countermeasure\ 1}) \geq\ (1 - CMF_{Countermeasure\ 2}),$$

$$then\ CMF_{Combined} = CMF_{Countermeasure\ 1},$$

$$else\ CMF_{Combined} = CMF_{Countermeasure\ 2}.$$

- **Dominant Common Residuals** – When there is some overlap between the countermeasures, analysts should calculate the dominant common residual as shown in Equation 8 and select the CMF from either the Dominant Effect or Dominant Common Residuals method; whichever provides the greatest reduction. The CMF used as the exponent is the CMF with the largest estimated crash reduction.

Equation 8 – Dominant common residuals approach to combining CMFs.

$$If\ (1 - CMF_{Countermeasure\ 1}) \geq\ (1 - CMF_{Countermeasure\ 2}),$$

$$then\ CMF_{Combined} = \ (CMF_{Countermeasure\ 1} * CMF_{Countermeasure\ 2})^{CMF_{Countermeasure\ 1}},$$

$$else\ CMF_{Combined} = \ (CMF_{Countermeasure\ 1} * CMF_{Countermeasure\ 2})^{CMF_{Countermeasure\ 2}}.$$

The procedure for selecting the appropriate CMF combination method is described with a flowchart in Figure 7. When analysts combine two CMFs, the method used and the logic supporting the selection of the method need to be documented.

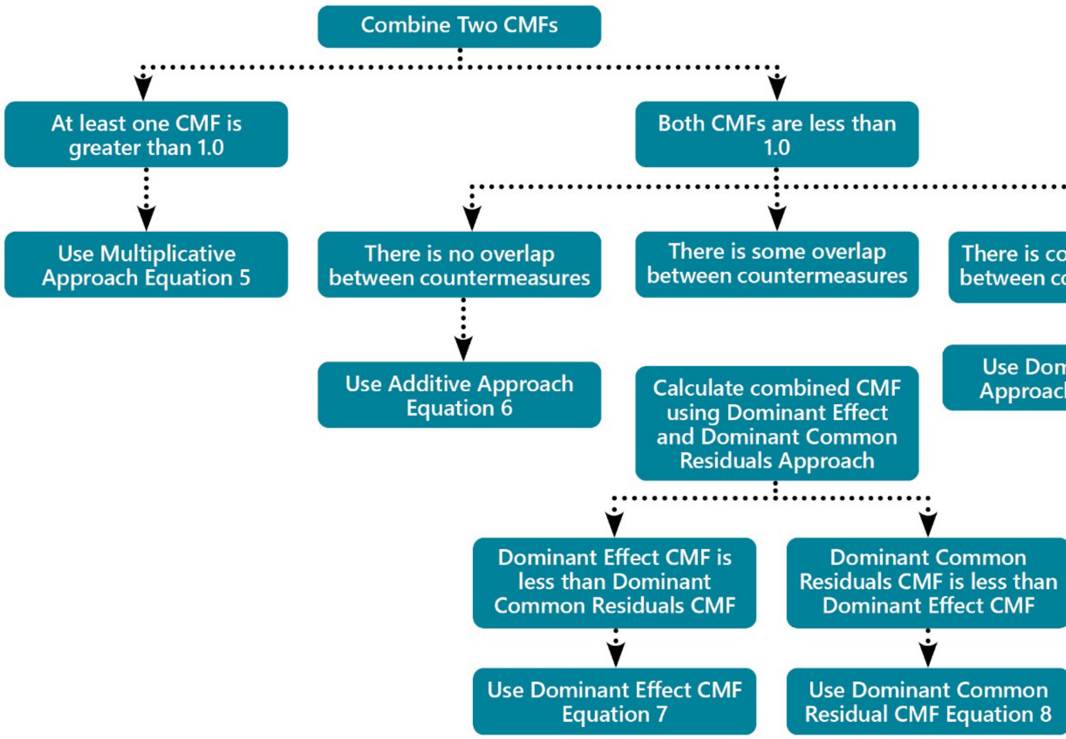


Figure 7 – Method for selecting the best approach to combine two CMFs.

Step 2B: Calculate Expected Reduction in Crashes for each Alternative

A CMF can be used to calculate the expected crash frequency for an alternative during a design year ($N_{exp,design,alternative}$) using Equation 9.

Equation 9 – Calculating expected crash frequency for an alternative using a CMF.

$$N_{exp,design,alternative} = N_{estimated,design,nobuild} * CMF_{alternative}$$

- $N_{exp,design,alternative}$ = the number of expected crashes in the design year for the alternative.
- $CMF_{alternative}$ = the CMF being applied for the safety countermeasure in the alternative.
- All other terms as previously defined.

The expected change in crashes for an alternative compared to the no-build conditions in the design year can be calculated using Equation 10. This computation should be repeated for each crash type or severity level included in the analysis.

Equation 10 – Calculating expected crash reduction for the design year for an alternative compared to the no-build.

$$N_{reduction,design,alternative} = N_{estimated,design,nobuild} - N_{exp,design,alternative}$$

- $N_{reduction,design,alternative}$ = the expected reduction in crashes in the design year for the alternative.
- All other terms as previously defined.

Step 3 – Economic Analysis

Average crash costs can be used to monetize the change in crashes by type and/or severity and summed to represent the net safety benefit (or disbenefit) for the countermeasure. This allows for a monetary comparison across alternatives as well as against the cost for each alternative. Crash costs represent the potential comprehensive costs to those involved in the crash, as well as society, which can arise from medical and property damage costs, lost productivity, and losses in quality of life. Definitions and additional details are available for each level of the KABCO scale from the *Model Minimum Uniform Crash Criteria (MMUCC) Guide, 5th Edition* (USDOT, 2017). Figure 8 describes the economic analysis step in a flowchart.

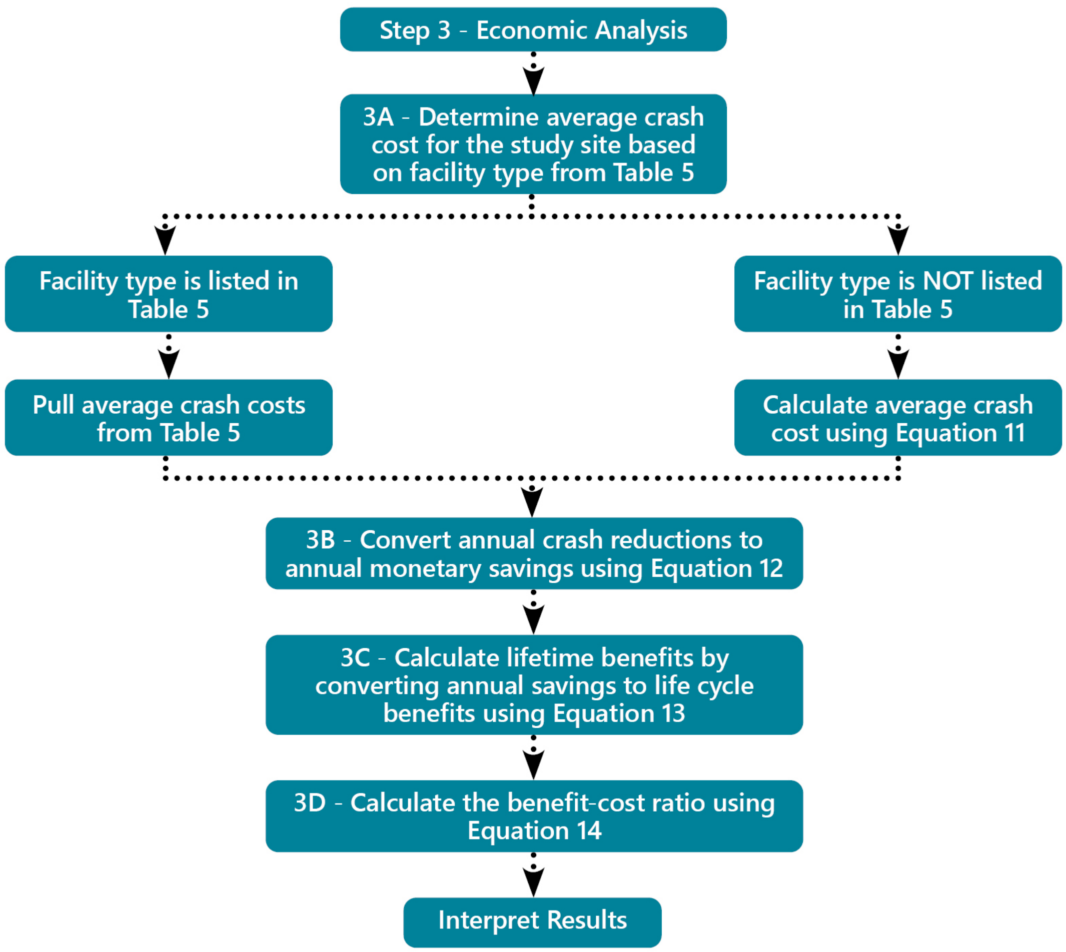


Figure 8 – Flowchart describing Step 3 – Economic Analysis.

The comprehensive crash cost for each KABCO level applies to the most severe injury reported in the crash. Harmon et al. (2018) estimated national comprehensive crash costs using 2016 dollars and also provided a method and conversion factors, based on average cost of living, to convert the national costs to State-specific costs. Table 4 lists the Massachusetts-adjusted costs grown to 2019 using the growth procedure described by Harmon et al. (2018).

Table 4 – Massachusetts-adjusted comprehensive crash costs in 2019 dollars[3].

Crash Severity Level	Rounded Massachusetts Cost, 2019 Dollars
K	$16,257,800
A	$941,300
B	$284,600
C	$179,600
O	$16,700
K+A	$2,764,700
K+A+B	$706,100
K+A+B+C	$441,000
K+A+B+C+O	$121,400

Step 3A: Determine Average Crash Cost for Study Site's Facility Type

Alternatives analysis is performed using aggregated severity levels (FI crashes and PDO crashes), thus comprehensive FI crash costs are needed. These average FI crash costs were estimated based on the severity distribution of FI crashes. Because this severity distribution varies for each facility type, an average FI crash cost was estimated for each facility type. Average FI and PDO crash costs for each facility are provided in Table 5. Note the PDO cost is constant for each facility type.

Analysts should use the costs in Table 5 when analyzing a listed facility type.

Table 5 – Average comprehensive FI and PDO crash costs by facility type in 2019 dollars.

Facility Type	Facility Type Code	Average FI Crash Cost	Average PDO Crash Cost
Urban Three-Leg Signalized Intersection	U3SG	$339,500	$16,700
Urban Three-Leg Stop-Controlled Intersection	U3ST	$352,800	$16,700
Urban Four-Leg Signalized Intersection	U4SG	$327,200	$16,700
Urban Four-Leg Stop-Controlled Intersection	U4ST	$319,100	$16,700
Urban Two-Lane Undivided Arterial	U2UA	$484,100	$16,700
Urban Two-Lane Undivided Arterial – District 1	U2UAD1	$501,300	$16,700
Urban Two-Lane Undivided Arterial – District 2	U2UAD2	$490,700	$16,700
Urban Two-Lane Undivided Arterial – District 3	U2UAD3	$532,100	$16,700
Urban Two-Lane Undivided Arterial – District 4	U2UAD4	$402,400	$16,700
Urban Two-Lane Undivided Arterial – District 5	U2UAD5	$522,500	$16,700
Urban Two-Lane Undivided Arterial – District 6	U2UAD6	$462,000	$16,700
Urban Four-Lane Undivided Arterial	U4UA	$481,300	$16,700
Urban Four-Lane Divided Arterial	U4DA	$530,800	$16,700
Rural Two-Lane Undivided Highway	R2U	$878,400	$16,700

[3] Analysts should contact the MassDOT Traffic and Safety Section to ensure they have the most up-to-date average crash costs.

Equation 11 was used to calculate the average FI comprehensive crash cost for each relevant facility in Table 5. This equation can also be used to calculate an average crash cost for facility types not provided in Table 5.

Equation 11 – Calculation of average FI crash costs for given facility.

$$\$_{Average,FI} = \frac{N_{Crashes,K} * \$_{Mass,K} + N_{Crashes,A} * \$_{Mass,A} + N_{Crashes,B} * \$_{Mass,B} + N_{Crashes,C} * \$_{Mass,C}}{N_{Crashes,K} + N_{Crashes,A} + N_{Crashes,B} + N_{Crashes,C}}$$

- $\$_{Average,FI}$ = the average comprehensive cost for FI crashes for the subject facility type.
- $N_{Crashes,K}$ = the number of fatal crashes in the SPF data for the subject facility type.
- $\$_{Mass,K}$ = the comprehensive costs for a fatal crash in Massachusetts in 2019 dollars.
- $N_{Crashes,A}$ = the number of incapacitating crashes in the SPF data for the subject facility type.
- $\$_{Mass,A}$ = the comprehensive costs for a suspected serious injury crash in Massachusetts in 2019 dollars.
- $N_{Crashes,B}$ = the number of non-incapacitating injury crashes in the SPF data for the subject facility type.
- $\$_{Mass,B}$ = the comprehensive costs for a suspected minor injury crash in Massachusetts in 2019 dollars.
- $N_{Crashes,C}$ = the number of possible injury crashes in the SPF data for the subject facility type.
- $\$_{Mass,C}$ = the comprehensive costs for a possible injury crash in Massachusetts in 2019 dollars.

Step 3B: Convert Crash Reductions to Annual Savings

Equation 12 can be used to calculate the net monetary benefit (or disbenefit) of the expected change in FI and PDO crashes for each alternative (see Step 2B) using and the applicable average crash costs from Table 5.

Equation 12 – Expected crash cost savings in the design year for an alternative.

$$\$_{savings,design,alternative} = N_{reduction,design,alternative,FI} * \$_{comprehensive,facility,FI} + N_{reduction,design,alternative,PDO} * \$_{comprehensive,facility,PDO}$$

- $\$_{savings,design,alternative}$ = expected savings from the reduction in crash costs for an alternative during the design year.
- $N_{reduction,design,alternative,FI}$ = expected reduction in FI crashes for an alternative during the design year, calculated using Equation 10.
- $\$_{comprehensive,facility,FI}$ = average FI comprehensive crash cost for the subject facility type, from Table 5.
- $N_{reduction,design,alternative,PDO}$ = expected reduction in PDO crashes for an alternative during the design year, calculated using Equation 10.
- $\$_{comprehensive,facility,PDO}$ = average PDO comprehensive crash cost for the subject facility type, from Table 5.

Step 3C: Calculate Lifetime Benefits

The design year benefit calculated using Equation 12 should be converted to a predicted lifetime (i.e., service life) benefit in terms of present value. Typically, this is done by estimating the expected crash reduction for an alternative for each year of the proposed service life. In this guide, this will be simplified by assuming the expected reduction in the design year is representative of the average expected annual reduction for the life of the project, meaning the expected savings calculated in Equation 12 ($\$_{savings,design,alternative}$) is representative of annual savings for society. This value can be converted to a present worth which can be compared to anticipated project costs for the alternative. This conversion is done using a “uniform series to present worth” conversion, as described in Equation 13 (AASHTO, 2010).

Equation 13 – Converting anticipated design year benefits to lifetime benefits for an alternative.

$$\$_{savings,lifetime,alternative} = \$_{savings,design,alternative} * \frac{(1+i)^t - 1}{i * (1+i)^t}$$

- $\$_{savings,lifetime,alternative}$ = expected monetary value of crash costs for the lifetime of the alternative.
- i = anticipated monetary discount rate for the analysis period, in decimal value.
- t = anticipated service life of the alternative, in years.
- All other terms as previously defined.

The discount rate (i) can vary based on economic factors. **For this guide, a standard discount rate of seven percent (7%) should be used.** The number of years (t) for the service life of the alternative depends on the alternative being proposed. For small projects, such as restriping, the life of the alternative may only be 2 years, while for larger infrastructure projects (e.g., intersection signalization or installation of median cable barrier) the lifetime is typically 20 years. Analysts should work with their MassDOT project manager to select the appropriate service life for the analysis and document the justification. FHWA's *Countermeasures Service Life Guide* can be used to inform this selection[4].

Step 3D: Calculating Benefit-Cost Ratio

The present value of the anticipated lifetime benefits for the countermeasure is calculated using Equation 13. Dividing this by the project cost ($\$_{project\ costs}$) produces the benefit-cost ratio (B/C); as calculated in Equation 14. This ratio conveys the amount of anticipated savings in societal crash cost per dollar spent on the alternative.

Equation 14 – Estimated benefit-cost ratio for the countermeasure.

$$B/_C = \frac{\$_{savings,lifetime,alternative}}{\$_{project\ costs}}$$

Interpretation of Results

Using the process described above, analysts can calculate expected lifetime safety benefits for each alternative. However, properly interpreting these results is just as important as calculating them. If selection between alternatives is being driven solely by safety benefits, comparison of lifetime benefits is a sufficient metric. Economically, this may not result in the most prudent choice. Different alternatives may have different costs, so while one alternative is shown to result in significantly more expected benefits, it may also cost much more than the other. For a comparison of safety benefits incorporating economic justification, benefit-cost ratios can be compared between each alternative. In computing benefit-cost ratios, it is important that the numerator and denominator represent the same units and timeframe. For example, if the safety benefits in the numerator are expressed in terms of present value, then the project costs in the denominator should also reflect the present value, accounting for the construction cost and annual maintenance costs over the life of the project[5]. Further, is important to weigh the safety results with other project benefits, such as user delay, emissions, and right-of-way impacts.

[4] https://safety.fhwa.dot.gov/hsip/docs/FHWA-SA-21-021_Countermeasure_Serv_Life_Guide.pdf

[5] Convert annual maintenance costs to service life maintenance costs using Equation 13. Add this service life maintenance cost to other project costs in the denominator of Equation 14.

Documentation

Given the influence these analyses have on the selection of an alternative, it is important to provide consistent, detailed documentation of the process. Documentation, whether as a stand-alone memorandum or a chapter in a larger report, should describe existing conditions at the site, including traffic, geometric, and safety conditions. Each alternative should be described in detail, with a specific focus applied to safety countermeasures. The results section of the documentation should clearly show the expected changes in safety performance, monetary benefits, and B/C ratios for each alternative compared to the no-build condition. Additionally, the analyst should document which (if any) tools were used for the analysis. This should include where the tool was acquired from and which version of the tool was used (if applicable). The documentation should also include a discussion of limitations.

All assumptions should be clearly stated and justified in the documentation. Potential assumptions include:

- The safety performance metric used for future no-build safety performance (e.g., the analysts used Method 3 – Observed Crashes for this analysis because there was no Massachusetts SPF for an 8-lane urban freeway segment).
- The projected future traffic volume at the study site (e.g., the local planning agency projects 1.5-percent annual traffic growth on the segment over the next 20 years). If using multiple future years such as an opening year and design year, document all volumes.
- Each SPF and CMF used in the analysis (e.g., the analysts used the Massachusetts Safety Analysis Tools for predictions and CMF X from the MassDOT State Preferred CMF List).
- The comprehensive crash costs applied for the analysis (e.g., the analysts used comprehensive crash costs for urban four-leg signalized intersections in Massachusetts).
- The projected cost of each alternative (e.g., the analysts used a cost estimation of $1.5 million for Alternative 1).

The following is a sample outline for the documentation of a safety analysis with two alternatives:

- Introduction
- Project Background
- Methodology
- No-Build Conditions
- Alternative 1
- Alternative 2
- Results
- Limitations
- Conclusions and Recommendations

Useful Tools

To ease the calculation process, MassDOT developed a crash prediction tool for urban and suburban intersections. The spreadsheet tool and specific instructional documentation are available upon request from MassDOT's Safety Group. Before use, analysts need to verify they have the most current version of the tool. The tool can be used at the analyst's discretion.

Massachusetts Safety Analysis Tools

The MassDOT Safety Analysis Tools contains Massachusetts-calibrated SPFs to estimate predicted crashes for four urban and suburban intersection types:

- Three-Leg Signalized Intersection.
- Four-Leg Signalized Intersection.
- Three-Leg Stop-Controlled Intersection.
- Four-Leg Stop-Controlled Intersection.

The tool is a modified, Massachusetts-specific version of the *Highway Safety Manual Spreadsheets*, which were developed as part of National Cooperative Highway Research Program Project 17-38 (Dixon et al., 2012). For each facility, there is a Massachusetts-specific SPF developed by Xie and Wen (2021). Figure 9 shows the input portion of the MassDOT spreadsheet for four-leg signalized intersections.

The required inputs are factors included in the SPF. For a four-leg signalized intersection (as pictured in Figure 9), this implies that the SPF is a function of major and minor road traffic volume, the presence of left- and right-turn lanes, left-turn phasing, right-turn-on-red prohibition, the presence of intersection red-light cameras, and additional conditions. Other characteristics of an intersection, such as the number of through lanes or bike lanes, are not captured in the prediction. Analysts should be aware of these limitations and document potential intersection characteristics which may affect safety performance.

This tool has the capabilities to perform each method for Step 1 – Method 1 (Expected Crashes with Empirical Bayes), Method 2 (Predicted Crashes), and Method 3 (Observed Crashes). It includes the ability to enter disaggregated crash data for methods 1 and 3. Additionally, users can enter disaggregated CMF values, including the ability to combine the CMFs following the CMF combination rules described previously. As such, when users enter multiple applicable CMFs, they select the combination method to be used. Finally, the results are presented as design year benefits, lifetime present value, and benefit-cost ratios for each alternative. Users can extract this data for use when selecting between alternatives.

Required Manual Input	Optional Manual Input	Select from Drop-Down List
Click to Reset Sheet		

General Information and Input Data for Urban and Suburban Arterial Intersections

General Information		Location Information	
Analyst:	Amanda Engineer	City:	Acton
Agency or Company:	MassDOT	Intersection:	Example
Date Performed (MM/DD/YYYY):	11/10/21	Jurisdiction:	MassDOT
Study Period (Years, 1 minimum, 10 maximum):	3	Analysis Year:	2021

Intersection Data	
Intersection Type:	4ST MassDOT
Intersection Lighting (Present/Not Present):	Not Present

Stop Controlled	
Number of major-road approaches with left-turn lanes (0,1,2):	0
Number of major-road approaches with right-turn lanes (0,1,2):	0

Step 1 – Expected Change in Safety Performance

Step 1.1A - Observed Crash Data for Intersection

Crash Type, Severity	Total	Average per Year	Year 1	Year 2	Year 3	Year 4
MV, FI	12	4.00	3	4	5	
MV, PDO	12	4.00	5	5	2	
SV, FI	0	0.00	0	0	0	
SV, PDO	1	0.33	1	0	0	
Ped, FI	1	0.33	1	0	0	
Ped, PDO	1	0.33	0	1	0	
Bike, FI	1	0.33	0	1	0	
Bike, PDO	0	0.00	0	0	0	

Step 1.1B - Traffic Data	Year 1	Year 2	Year 3	Year 4
Present AADT(Major):	10,000	10,250	10,500	
AADT Check	AADT OK	AADT OK	AADT OK	
Present AADT(Minor):	4,000	3,950	3,900	
AADT Check	AADT OK	AADT OK	AADT OK	

Design Year AADT(Major):	11,000
AADT Check	AADT OK
Design Year AADT(Minor):	4,400
AADT Check	AADT OK

Figure 9 – Screenshot of the inputs for the four-leg signalized intersection MassDOT Safety Analysis Tools with Method 1.

MassDOT Intersection Control Evaluation

MassDOT is implementing FHWA's ICE framework, a three-stage approach to develop traffic control alternatives for intersections. ICE considers potential safety impacts, operational impacts, and multimodal factors for each alternative (FHWA, 2018b). This guide and the MassDOT Safety Analysis Tools should be used to develop safety inputs for ICE analysis. ICE is used to evaluate the feasibility of the following intersection configurations for a study intersection:

- Signalized intersection.
- Stop-controlled intersection.
- Displaced left-turn intersection.
- Median U-turn intersection.
- Signalized restricted crossing U-turn (RCUT) intersection or "Superstreet".

- Unsignalized RCUT or "J-turn" intersection.
- Jughandle intersection.
- Diverging diamond interchange.
- Roundabout intersection.

When using the Safety Analysis Tools to inform ICE, users can extract the results from Step 2 and input them into the ICE tool.

Example

A four-leg stop-controlled intersection was identified as an HSIP crash cluster and is under consideration for improvement. The intersection is a suburban intersection with traffic volumes of 10,000 vehicles per day (vpd) on the major roadway and 4,000 vpd on the minor roadway measured in Year 1 and volumes of 10,500 vpd on the major roadway and 3,900 vpd measured in Year 3. There are no left- or right-turn lanes on any of the approaches, nor is there lighting. Figure 10 provides a graphic of this intersection. MassDOT is considering three alternatives for the intersection:

1. Adding left-turn and right-turn lanes to the major approaches.
2. Signalizing the intersection.
3. Converting the intersection to a single-lane roundabout.

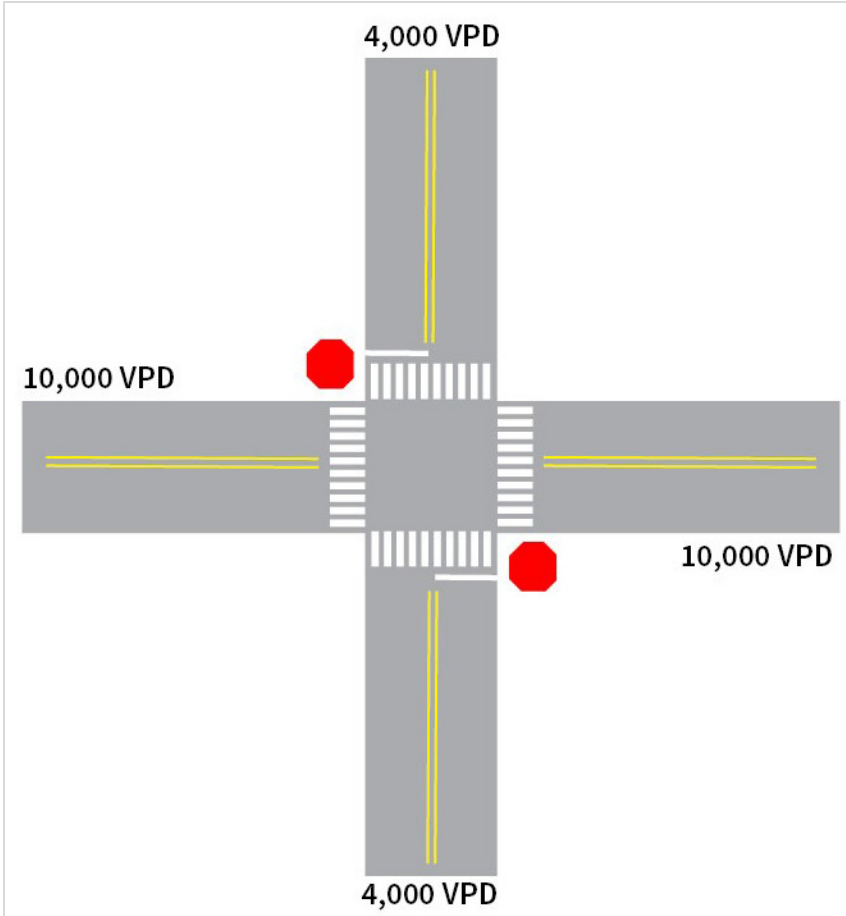


Figure 10 – Four-leg stop-controlled intersection used for the example. The traffic volumes indicate the volumes measured in Year 1.

This example will highlight the three methods to complete Step 1, as well as the process of completing Steps 2 and 3 for safety analysis.

Step 1 – Future No-Build Safety Performance with Method 1

Step 1.1A: Collect Observed Crash Data for the Study Period

Crash data were obtained for the three years prior to analysis; Table 6 summarizes these data. Analysts pulled the crash data using a spatial query in IMPACT then obtained crash records from the local policy agency to supplement the totals.

Table 6 – Observed crash data for example intersection.

Crash Type, Severity[6]	Year 1	Year 2	Year 3	Total	Average per Year
MV, FI	3	4	5	12	4.00
SV, FI	0	0	0	0	0
Ped, FI	1	0	0	1	0.33
Bike, FI	0	1	0	1	0.33
MV, PDO	5	5	2	12	4.00
SV, PDO	1	0	0	1	0.33
Ped, PDO	0	1	0	1	0.33
Bike, PDO	0	0	0	0	0

Step 1.1B: Collect Traffic Data for the Study Period

The traffic volumes in Figure 10 represent measurements for Year 1. A traffic count in Year 3 returned traffic volumes of 10,500 vpd on the major roadway and 3,900 vpd. Per the previously described guidance, linear interpolation was used to estimate traffic volumes for Year 2. The interpolated traffic volumes are 10,250 vpd for the major road and 3,950 vpd for the minor road. The local planning agency expects traffic at this intersection to grow 1 percent per year, meaning the design year AADT will be 11,000 vpd on the major road and 4,400 vpd on the minor road.

Step 1.1C: Predict Crashes for the Study Period and Design Year

Given the traffic volumes above, the Method 1 MassDOT Safety Analysis Tool is used to predict crash frequency at the intersection. This SPF predicts the number of crashes by aggregate type (multi-vehicle, single-vehicle, vehicle-pedestrian, and vehicle-bicycle) and severity. Figure 11 is a screenshot of the crash prediction inputs for the Safety Analysis Tool, while Figure 12 is a screenshot of the predicted crash results from the spreadsheet. In Figure 11, yellow cells indicate the need for typed input while blue cells indicate inputs selected from a drop-down list. The predicted frequencies for each year are summarized in Table 7 along with the predicted number of crashes for the study period.

[6] MV=multi-vehicle crash, SV=single-vehicle crash, Ped=vehicle-pedestrian crash, Bike=vehicle-bicycle crash.

Required Manual Input	Optional Manual Input	Select from Drop-Down List

Click to Reset Sheet

General Information and Input Data for Urban and Suburban Arterial Intersections

General Information		Location Information	
Analyst:	Rebecca Engineer	City:	Acton
Agency or Company:	MassDOT	Intersection:	Main and Example
Date Performed (MM/DD/YYYY):	12/01/21	Jurisdiction:	
Study Period (Years, 1 minimum, 10 maximum):	3	Analysis Year:	2018-2020

Intersection Data

Intersection Type:	4ST MassDOT
Intersection Lighting (Present/Not Present):	Not Present

Stop Controlled

Number of major-road approaches with left-turn lanes (0,1,2):	0
Number of major-road approaches with right-turn lanes (0,1,2):	0

Step 1 – Expected Change in Safety Performance

Step 1.1A - Observed Crash Data for Intersection

Crash Type, Severity	Total	Average per Year	Year 1	Year 2	Year 3	Year 4
MV, FI	12	4.00	3	4	5	
MV, PDO	12	4.00	5	5	2	
SV, FI	0	0.00	0	0	0	
SV, PDO	1	0.33	1	0	0	
Ped, FI	1	0.33	1	0	0	
Ped, PDO	1	0.33	0	1	0	
Bike, FI	1	0.33	0	1	0	
Bike, PDO	0	0.00	0	0	0	

Step 1.1B - Traffic Data

	Year 1	Year 2	Year 3	Year 4
Present AADT(Major):	10,000	10,250	10,500	
AADT Check	AADT OK	AADT OK	AADT OK	
Present AADT(Minor):	4,000	3,950	3,900	
AADT Check	AADT OK	AADT OK	AADT OK	

Design Year AADT(Major):	11,000
AADT Check	AADT OK
Design Year AADT(Minor):	4,400
AADT Check	AADT OK

Figure 11 – Screenshot of the MassDOT Safety Analysis Tools depicting inputs for the example alternative analysis.

Results *Step 1.1C - Predicted Crash Frequency for the Sample Intersection*

Crash Type, Severity	Total Predicted Crashes during the Study Period ($N_{pr,study}$)	Average Crash Frequency per Year	Predicted Crash Frequency per Year (From Prediction Spreadsheet [Predicted Nb])									
			Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
MV, FI	3.08	1.03	1.02	1.03	1.03							
MV, PDO	8.43	2.81	2.79	2.81	2.83							
SV, FI	0.10	0.03	0.03	0.03	0.03							
SV, PDO	0.34	0.11	0.11	0.11	0.11							
Ped, FI	0.15	0.05	0.05	0.05	0.05							
Ped, PDO												
Bike, FI	0.15	0.05	0.05	0.05	0.05							
Bike, PDO												

Figure 12 – Screenshot of the crash prediction results in the MassDOT Safety Analysis Tools.

Table 7 – Predicted crash frequency for the sample intersection.

Crash Type, Severity	Predicted Crash Frequency, Year 1	Predicted Crash Frequency, Year 2	Predicted Crash Frequency, Year 3	Predicted Crashes during the 3-year Study Period[7]
MV, FI	1.02	1.03	1.03	3.08
SV, All	*0.14*	*0.14*	*0.14*	*0.44*
SV, FI[8]	0.03	0.03	0.03	0.10
Ped, FI	0.05	0.05	0.05	0.15
Bike, FI	0.05	0.05	0.05	0.15
MV, PDO	2.79	2.81	2.83	8.43
SV, PDO	0.11	0.11	0.11	0.34
Ped, PDO	0	0	0	0
Bike, PDO	0	0	0	0

[7] Rounding leads to slight differences in the sums displayed in this column.

[8] Calculated as the difference between SV, All and SV, PDO

Step 1.1D: Calculate Expected Number of Crashes for the Study Period

Because both observed and predicted crash data are available, the EB method can be used to estimate the expected crash frequency. As described previously, EB is a weighted average of the observed and predicted crash frequency. Given the observed and predicted number of crashes, expected crash frequency is calculated using Equation 1 and Equation 2. The number of observed crashes ($N_{obs,study}$) for each type and severity are available in Table 6 while the predicted number of crashes ($N_{obs,study}$) are available in Table 7.

To calculate the weight (w) for the EB method, the overdispersion parameter (k) for the SPF is required. Per the worksheet, the overdispersion parameter for the four-leg stop-controlled intersection multi-vehicle FI SPF is 1.75[9]. A k value is provided for each SPF except for vehicle-bicycle and pedestrian crashes on stop-controlled intersections; for these, assume a value of zero. The weight and expected number of crashes are calculated using Equation 1 and Equation 2. The calculations for this example, with inputs for multi-vehicle FI crashes, are provided in Example Equation 1 and Example Equation 2. Expected crash frequency for each crash type and severity category is shown in Table 8. Figure 13 is a screenshot of these results from the spreadsheet tool.

Example Equation 1 – Example weight calculation for EB, multi-vehicle FI crashes.

$$w_{MV,FI} = \frac{1}{1 + k * N_{pr,MV,FI,study}} = \frac{1}{1 + 1.75 * 3.08} = 0.1565$$

Example Equation 2 – Example calculation of expected multi-vehicle FI crashes for the study period using EB.

$$N_{exp,MV,FI,study} = w_{MV,FI} * N_{pr,MV,FI,study} + (1 - w_{MV,FI}) * N_{obs,MV,FI,study} = 0.1565 * 3.08 + (1 - 0.1565) * 12 = 10.61$$

Table 8 – Expected number of crashes during the study period, calculated using EB.

Crash Type, Severity	Predicted Crashes during the Study Period ($N_{pr,study}$)	Observed Crashes during the Study Period ($Nobs_{,study}$)	Overdispersion Parameter (k)	Weight (w)	Expected Crashes during the Study Period ($Nexp_{,study}$)
MV, FI	3.08	12	1.75	0.16	10.61
SV, All	*0.44*	*1*	*2.45*	*0.48*	*0.73*
SV, FI	0.10	0	N/A	N/A	0.19
Ped, FI	0.15	1	0	1	0.15
Bike, FI	0.15	1	0	1	0.15
Total, FI	3.49	14.00			11.10
MV, PDO	8.43	12	1.03	0.10	11.63
SV, PDO	0.34	1	1.27	0.70	0.54
Ped, PDO	N/A	N/A	N/A	N/A	N/A
Bike, PDO	N/A	N/A	N/A	N/A	N/A
Total, PDO	8.77	13.00			12.17

[9] Overdispersion parameters are also provided in Worksheets 2C, 2E, and 2G of the MassDOT spreadsheet tool. See Column 4 in Table 8.

Step 1.1D - Expected number of crashes during the study period, calculated using EB

Crash Type, Severity	Predicted Crashes during the Study Period ($N_{pr,study}$)	Observed Crashes during the Study Period ($N_{obs,study}$)	Overdispersion Parameter (K)	Weight (w)	Expected Crashes during the Study Period ($N_{exp,study}$)
MV, FI	3.08	12	1.75	0.16	10.61
MV, PDO	8.43	12	1.03	0.10	11.63
SV, All	*0.44*	*1*	*2.45*	*0.48*	*0.73*
SV, FI	0.10	0	0	1.00	0.19
SV, PDO	0.34	1	1.27	0.70	0.54
Ped, FI	0.15	1	0	1.00	0.15
Ped, PDO					
Bike, FI	0.15	1	0	1.00	0.15
Bike, PDO					
Total (FI)	**3.49**	**14.00**	-	-	**11.10**
Total (PDO)	**8.77**	**13.00**	-	-	**12.17**

Figure 13 – Screenshot of expected crash results from the MassDOT Safety Analysis Tools.

Step 1.1E: Calculate Expected Number of Crashes in the Design Year

For this example, the design year is 10 years into the future from year 3 of the analysis. Expected crash frequency can be adjusted to the design year using Equation 5, which requires a calculation of predicted crashes for the design year ($N_{pr,design}$) using the SPF and design year traffic volumes (for this example, the predicted number of multi-vehicle FI crashes in the design year was found to be 1.101). Example Equation 3 is an example of this calculation. The predicted and expected future crash frequency for the intersection are summarized in Table 9. Figure 14 is a screenshot of the related output from the spreadsheet tool. The expected future crash frequency ($N_{exp,,design,nobuild}$) serves as the baseline against which the alternatives will be compared, shown in the equation as $N_{estimated,MV,FI,design,nobuild}$.

Example Equation 3 – Example calculation of expected multi-vehicle FI crash frequency for the design year using Method 1.

$$N_{exp,MVFI,design,nobuild} = \frac{N_{pr,MVFI,design}}{N_{pr,MVFI,study}} * N_{exp,MVFI,study} = \frac{1.101}{3.083} * 10.61 = 3.79 = N_{estimated,MVFI,design,nobuild}$$

- $N_{pr,MVFI,design}$ = the predicted number of multi-vehicle FI Crashes during the design year (one-year period in the example), obtained from the SPF using design year traffic volumes.
- $N_{pr,MVFI,study}$ = the predicted number of multi-vehicle FI crashes during the study period (three-year period in the example), obtained from the SPF using traffic volumes for each year of the study period.
- $N_{exp,MVFI,study}$ = the expected number of multi-vehicle FI crashes during the study period (three-year period in the example).

Table 9 – Expected crashes during the design year under no-build conditions.

Crash Type, Severity	Predicted Crashes during the Study Period ($N_{pr,study}$)	Predicted Crashes during the Design Year ($N_{pr,design}$)	Growth Ratio ($N_{pr,design}/N_{pr,study}$)	Expected Crashes during the Study Period ($N_{exp,study}$)	Estimated Crashes during the Design Year ($N_{estimated,design,nobuild}$)
MV, FI	3.08	1.10	0.36	10.61	3.79
SV, FI	0.10	0.03	0.35	0.19	0.07
Ped, FI	0.15	0.06	0.37	0.15	0.06
Bike, FI	0.15	0.06	0.37	0.15	0.06
Total, FI	3.49	1.25		11.10	3.97
MV, PDO	8.43	3.19	0.38	11.63	4.40
SV, PDO	0.34	0.12	0.35	0.54	0.19
Ped, PDO	0	0	N/A	0	0
Bike, PDO	0	0	N/A	0	0
Total, PDO	8.77	3.30		12.17	4.58

Step 1.1E - Calculate Expected Number of Crashes in the Design Year

Crash Type, Severity	Predicted Crashes during the Study Period ($N_{pr,study}$)	Predicted Crashes during the Design Year ($N_{pr,design}$)	Growth Ratio ($N_{pr,design}/N_{pr,study}$)	Expected Crashes during the Study Period ($N_{exp,study}$)	Estimated Crashes during the Design Year ($N_{estimated,design,nobuild}$)
MV, FI	3.083	1.101	0.36	10.61	3.79
MV, PDO	8.433	3.186	0.38	11.63	4.40
SV, FI	0.097	0.034	0.35	0.19	0.07
SV, PDO	0.339	0.117	0.35	0.54	0.19
Ped, FI	0.152	0.057	0.37	0.15	0.06
Ped, PDO					
Bike, FI	0.152	0.057	0.37	0.15	0.06
Bike, PDO					
Total (FI)	**3.49**	**1.25**	-	-	**3.97**
Total (PDO)	**8.77**	**3.30**	-	-	**4.58**
Total	**12.26**	**4.552**	-	-	**8.55**

Figure 14 – Screenshot of calculation of expected crashes in the design year from the MassDOT Safety Analysis Tools.

Step 1 - Future No-Build Safety Performance with Method 2

What if the analysts in this example were unable to obtain relevant crash data for this intersection because the intersection was converted from yield-control to stop-control in the last year, meaning there was less than one year of relevant observed crash data? As such, they would then use Method 2 to perform Step 1, which consists of using average predicted crash frequency to estimate safety performance.

Step 1.2A: Collect Traffic Data for the Study Period

The traffic volumes in Figure 10 represent measurements for Year 1. A traffic count in Year 3 returned traffic volumes of 10,500 vpd on the major roadway and 3,900 vpd. Per the previously described guidance, linear interpolation was used to estimate traffic volumes for Year 2. The interpolated traffic volumes are 10,250 vpd for the major road and 3,950 vpd for the minor road. The local planning agency expects traffic at this intersection to grow 1 percent per year, meaning the design year AADT will be 11,000 vpd on the major road and 4,400 vpd on the minor road.

Step 1.2B: Calculate the Predicted Number of Crashes for the Design Year Under No-Build Conditions

The analysts used projected traffic volumes for the design year and the MassDOT Safety Analysis Tools to predict crash frequency for the design year. Table 10 provides the results of this prediction. The analysts then proceeded to Step 2 using the frequencies in Table 10 as the estimated crash frequency in the design year. Figure 15 shows the inputs for the MassDOT Safety Analysis Tools under Method 2, while Figure 16 is a screenshot of the crash prediction results from the tool.

Table 10 – Predicted crash frequency during the design year under no-build conditions.

Crash Type, Severity	Predicted Crashes during the Design Year ($N_{pr,design}$)
MV, FI	1.101
SV, FI	0.034
Ped, FI	0.057
Bike, FI	0.057
Total, FI	1.25
MV, PDO	3.186
SV, PDO	0.117
Ped, PDO	0
Bike, PDO	0
Total, PDO	3.30

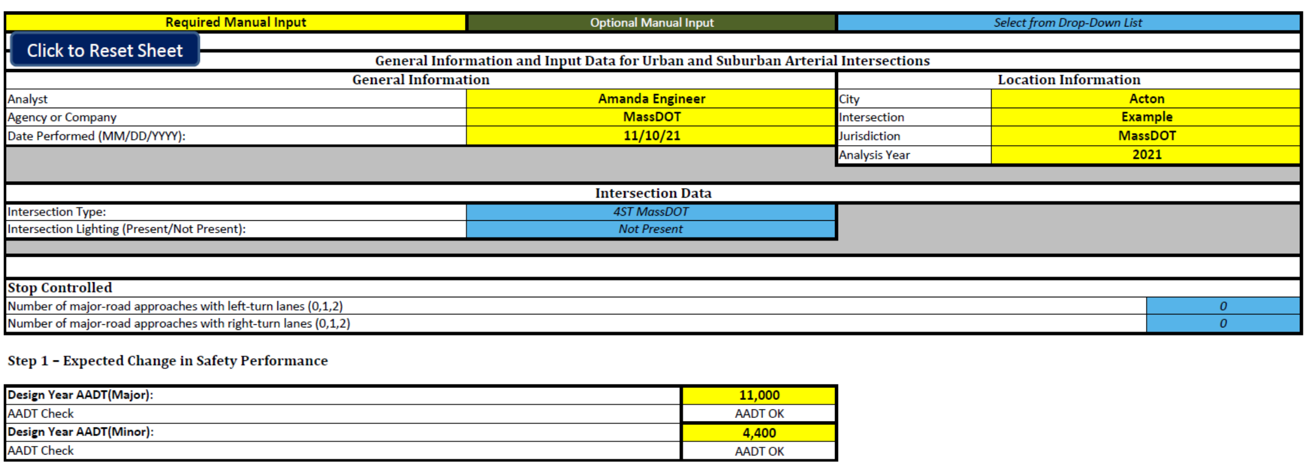


Figure 15 – Screenshot of the MassDOT Safety Analysis Tools depicting inputs for the example alternative analysis using Method 2.

Results

Step 1.2 - Calculate Predicted Number of Crashes in the Design Year

Crash Type, Severity	Predicted Crashes during the Design Year ($N_{pr,design}$)
MV, FI	1.101
MV, PDO	3.186
SV, FI	0.034
SV, PDO	0.117
Ped, FI	0.057
Ped, PDO	
Bike, FI	0.057
Bike, PDO	
Total (FI)	**1.25**
Total (PDO)	**3.30**
Total	**4.552**

Figure 16 - Screenshot of the crash prediction results in the MassDOT Safety Analysis Tools for Method 2.

Step 1 - Future No-Build Safety Performance with Method 3

What if the analysts in this example were working on a facility type for which no SPF or crash prediction tool was available?

Step 1.3A: Collect Observed Crash Data

Under these conditions, the analysts would perform Step 1 of the safety analysis using Method 3 – obtaining at least 5 years of historical crash data to perform the analysis. The analysts reviewed the history of the site and found no significant changes to the traffic volume, traffic control devices, or design of the intersections for the past 6 years, so they elected to pull 6 years of crash data. They first obtained the crash data through a spatial search on IMPACT. The analysts supplemented this crash data with crash reports obtained from the police department who has jurisdiction over the intersection. After reviewing the crashes from both sources, the analysts summarized the total crashes for each year in Table 11.

Table 11 – Summary of six years of observed crashes at the study intersection.

Crash Type, Severity	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Total Crashes
MV, FI	6	2	1	3	4	5	21
SV, FI	0	1	0	0	0	0	1
Ped, FI	0	0	0	1	0	0	1
Bike, FI	0	0	0	0	1	0	1
MV, PDO	8	4	7	5	5	2	31
SV, PDO	1	0	0	1	0	0	2
Ped, PDO	0	0	0	0	1	0	1
Bike, PDO	1	0	0	0	0	0	1

Step 1.3B: Collect Traffic Volumes for the Study Period and Design Year

Over the six years of the study period, the analysts determined the average entering volume from the major road approaches is 9,600 vpd and from the minor road approaches is 3,850 vpd, for a total of average daily entering traffic volume ($AADT_{study}$) of 13,450 vpd. For the design year, the entering traffic volume is expected to be 15,450 vpd.

Step 1.3C: Calculate Estimated Number of Crashes for the Design Year

The analysts then used Equation 4 to calculate the estimated number of crashes in the design year. Having calculated the number of observed crashes ($N_{obs,study}$) and the number of years ($Y_{years,study}$) in the study period, the analysts still needed to determine the average entering traffic volume during the study period and the design year. The analysts' calculation of estimated crash frequency during the design year under no-build conditions for MV, FI crashes is provided in Example Equation 4. The estimated frequencies for all crash types and severity are provided in Table 12. The analysts then proceeded with Step 2.

Example Equation 4– Example calculation of estimated number of multi-vehicle FI crashes for the design year under no-build conditions using Method 3.

$$N_{estimated,design,nobuild,MV,FI} = N_{obs,design} = \frac{N_{obs,study}}{AADT_{study} * Y_{years,study}} * AADT_{Design}$$

$$= \frac{21\ MV, FI\ Crashes}{13{,}450\ vpd * 6\ years} * 15{,}450\ vpd = 4.02$$

Table 12 – Estimated crash frequency during the design year under no-build conditions using Method 3.

Crash Type, Severity	Estimated Crashes During the Design Year using Method 3, No-Build
MV, FI	4.02
SV, FI	0.19
Ped, FI	0.19
Bike, FI	0.19
MV, PDO	5.93
SV, PDO	0.38
Ped, PDO	0.19
Bike, PDO	0.19

Step 2 – Expected Change in Safety Performance

Three alternatives have been proposed for the intersection:

1. Add left-turn lanes and right-turn lanes to both major road approaches.
2. Signalize the intersection.
3. Convert the intersection to a single-lane roundabout.

CMFs can be taken from the MassDOT State-Preferred CMF List (in the Massachusetts Safety Analysis Tools) to calculate the expected change in safety performance for each alternative, as explained below.[10] Figure 17 is a screenshot showing the required inputs for the MassDOT Safety Analysis Tools to describe the proposed countermeasures. Note users enter the number of alternatives, descriptions of the countermeasures in each, projected service lives, and the estimated cost.

Step 2 – Expected Change in Safety Performance

Facility Type:	U4ST	Urban Four-Leg Stop-Controlled Intersection	
Discount Rate (i)	7%	Number of Proposed Alternatives:	3

	Alternative 1	Alternative 2	Alternative 3	Alternative 4
Name of Countermeasure 1	Add Left Turn Lanes to Major Road Approaches	Signalize Intersection	Convert to Single-Lane Roundabout	
Name of Countermeasure 2 (If Desired)	Add Right Turn Lanes to Major Road Approaches			
Estimated Service Life	20	20	20	
Estimated Improvement Cost	$750,000	$900,000	$1,500,000	

Figure 17 - Screenshot from the MassDOT Safety Analysis Tools showing the required inputs for Step 2.

Alternative 1- Turn Lanes

Alternative 1 proposes the installation of exclusive left-turn lanes and right-turn lanes on both major road approaches.

Step 2A – Identify a CMF for Alternative 1

Under existing conditions, none of the approaches have left-turn lanes nor right-turn lanes. Per the State-preferred CMF list in the Massachusetts Safety Analysis Tools, the same CMFunction applies for both All and FI crashes for increasing the number of major road approaches with left-turn lanes. This function uses *X* to represent the initial number of approaches with left-turn lanes and *Y* to represent the proposed number of approaches with left-turn lanes. The CMFunction calculation is provided as Example Equation 5, which shows a CMF of 0.53 (a 47-percent reduction in crash frequency) due to adding the left-turn lanes.

Example Equation 5 – CMFunction calculation for change in the number of major road approaches with left-turn lanes.

$$CMF_{Alternative1,LTL} = 0.73^{Y-X} = 0.73^{2-0} = 0.53$$

- *Y* = the number of approaches with left-turn lanes under the proposed design.

[10] The calculations in this step of the example use the expected crash frequency calculated previously using Method 1.

- X = the number of approaches with left-turn lanes under existing conditions.
- $CMF_{Alternative1,LTL}$ = the CMF value for left-turn lanes at Alternative 1.

A CMFunction is also used to estimate the CMF for right-turn lanes. The CMFunction calculation is provided as Example Equation 6, which shows a CMF of 0.74 (a 26-percent reduction in crash frequency) due to adding the right-turn lanes for both All and FI crashes.

Example Equation 6 – CMFunction calculation for change in the number of major road approaches with right-turn lanes.

$$CMF_{Alternative1,RTL} = 0.86^{Y-X} = 0.86^{2-0} = 0.74$$

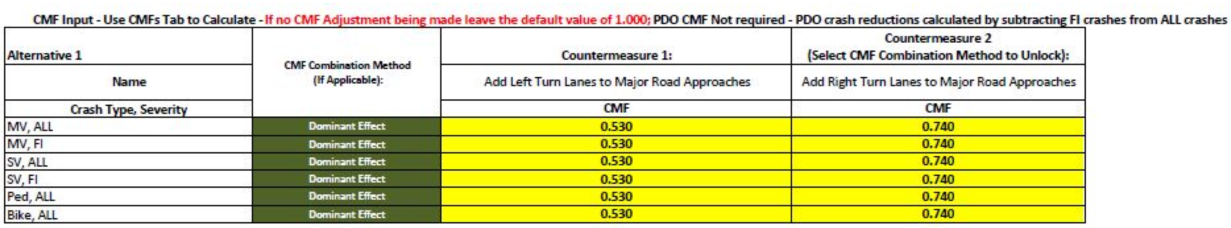
- Y = the number of approaches with right-turn lanes under the proposed design.
- X = the number of approaches with right-turn lanes under existing conditions.
- $CMF_{Alternative1,RTL}$ = the CMF value for right-turn lanes at Alternative 1.

The purpose of the left-turn lanes is to reduce rear-end crashes on the major approaches as well as left-turn crashes from the major approaches. Similarly, the right-turn lanes are being built to reduce rear-end crashes on the major approaches as well as right-turn crashes from the major approaches. To combine these CMFs, these countermeasures are considered to have some overlap. As such, the dominant effect and dominant common residual should be compared to determine which method indicates the largest reduction in crashes. For the dominant effect, the left-turn lane CMF of 0.53 has a larger crash reduction (47 percent) than the right-turn lane CMF of 0.74 (26-percent reduction), so 0.53 should be used. Compare this to the dominant common residuals result from Equation 8, as shown in Example Equation 7.

Example Equation 7 – Dominant common residuals calculation for Alternative 1.

$$CMF_{Alternative1,DCR} = (0.53 * 0.74)^{0.53} = 0.61$$

The dominant effect CMF of 0.53 predicts a larger reduction than the dominant common residual; as such, a CMF of 0.53 is used for the Alternative 1 analysis ($CMF_{Alternative1}$).



CMF Input - Use CMFs Tab to Calculate - If no CMF Adjustment being made leave the default value of 1.000; PDO CMF Not required - PDO crash reductions calculated by subtracting FI crashes from ALL crashes

Alternative 1	CMF Combination Method (If Applicable):	Countermeasure 1:	Countermeasure 2 (Select CMF Combination Method to Unlock):
Name		Add Left Turn Lanes to Major Road Approaches	Add Right Turn Lanes to Major Road Approaches
Crash Type, Severity		CMF	CMF
MV, ALL	Dominant Effect	0.530	0.740
MV, FI	Dominant Effect	0.530	0.740
SV, ALL	Dominant Effect	0.530	0.740
SV, FI	Dominant Effect	0.530	0.740
Ped, ALL	Dominant Effect	0.530	0.740
Bike, ALL	Dominant Effect	0.530	0.740

Figure 18 – Screenshot from the MassDOT Safety Analysis Tools showing the required inputs for the CMFs for Alternative 1. Note only an All Severity CMF is required for vehicle-pedestrian and vehicle-bicycle crashes.

Step 2B – Calculate the Expected Reduction in Crashes for Alternative 1

The estimated crash frequency for the alternative is calculated using Equation 9 and the reduction from the no-build is calculated using Equation 10. Example Equation 8 and Example Equation 9 provide examples of these calculations. The expected reduction in crashes is summarized in Table 13. Figure 19 includes a screenshot of these results from the MassDOT Safety Analysis Tools.

Example Equation 8 – Example calculation for the estimated number of multi-vehicle FI crashes for Alternative 1.

$$N_{estmated,MVFI,design,Alternative1} = N_{estimated,MVFI,design,nobuild} * CMF_{MVFI,Alternative1} = 3.79 * 0.53 = 2.01$$

Example Equation 9 – Example calculation for the estimated reduction of multi-vehicle FI crashes for Alternative 1.

$$N_{reduction,MVFI,design,Alternative1} = N_{estimated,MVFI,design,nobuild} - N_{estimated,MVFI,design,Alternative1} = 3.79 - 2.01 = 1.78$$

Table 13 – Calculating expected crash reduction for Alternative 1.

Crash Type, Severity	Estimated Crashes during the Design Year	CMF	Estimated Crashes during the Design Year for Alternative 1	Reduced Crashes for Alternative 1
MV, All	8.18	0.53	4.34	3.85
SV, All	0.25	0.53	0.13	0.12
Ped, All	0.06	0.53	0.03	0.03
Bike, All	0.06	0.53	0.03	0.03
Total, All	8.55		4.53	4.03
MV, FI	3.79	0.53	2.01	1.78
SV, FI	0.07	0.53	0.03	0.03
Ped, FI	0.06		0.03	0.03
Bike, FI	0.06		0.03	0.03
Total, FI	3.97		2.10	1.86
MV, PDO	4.40		2.33	2.07
SV, PDO	0.19		0.10	0.09
Ped, PDO	0		0	0
Bike, PDO	0		0	0
Total, PDO	4.58		2.43	2.17

Alternative 1					**Estimated Lifetime of Alternative 1:**	20
Countermeasure 1:	**Add Left Turn Lanes to Major Road Approaches**		**Countermeasure 2:**	**Add Right Turn Lanes to Major Road Approaches**		
Crash Type, Severity	**Estimated Crashes during the Design Year**	**CMF1**	**CMF2 (If Applicable)**	**Resultant CMF**	**Estimated Crashes during the Design Year for Alternative 1**	**Reduced Crashes for Alternative 1**
MV, ALL	8.18	0.530	0.740	0.530	4.34	3.85
MV, FI	3.79	0.530	0.740	0.530	2.01	1.78
MV, PDO	4.40				2.33	2.07
SV, ALL	0.25	0.530	0.740	0.530	0.13	0.12
SV, FI	0.07	0.530	0.740	0.530	0.03	0.03
SV, PDO	0.19				0.10	0.09
Ped, ALL	0.06	0.530	0.740	0.530	0.03	0.03
Ped, FI	0.06				0.03	0.03
Ped, PDO						
Bike, ALL	0.06	0.530	0.740	0.530	0.03	0.03
Bike, FI	0.06				0.03	0.03
Bike, PDO						
Total, FI	3.97				2.10	1.86
Total, PDO	4.58				2.43	2.15

Figure 19 – Screenshot of the Alternative 1 results from the MassDOT Safety Analysis Tools.

Alternative 2 – Signalization

Alternative 2 proposes to convert the intersection from a stop-controlled intersection to a signalized intersection.

Step 2A - Identify a CMF for Alternative 2

The MassDOT State-Preferred CMF List (in the Massachusetts Safety Analysis Tools) indicates the CMF for converting a stop-controlled intersection to a signalized intersection is 0.46 for MV, FI crashes and 0.57 for MV, All crashes. Figure 20 shows the CMF inputs for the MassDOT Safety Analysis Tools for Alternative 2.

Alternative 2	CMF Combination Method (If Applicable):	Countermeasure 1:	Countermeasure 2 (Select CMF Combination Method to Unlock):
Name		Signalize Intersection	
Crash Type, Severity		CMF	CMF
MV, ALL	Not Applicable	0.570	1.000
MV, FI	Not Applicable	0.460	1.000
SV, ALL	Not Applicable	1.000	1.000
SV, FI	Not Applicable	1.000	1.000
Ped, ALL	Not Applicable	1.000	1.000
Bike, ALL	Not Applicable	1.000	1.000

Figure 20 – Screenshot from the MassDOT Safety Analysis Tools showing the required inputs for the CMFs for Alternative 2.

Step 2B – Calculate the Expected Reduction in Crashes for Alternative 2

As with Alternative 1, these CMFs are applied using Equation 9 and the anticipated reduction is calculated using Equation 10. Example Equation 10 and Example Equation 11 are examples of these calculations. Table 14 summarizes the expected reduction in crashes for Alternative 2. Figure 21 is a screenshot of these results from the MassDOT Safety Analysis Tools.

Example Equation 10 – Example calculation of the estimated number of multi-vehicle FI crashes for Alternative 2.

$$N_{estmated,MVFI,design,Alternative2} = N_{estimated,MVFI,design,nobuild} * CMF_{MVFI,Alternative2} = 3.79 * 0.46 = 1.74$$

Example Equation 11 – Example calculation of the expected reduction of multi-vehicle FI crashes for Alternative 2.

$$N_{reduction,MVFI,design,Alternative2} = N_{estimated,MVFI,design,nobuild} - N_{estimated,MVFI,design,Alternative2} = 3.79 - 1.74 = 2.05$$

Table 14 – Calculating expected crash reduction for Alternative 2.

Crash Type, Severity	Estimated Crashes during the Design Year	CMF	Estimated Crashes during the Design Year for Alternative 2	Reduced Crashes for Alternative 2
MV, All	8.18	0.57	4.66	3.52
SV, All	0.25	1	0.25	0
Ped, All	0.06	1	0.06	0
Bike, All	0.06	1	0.06	0
Total, All	8.55		5.03	3.52
MV, FI	3.79	0.46	1.74	2.05
SV, FI	0.07	1	0.07	0
Ped, FI	0.06	1	0.06	0
Bike, FI	0.06	1	0.06	0
Total, FI	3.97		1.92	2.05
MV, PDO	4.40		2.92	1.47
SV, PDO	0.19		0.19	0
Ped, PDO	0		0	0
Bike, PDO	0		0	0
Total, PDO	4.58		3.11	1.47

Alternative 2					**Estimated Lifetime of Alternative 2:**	20
Countermeasure 1:	**Signalize Intersection**		**Countermeasure 2:**			
Crash Type, Severity	**Estimated Crashes during the Design Year**	**CMF1**	**CMF2 (If Applicable)**	**Resultant CMF**	**Estimated Crashes during the Design Year for Alternative 2**	**Reduced Crashes for Alternative 2**
MV, ALL	8.18	0.570		0.570	4.66	3.52
MV, FI	3.79	0.460		0.460	1.74	2.05
MV, PDO	4.40				2.92	1.47
SV, ALL	0.25	1.000		1.000	0.25	0.00
SV, FI	0.07	1.000		1.000	0.07	0.00
SV, PDO	0.19	[redacted]		[redacted]	0.19	0.00
Ped, ALL	0.06	1.000		1.000	0.06	0.00
Ped, FI	0.06				0.06	0.00
Ped, PDO						
Bike, ALL	0.06	1.000		1.000	0.06	0.00
Bike, FI	0.06				0.06	0.00
Bike, PDO						
Total, FI	3.97				1.92	2.05
Total, PDO	4.58				3.11	1.47

Figure 21 - Screenshot of the Alternative 2 results from the MassDOT Safety Analysis Tools.

Alternative 3 – Conversion to Roundabout

Alternative 3 proposes to convert the intersection to a single-lane roundabout.

Step 2A - Identify a CMF for Alternative 3

The MassDOT State-Preferred CMF List indicates the CMF for converting a stop-controlled intersection to a single-lane roundabout is 0.16 for MV, FI crashes and 0.48 for MV, All crashes. Figure 22 shows the CMF inputs for the MassDOT Safety Analysis Tools for Alternative 3.

Alternative 3	CMF Combination Method (If Applicable):	Countermeasure 1:	Countermeasure 2 (Select CMF Combination Method to Unlock):
Name		Convert to Single-Lane Roundabout	
Crash Type, Severity		CMF	CMF
MV, ALL	Not Applicable	0.480	1.000
MV, FI	Not Applicable	0.160	1.000
SV, ALL	Not Applicable	1.000	1.000
SV, FI	Not Applicable	1.000	1.000
Ped, ALL	Not Applicable	1.000	1.000
Bike, ALL	Not Applicable	1.000	1.000

Figure 22 – Screenshot from the MassDOT Safety Analysis Tools showing the required inputs for the CMFs for Alternative 3.

Step 2B – Calculate the Expected Reduction in Crashes for Alternative 3

As with Alternative 1, these CMFs are applied using Equation 9 and the anticipated reduction is calculated using Equation 10. Example Equation 12 and Example Equation 13 are examples of this calculation. Table 15 summarizes the expected reduction in crashes for Alternative 3. Figure 23 is a screenshot of the results from the MassDOT Safety Analysis Tools.

Example Equation 12 – Example calculation of the estimated number of multi-vehicle FI crashes for Alternative 3.

$$N_{estmated,MVFI,design,Alternative3} = N_{estimated,MVFI,design,nobuild} * CMF_{MVFI,Alternative3} = 3.79 * 0.16 = 0.61$$

Example Equation 13 – Example calculation of the estimated reduction of multi-vehicle FI crashes for Alternative 3.

$$N_{reduction,MVFI,design,Alternative3} = N_{estimated,MVFI,design,nobuild} - N_{estimated,MVFI,design,Alternative3} = 3.79 - 0.61 = 3.18$$

Table 15 – Calculating expected crash reduction for Alternative 3.

Crash Type, Severity	Estimated Crashes during the Design Year	CMF	Estimated Crashes during the Design Year for Alternative 3	Reduced Crashes for Alternative 3
MV, All	8.18	0.48	3.93	4.26
SV, All	0.25	1	0.25	0
Ped, All	0.06	1	0.06	0
Bike, All	0.06	1	0.06	0
Total, All	8.55		4.30	4.26
MV, FI	3.79	0.16	0.61	3.18
SV, FI	0.07	1	0.07	0
Ped, FI	0.06	1	0.06	0
Bike, FI	0.06	1	0.06	0
Total, FI	3.97		0.79	3.18
MV, PDO	4.40		3.32	1.07
SV, PDO	0.19		0.19	0
Ped, PDO	0		0	0
Bike, PDO	0		0	0
Total, PDO	4.58		3.51	1.07

Alternative 3					Estimated Lifetime of Alternative 3:	20
Countermeasure 1:	Convert to Single-Lane Roundabout		Countermeasure 2:			
Crash Type, Severity	Estimated Crashes during the Design Year	CMF1	CMF2 (If Applicable)	Resultant CMF	Estimated Crashes during the Design Year for Alternative 3	Reduced Crashes for Alternative 3
MV, ALL	8.18	0.480		0.480	3.93	4.26
MV, FI	3.79	0.160		0.160	0.61	3.18
MV, PDO	4.40				3.32	1.07
SV, ALL	0.25	1.000		1.000	0.25	0.00
SV, FI	0.07	1.000		1.000	0.07	0.00
SV, PDO	0.19				0.19	0.00
Ped, ALL	0.06	1.000		1.000	0.06	0.00
Ped, FI	0.06				0.06	0.00
Ped, PDO						
Bike, ALL	0.06	1.000		1.000	0.06	0.00
Bike, FI	0.06				0.06	0.00
Bike, PDO						
Total, FI	3.97				0.79	3.18
Total, PDO	4.58				3.51	1.07

Figure 23 - Screenshot of the Alternative 3 results from the MassDOT Safety Analysis Tools.

Step 3 – Economic Analysis

The expected reductions for each alternative were provided in Table 13, Table 14, and Table 15. These reductions can be compared to the changes in crash frequency and severity across alternatives. Additionally, monetization of these reductions can be used to compare the anticipated benefits with project costs.

Step 3A: Determine Average Crash Cost

Average comprehensive crash costs for a four-leg stop-controlled intersection in Massachusetts are provided in Table 5 (U4ST); the average FI crash is equivalent to \$319,100 and a PDO is equivalent to \$16,700.

Step 3B: Convert Annual Crash Reduction to Annual Savings

Using these costs, design year benefits can be calculated with Equation 12 (Example Equation 14 is an example calculation of these benefits); the results are summarized in Table 16[11]. Figure 24 is a screenshot of these results from the MassDOT Safety Analysis Tools.

Example Equation 14 – Example calculation of annual benefits for Alternative 1.

$$
\begin{aligned}
\$_{savings,design,Alternative1} &= N_{reduction,design,Alternative1,FI} * \$_{comprehensive,U4ST,FI} + N_{reduction,design,Alternative1,PDO} \\
&* \$_{comprehensive,U4ST,PDO} = 1.864 * \$319{,}100 + 2.153 * \$16{,}700 = \$630{,}970
\end{aligned}
$$

Table 16 – Estimated reduction in crash costs for each alternative in the design year compared to the no-build.

	Alternative 1 Reduction	Alternative 1 Benefits	Alternative 2 Reduction	Alternative 2 Benefits	Alternative 3 Reduction	Alternative 3 Benefits
Total, FI	1.86	\$595,013	2.05	\$652,805	3.18	\$1,015,475
Total, PDO	2.15	\$35,957	1.47	\$24,602	1.07	\$17,921
Total, All	4.02	\$630,970	3.52	\$677,407	4.26	\$1,033,396

Step 3 – Economic Analysis

	Add Left Turn Lanes to Major Road Approaches		Signalize Intersection		Convert to Single-Lane Roundabout			
	Reduction	Benefits	Reduction	Benefits	Reduction	Benefits		
Total, FI	1.86	\$595,013	2.05	\$652,805	3.18	\$1,015,475		
Total, PDO	2.15	\$35,957	1.47	\$24,602	1.07	\$17,921		
Total, All	4.02	\$630,970	3.52	\$677,407	4.26	\$1,033,396		

Figure 24 - Screenshot of the estimated reductions for each alternative from the MassDOT Safety Analysis Tools.

Step 3C: Calculate Lifetime Benefits and 3D – Calculate Benefit-Cost Ratio

Comparing the total benefits for each alternative (both in terms of crash reduction and benefits), Alternative 3 is expected to provide the most societal benefits due to the expected reduction in crash frequency and severity. However, does that alternative prove to be the most economically efficient? Consider the following estimated costs for each alternative:

1. Turn Lanes = \$750,000
2. Signalization = \$900,000
3. Roundabout = \$1,500,000

The benefits calculated in Table 16 can be converted to a present value to calculate benefit-cost ratios for each alternative. The conversion to present value is done using Equation 13 (Example Equation 15 is an example of this calculation). For this example, the lifetime of each alternative is assumed to be 20 years and the discount rate is 7

[11] The calculations in this step of the example use the expected crash frequency calculated previously using Method 1.

percent. Table 17 summarizes these calculations for each alternative. Figure 25 is a screenshot of those results from the spreadsheet tool.

Example Equation 15 – Example calculation of lifetime benefits for Alternative 1.

$$\$_{savings,lifetime,Alternative1} = \$_{savings,design,Alternative1} * \frac{(1+i)^t - 1}{i * (1+i)^t} = \$630{,}970 * \frac{(1+0.07)^{20} - 1}{0.07 * (1+0.07)^{20}}$$
$$= \$630{,}970 * 10.59 \cong \$6{,}684{,}508$$

Table 17 – Calculating present value of lifetime benefits and benefit-cost ratio for each alternative.

	Alternative 1	Alternative 2	Alternative 3
Design Year Benefit	$630,970	$677,407	$1,033,396
Present Value Conversion Factor (from Equation 13)	10.59	10.59	10.59
Lifetime Present Value	$6,684,508	$7,176,457	$10,947,812
Cost	$750,000	$900,000	$1,500,000
Benefit-Cost Ratio	8.9	8.0	7.3

	Add Left Turn Lanes to Major Road Approaches	Signalize Intersection	Convert to Single-Lane Roundabout	
Design Year Benefit	$630,970	$677,407	$1,033,396	
Present Value Conversion Factor (from Equation 13)	10.59	10.59	10.59	
Lifetime Present Value	$6,684,508	$7,176,457	$10,947,812	
Cost	$750,000	$900,000	$1,500,000	
Benefit-Cost Ratio	8.9	8.0	7.3	

Figure 25 - Screenshot of the estimated design year benefits, service life benefits, and benefit-cost ratio from the MassDOT Safety Analysis Tools.

Interpret Results

Reviewing the benefit-cost ratios in Table 17 shows that while Alternative 3 is expected to produce the most total safety benefits, Alternative 1 proves to be the most economically efficient because of the higher benefit-cost ratio. All three alternatives have benefit-cost ratios larger than one, so all three are economically justified. Given these results, other factors should now be taken into consideration, such as operational benefits, potential environmental or right-of-way impacts, before selecting the preferred alternative.

Conclusions and Recommendations

To meet the HSIP goal of reducing fatalities and serious injuries on public roadways, MassDOT is adopting a data-driven approach to evaluate design alternatives for HSIP projects. This guide describes the method for evaluating alternatives for potential safety performance, where safety performance is measured by the change in the expected frequency and severity of crashes. No-build crash frequency and severity need to be estimated first as a baseline. Ideally, this is done using the EB method to calculate expected crash frequency in the design year. Where the EB method is not possible, predicted or observed crash data can be used as an estimate. CMFs, taken from MassDOT's State-preferred CMF list, should then be used to estimate the expected change in crashes by severity for each alternative. Given the expected change in crashes for each alternative, average comprehensive crash costs can be used to monetize the change in crashes as societal benefits which account for changes in both frequency and severity. These costs can be used to evaluate the effectiveness of an alternative, both in terms of net present value and cost effectiveness via a benefit-cost ratio. Analysts can use the MassDOT Safety Analysis Tools to assist with these calculations. The safety benefits can then be combined with operational impacts, environmental impacts, construction costs, or right-of-way costs for a full comparison of the alternatives.

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Appendix A – Relevant Links

Massachusetts Strategic Highway Safety Plan, 2018:
https://www.mass.gov/files/documents/2019/01/18/dot_SHSP_2018.pdf

MassDOT Crash Data Portal – IMPACT: https://apps.impact.dot.state.ma.us/cdp/home

MassDOT GIS Road Inventory: https://gis.massdot.state.ma.us/roadinventory/

MassDOT HSIP Clusters Map: https://gis.massdot.state.ma.us/topcrashlocations/

MassDOT HSIP Webpage: https://www.mass.gov/service-details/highway-safety-improvement-program

MassDOT Interactive Traffic Volume Map: https://mhd.ms2soft.com/tcds/tsearch.asp?loc=Mhd&mod=

FHWA Countermeasure Service Life Guide:

https://safety.fhwa.dot.gov/hsip/docs/FHWA-SA-21-021_Countermeasure_Serv_Life_Guide.pdf

FHWA Crash Costs for Highway Safety Analysis: https://safety.fhwa.dot.gov/hsip/docs/fhwasa17071.pdf

FHWA Highway Safety Benefit-Cost Analysis Guide: https://safety.fhwa.dot.gov/hsip/docs/fhwasa18001.pdf

FHWA HSIP Webpage: https://safety.fhwa.dot.gov/hsip/

AASHTO Highway Safety Manual Tools: http://www.highwaysafetymanual.org/Pages/Tools.aspx

Appendix B – Safety Performance Functions

SPFs are used to estimate the predicted crash frequency for a site of a specific facility type. For a roadway segment, SPFs typically follow the functional form in Equation 15, while for intersections, SPFs typically follow the functional form in Equation 16 (AASHTO, 2010).

Equation 15 – Typical functional form for a segment SPF.

$$N_{pr,segment,m,n} = L * e^{\left(\beta_0+\beta_{AADT}\ln\left(AADT_{segment}\right)+\sum\beta_i x_i\right)}$$

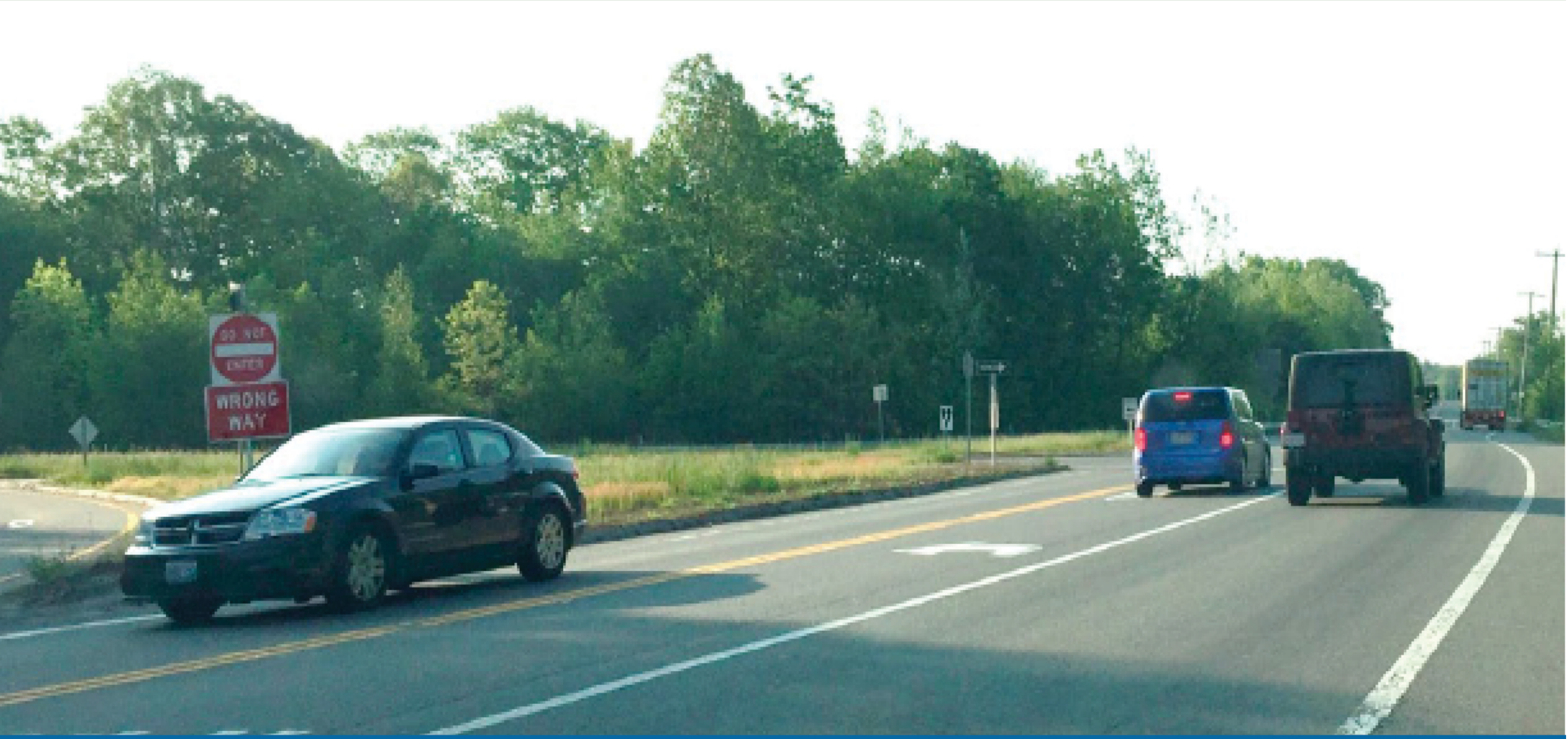
Equation 16 – Typical functional form for an intersection SPF.

$$N_{pr,intersection,m,n} = e^{\left[\beta_0+\beta_{major}\ln\left(AADT_{major}\right)+\beta_{minor}\ln\left(AADT_{minor}\right)+\sum\beta_i x_i\right]}$$

- $N_{pr,segment,m,n}$ = the predicted number of crashes of type m and severity n per year for a segment, in crashes per year.
- $N_{pr,intersection,m,n}$ = the predicted number of crashes of type m and severity n per year for an intersection, in crashes per year.
- L = length of the study segment, in miles.
- β_0 = constant.
- $AADT_{segment}$ = AADT for the study segment, in vpd.
- β_{AADT} = coefficient for AADT.
- $\Sigma\beta_i x_i$ = a series of adjustment factors which varies for each SPF. In some cases, there are no adjustment factors.
- $AADT_{major}$= AADT for the major roadway of the study intersection, in vpd.
- β_{major} = coefficient for AADT on the major roadway.
- $AADT_{minor}$ = AADT for the minor roadway of the study intersection, in vpd.
- β_{minor} = coefficient for AADT on the minor roadway.

For both segments and intersections, traffic volume is the most significant predictor of crash frequency. The regression coefficient for AADT ($\beta_{AADT,}$ $\beta_{Major,}$ β_{Minor}) can range between values less than and greater than one. When less than one, the slope of the crash frequency-AADT curve becomes gradually less steep; when greater than one, the slope becomes gradually steeper. The coefficient can also, at times, equal one, in which case the steepness of the slope remains constant. Differences in slope imply that an increase in AADT of, for example, one percent results in different increases in crash frequency depending on the original AADT. Analysts can obtain values for the coefficients from SPF documentation, both local (i.e., MassDOT) and national (i.e., HSM). There are few variations to this functional form; the most noteworthy in the HSM are SPFs for multi-vehicle driveway-related crashes on urban and suburban arterials and SPFs for vehicle-pedestrian crashes at signalized urban and suburban intersections.

Most SPFs are estimated using negative binomial regression and are reported along with an overdispersion parameter. Crash data are count data, which are typically described using a Poisson distribution. A key feature of the Poisson distribution is the mean and variance of the data are equal. Crash data are typically overdispersed, meaning the variance is larger than the mean. Negative binomial distribution, a modification of a Poisson distribution, accounts for this overdispersion. When modeling using negative binomial regression, the overdispersion parameter accounts for the overdispersion of the data (Hauer, 2015). The overdispersion parameter is reported with the models because it is included in the EB method, specifically Equation 2. The MassDOT intersection SPFs were developed by Xie and Chen (2021).


DO NOT
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