Development and Application of Work Zone Crash Modification Factors

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16. Abstract

Crash modification factor (CMF) provides the expected change in crash frequency due to the implementation of a countermeasure or a change in a particular site condition. State and local transportation agencies determine CMF values by utilizing the Highway Safety Manual (HSM). The HSM provides CMF values for various types of facilities and treatments. However, the HSM's coverage of work zone-related CMF values is limited. This report introduces practitioners to: the procedure for evaluating work zone countermeasures using existing CMFs and the procedures for developing new work zone CMFs. Once derived, CMFs can be used for selecting countermeasures and scheduling lane closures.

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1. Introduction

The purpose of this document is to provide work zone practitioners with information on the use and development of **crash modification factors (CMFs)**, which provide the expected change in crash frequency due to the implementation of a countermeasure or a change in a particular site condition. This document is intended for engineers from state and local agencies who are familiar with the Highway Safety Manual (HSM) (AASHTO, 2014) and crash prediction models.

2. SPF and CMF Overview

The HSM (AASHTO, 2014) provides quantitative methods to evaluate safety of roadway facilities. The crash prediction models in the HSM are based on **Safety Performance Functions (SPFs)** which are regression equations for estimating site-specific average crash frequency (e.g., crashes/year) based on a given set of base conditions. Specified base conditions are established for several geometric characteristics, which may include lane width, shoulder presence, and intersection skew angle. The SPF is based on the annual average daily traffic (AADT) and (in the case of roadway segments), the segment length (L) (AASHTO, 2014). When calculating average crash frequency for a specific situation in which conditions have changed, the frequency estimated by the SPF is multiplied by **crash modification factors (CMFs)** and the calibration **factor**. Equation (1) shows the general form of a crash prediction model for a site.

$$N_{predicted} = N_{SPF} * CMF_1 * CMF_2 \ldots * C \quad (1)$$

Where:

$N_{predicted}$ is the predicted crash frequency for a site,

N_{SPF} is the predicted crash frequency for specified base conditions,

CMF_i is the crash modification factor i reflecting a prevailing site condition that differs from the base condition,

C is the calibration factor which accounts for differences (jurisdictional and time period) between the sample used for SPF development and the one for which the crash frequency is currently being estimated.

When all other conditions and site characteristics remain constant, CMFs represent the relative change in crash frequency due to a change in one specific condition (AASHTO, 2010). Thus, CMFs can provide estimates of the effect of various geometric characteristics, traffic control variables, and countermeasures. The HSM provides CMF values for several facility types derived by synthesizing previous research. For example, CMF values for lane width on undivided rural multilane roadway segments are provided. The base condition for lane width is 12 ft-wide lanes. A 9 ft-wide lane on a facility with AADT higher than 2000 vehicles per day has a CMF value of 1.38, indicating a 38% increase in crash frequency due to the lane width reduction from 12 ft to 9 ft. Conversely, a CMF value of less than 1.0 indicates a reduction in crash frequency.

The availability of existing CMFs for work zones is very limited. The HSM includes CMFs for work zone duration and length, and there are a few additional work zone CMFs available in the **CMF Clearinghouse** which is an online database of CMFs hosted by FHWA (FHWA, 2016). The CMF Clearinghouse contains additional resources such as a CMF guide (http://www.cmfclearinghouse.org/collateral/CMF_Guide.pdf) and tips for developing effective CMFs (http://www.cmfclearinghouse.org/collateral/HighQualityCMFs.pdf). The adjusted crash frequency is calculated by multiplying the work zone CMFs with the **predicted crash frequency** with the work zone in place (i.e. base conditions when work zone is present).

There are many CMF resources available at cmfclearinghouse.org

2.1. Work Zone CMFs in HSM

The work zone CMFs in the HSM specify a linear relationship between the CMF value and duration or length and were developed based on data from 36 high impact freeway work zones in California.

The CMF for work zone duration for all crash severities is presented as (AASHTO, 2014):

$$CMF_{d,all} = 1.0 + \frac{(\text{\% increase in duration } x\ 1.11)}{100} \quad (2)$$

The CMF for work zone length for all crash severities is presented as (AASHTO, 2014):

$$CMF_{l,all} = 1.0 + \frac{(\text{\% increase in length } x\ 0.67)}{100} \quad (3)$$

2.2. Work Zone CMFs in CMF Clearinghouse

The FHWA CMF Clearinghouse (FHWA, 2016) reports additional work zone CMFs based on prior work zone safety research. As of the writing of this document, the CMF Clearinghouse includes CMFs for the following work zone countermeasures:

1) Active work with no lane closure compared to no work zone
2) Active work with temporary lane closure compared to no work zone
3) No active work with no lane closure compared to no work zone
4) Left-hand merge and downstream lane shift, also called Iowa weave
5) Increasing the inside shoulder width inside the work zone by 1-ft
6) Increasing the outside shoulder width inside the work zone by 1-ft
7) Two way two lane operations in work zones.

The HSM includes CMFs for work zone length and duration

The work zone duration and length CMFs reported in the HSM are also included in the CMF Clearinghouse.

3. Procedure for Evaluating Work Zone Countermeasures Using Existing CMFs

The existing CMFs can be used to evaluate the safety effectiveness of work zone **countermeasures** which are treatments that are applied at a transportation facility to improve safety and reduce the **crash frequency**. The steps for this procedure are shown in Figure 1. These steps are described in further detail in the following sections. This procedure would ideally be applied in the project development and planning stages so that the appropriate countermeasures can be included in the project plans.

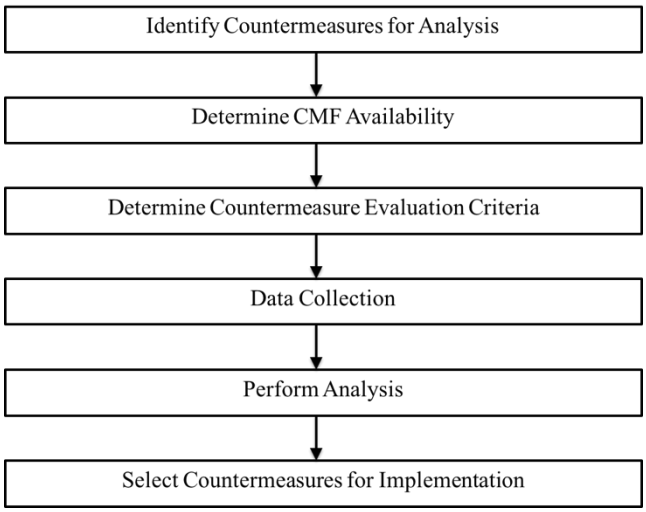

Figure 1. Procedure for evaluation of work zone countermeasures using existing CMFs

3.1. Identify Countermeasures for Analysis

The work zone countermeasures to be analyzed are identified in the first step. Examples of countermeasures that could be used to improve safety in work zones include ITS deployment, changeable speed warning signs, variable speed limits, automated enforcement, alternate merge systems, innovative flagging procedures, portable rumble strips, and innovative contracting strategies.

3.2. Determine CMF Availability

The availability of existing CMFs for the countermeasures under consideration is first investigated. As described previously in Section 2, there are CMFs for work zone length and duration in the HSM and a limited selection of other work zone CMFs on the CMF clearinghouse. A quality rating is assigned to each CMF in the CMF clearinghouse based on the study design, sample size, standard error, source of data, and any potential bias of the research that generated the CMF. This rating can be used to help determine the applicability of the CMF to a given situation. If a CMF is not available for the countermeasure under consideration, the development of a new CMF can be considered. The procedure for CMF development is described in Section 4 of this document.

3.3. Determine Countermeasure Evaluation Criteria

The criteria for implementation of the countermeasure are established. For example, the criteria for the application of a given countermeasure could be a benefit-cost ratio greater than one or a total crash reduction of 50 percent.

3.4. Data Collection

All data needed to apply the CMF are collected. Depending on the countermeasure being evaluated, these data could include lane closure configurations, work zone duration, work zone length, lane and shoulder widths, and the presence of work zone speed enforcement. Information on construction costs of the countermeasure should be obtained if the countermeasure cost is included as part of the evaluation criteria.

3.5. Perform Analysis

Once the data are collected, the practitioner performs the analysis by calculating and applying the CMFs for the countermeasures under consideration. If a monetary estimate of crash cost savings is needed, the CMFs should be multiplied by the expected crash rate reduction (without the countermeasures) and the estimated crash cost.

3.6. Select Countermeasures for Implementation

Finally, the practitioner determines if the countermeasure should be implemented for a given site based on the defined criteria. For example, a countermeasure may be implemented if its benefit-cost ratio is 1.2, which is greater than one.

3.7. Example: Outside Shoulder Width

In this example, a highway agency would like to assess the benefits of increasing the work zone outside shoulder width by 1 ft on a two-mile section of urban interstate.

Source: http://ops.fhwa.dot.gov/freewaymgmt/

Step 1: Identify Countermeasures for Analysis

The countermeasure to be investigated involves increasing the outside shoulder width by 1 ft within the work zone.

Step 2: Determine CMF Availability

A review of the CMF Clearinghouse (FHWA, 2015) indicates that a CMF is available for this countermeasure. The CMF value is 0.948, indicating a 5.2 percent decrease in crashes. The CMF has a star quality of 3. The CMF is determined to be applicable to the given set of circumstances.

Step 3: Determine Countermeasure Evaluation Criteria

The agency has determined that the countermeasure will be implemented if the benefit-cost ratio is greater than 1.25.

Step 4: Data Collection

The estimated cost of the improvement is $3,000 per mile, and the expected number of total crashes in this work zone is eight crashes. The anticipated cost of each crash is $20,000.

Step 5: Perform Analysis

The total estimated cost of the improvement is 2 miles * $3,000 per mile = $6,000.

The estimated reduction in the number of crashes is 0.052 * 8 = 0.416 crashes.

The estimated crash cost savings is 0.416 crashes * $20,000 per crash = $8,320.

The benefit-cost ratio is calculated as $8,320/$6,000 = 1.39.

Step 6: Select Countermeasures for Implementation

In this example, the agency chooses to implement the countermeasure because the benefit-cost ratio is 1.39 which is greater than 1.25.

4. Procedure for Developing Work Zone CMFs

In cases where work zone CMFs for a given countermeasure either do not exist or are not applicable to a given situation, it may be necessary to develop CMFs. The steps for developing work zone CMFs are shown in Figure 2. These steps are described in further detail in the following sections.

4.1. Select Countermeasure for CMF Development

The process begins with the selection of the countermeasure for which the CMF will be developed. This may be a countermeasure for which existing CMFs are either not available or not applicable to a given set of circumstances. Some example countermeasures were described previously in Section 3.1.

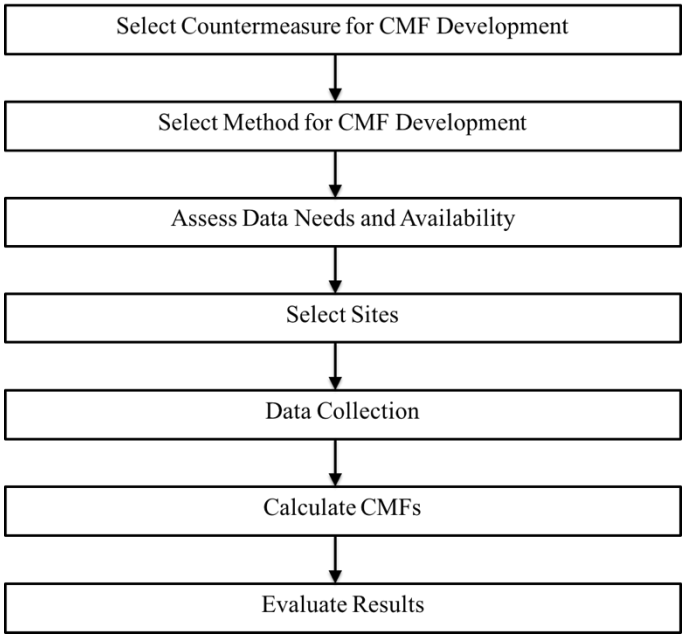

Figure 2. Procedure for development of work zone CMFs

4.2. Select Method for CMF Development

The practitioner determines which method will be used to generate the CMFs. Two of the more common methods used to generate CMFs include the **Empirical Bayes (EB)** before-after study approach and the **cross-sectional study** approach. The EB before-after method utilizes SPFs to estimate the average crash frequency for treated sites during the after period as though the treatment had not been applied (AASHTO, 2014). A **cross-sectional study** compares the crash performance at **treatment sites** with the crash performance at **control sites** (that have not received any treatment) over the same period of time.

The best method for use in a given situation depends on many factors such as the availability of data during the before and after periods and the availability of control sites. One instance where a cross-sectional study is recommended is when there are few treatment sites.

4.3. Assess Data Needs and Availability

An important step in CMF development involves assessing the availability of existing data. In this step, data sources are identified, and procedures for processing the data are developed. In many cases, work zone and crash data reside in different databases which must be joined temporally and spatially to link work zones and crashes. There are several challenges related to obtaining the data necessary for developing work zone CMFs. These challenges are separated into four categories:

Data fusion is often required due to the complex nature of work zone and crash data

1) Accuracy of work zone presence and schedule,
2) Inconsistency between crash database and crash report description,
3) Difficulty in determining the spatial influence of work zones for assigning work zone-related crashes, and
4) Lack of actual traffic volumes (e.g., historical AADT as a surrogate).

In evaluating the data requirements, an understanding of the tradeoffs between accuracy and level of effort is needed. For example, a greater understanding of the linkage of crashes to work zones can be gained by reviewing individual crash reports. However, the process of reviewing individual reports is very labor-intensive and time-consuming.

4.4. Select Sites

Once the data requirements have been established, the sites for analysis should be selected. For a cross-sectional study, both treatment sites and control sites (that have not received any treatment) are needed. The sample size needs to be carefully chosen to balance the statistical needs (e.g., low standard error) with the level of effort needed to obtain accurate data. Additional considerations for minimum sample size requirements are thoroughly discussed in Gross et al. (2010) and Carter et al. (2012).

4.5. Data Collection

Once the data requirements and sample sites have been determined, various types of data need to be collected, including work zone data, traffic data, geometric data, and crash data. It may be necessary to obtain these data from a variety of sources and fuse them together. Crashes and work zones must be linked in both time and space to determine if a crash was work-zone related.

4.6. Calculate CMFs

After the data are collected, the CMF needs to be calculated. For the EB before-after method, the CMF is calculated based on the **observed crash frequencies** during the before and after periods, the **expected crash frequencies** during the before and after periods, and the variance of the expected crash period during the after period. Unlike the **predicted crash frequencies**, the expected crash frequencies include consideration of observed crash frequencies. For the cross-sectional method, the CMF can be estimated as the ratio of the crash frequency averaged across all sites receiving treatment and the crash frequency averaged across all control sites. Another cross-sectional approach is to develop multivariate regression models and determine the CMF value for the treatment variable from the regression model coefficients.

4.7. Evaluate Results

The results for the developed CMF should be evaluated for reasonableness. A CMF value less than one indicates that the countermeasure reduces the crash frequency, while a CMF value

Developed CMFs should be reasonable in their effects on crashes

greater than one indicates that the countermeasure increases the crash frequency. An understanding of the applicability of the CMF (for example, range of variables for which the CMF is valid) should be developed and documented for future use. The calculated CMF can then be used to evaluate countermeasures using the procedures described in Section 3 of this implementation guide.

4.8. CMF Development Examples

Two examples of CMF development are described in the following sections. The first example uses freeway work zone data from Missouri while the second example uses data from a freeway work zone project in Indiana.

4.8.1. Example 1: CMF Development for Freeway Work Zones Using Missouri Data

This example describes a research study undertaken by Rahmani et al. (2016) to develop freeway work zone CMFs from Missouri data.

Step 1: Select Countermeasure for CMF Development

In this study, CMFs were developed for AADT, work zone length, and work zone duration using freeway work zone data from Missouri. CMFs for work zone length and duration based on California data are included in the HSM.

Step 2: Select Method for CMF Development

This study used a form of cross-sectional study that estimates negative binomial regression models, to predict crash frequencies, using data from work zones in Missouri. The CMF values for the treatment variables can then be inferred from their coefficients in the regression model.

Step 3: Assess Data Needs and Availability

To perform the analysis, it was necessary to collect data from several Missouri Department of Transportation (MoDOT) databases, including a work zone database, crash database, and road segment database. Information contained in the work zone database includes work zone ID, roadway segment ID, work zone start and end date, and work zone start and end location. Archived highway patrol reports are included in the crash database. Other road segment data such as AADT are contained in the road segment database.

Step 4: Select Sites

Potential sites included all of the freeway work zones in Missouri between 2009 and 2014. However, there was a concern that most of these work zones were short in length and duration and did not have many crashes. Therefore, only work zones with a length greater than 0.1 miles and duration greater than 10 days were included in the study. The optimum minimum length and

duration thresholds were determined from analysis. The large sample included 1,571 freeway work zones in Missouri. A second stratified sample of 152 work zones was also analyzed.

Step 5: Data Collection

The data described in Step 3 were collected and fused together to link work zones and crashes. Crashes were assigned to the work zones based on spatial and temporal matching of the crash data and work zone data. Variable thresholds based on the MUTCD (FHWA, 2009) were used to assign crashes to the different work zone locations, including advance warning area, transition area, buffer area, work area, and termination area.

Step 6: Calculate CMFs

Using negative binomial regression, crash prediction models were developed with the following functional form (Rahmani et al., 2016):

$$\boldsymbol{N_C = AADT^{\beta_1} L^{\beta_2} D^{\beta_3} e^{\beta_4 Urban} e^{\beta_5 Injury} e^{\beta_6}}$$

where:

N_C = Number of fatal/injury or PDO crashes, based on Injury variable;
N_{PDO} = Number of PDO crashes;
N_{Inj} = Number of fatal/injury crashes;
AADT =Annual Average Daily traffic;
D = Duration of observation (days);
L = Segment length (mi.);
Urban – Dummy variable for work zone location, 1= urban, 0 = rural;
Injury – Dummy variable for crash severity, 1 = fatal/injury, 0 = PDO.

The parameters for the model based on the large sample are shown in Table 4.1.

Table 4.1. Crash prediction model parameters for large sample (Rahmani et al., 2016)

Parameter	Value
$ß_1$	0.8116
$ß_2$	0.6220
$ß_3$	1.0142
$ß_4$	0.2696
$ß_5$	-1.1280
$ß_6$	-11.7257

The CMFs for work zone length, work zone duration, and AADT were then determined from the crash prediction models based on a 1% increase in the value of the explanatory variables. The CMFs are shown in equation (3), (4), and (5).

$$CMF_{AADT} = 1.0 + \frac{(\text{\% increase in AADT } x\ 0.81)}{100} \quad (4)$$

$$CMF_{Length} = 1.0 + \frac{(\text{\% increase in Length } x\ 0.62)}{100} \quad (5)$$

$$CMF_{Duration} = 1.0 + \frac{(\text{\% increase in Duration } x\ 1.01)}{100} \quad (6)$$

Step 7: Evaluate Results

As discussed earlier, the CMF values obtained in the previous step must be evaluated for reasonableness. All three CMFs reported in equations (3), (4), and (5) are greater than 1. This is reasonable as we expect the number of crashes in a work zone to increase with increase in AADT, length and duration of work zone.

4.8.2. Example 2: CMFs Derived from Study of I-70 High Speed Work Zone in Indiana

This CMF example describes a research study undertaken by Tarko et al. (2011) to evaluate the safety effectiveness of various countermeasures for a work zone on an interstate reconstruction project in Indianapolis, Indiana. The reconstruction took place on a section of I-70 between March and November of 2007. As a result of this study, CMFs were developed for inside and outside shoulder widths.

Step 1: Select Countermeasure for CMF Development

This study investigated several countermeasures including increased enforcement, reduced speed limits, movable traffic barriers, wider shoulders, ramp closures, and rerouting of heavy vehicles to alternate interstate routes in the area.

Step 2: Select Method for CMF Development

This study used a cross sectional method with binary logistic regression to develop models to predict the likelihood of a crash on a given segment in 30-minute intervals. The crash frequency for longer periods could be found by adding the individual crash likelihoods for the 30 minute intervals. A before-and-after study was also used to investigate the safety of the impact area surrounding the work zone.

Step 3: Assess Data Needs and Availability

This project utilized data from a variety of sources. Crash data were obtained from the Indiana State Police crash database. Detectors were installed by the Indiana Department of Transportation (INDOT) to obtain traffic data. Other data sources included Google Earth and project drawings for geometric data, project drawings for maintenance data, project activity logs for enforcement data, and the National Climatic Weather Center for weather data.

Step 4: Select Sites

This study was focused on one work zone and its surrounding area. The study area was divided into segments that were each approximately 0.25 miles in length. Because the entire sample of segments and 30-minute intervals included more than 11 million observations, it was necessary to use random sampling to obtain a smaller and more manageable sample size. The sub-sample used to develop the models included all 30-minute intervals in which a crash occurred and approximately one percent of the 30-minute intervals in which a crash did not occur. Approximately one half of the sample was developed from sections on I-70 while the remaining half used other sections. The final sample used to develop the models included approximately 450,000 observations.

Step 5: Data Collection

The data described in Step 3 were collected, converted, and fused together to match the data spatially and temporally. Some of the necessary data conversions included modifications to units, removal of unnecessary variables, development of new variables from existing variables, and data aggregation. The data fusion process involved linking variables that were common between datasets. The process of locating crashes in the original crash dataset and matching them with work zones involved processing several variables such as the mile marker and distance and direction from the mile marker. The remaining datasets were fused together using appropriate linking variables such as Date and Time, Segment ID, Road Name, and Travel Direction.

Step 6: Calculate CMFs

A model was developed to predict the likelihood of a crash based on various input variables. Models were also estimated for the likelihood of single-vehicle crashes and the likelihood of a fatality or injury given that a crash has occurred. The incremental effects of various variables were calculated from the model coefficients. For example, increasing the inside shoulder width by 1 ft reduced the number of crashes per year by 0.043 while increasing the outside shoulder width by 1 ft reduced the number of crashes per year by 0.077. These crash reductions resulted in CMFs of 0.97 and 0.948, respectively. The CMFs for inside and outside shoulder width that were developed in this study are listed on the CMF Clearinghouse (FHWA, 2016).

Step 7: Evaluate Results

The results indicate that increasing the inside and outside shoulder widths leads to a decrease in the number of work zone crashes. This result conforms with expectations. Tarko et al. (2011) suggest that the decrease in crashes could be due to many factors. First, wider shoulders provide more space for errant vehicles to recover. In addition, the use of wider shoulders also reduces the likelihood that vehicles involved in a crash will return to the travel lanes. Finally, drivers may feel more comfortable moving to a wider shoulder to avoid a collision with another vehicle.

Regarding some of the other countermeasures that were evaluated, the study found that the rerouting of heavy vehicles onto other interstate routes had the most positive impact on safety. Safety benefits were also realized due to police enforcement, lower speed limits in the work zone, and other countermeasures related to traffic management. The research was not able to determine if movable barriers had a positive impact on safety.

5. Conclusion

There are many challenges involved with work zone crash data analysis, including a relatively low number of existing work zone CMFs and the difficulties encountered in working with work zone and crash data. Despite these challenges, the procedures described in this document can be used by practitioners to apply existing CMFs or to develop new CMFs to evaluate work zone safety countermeasures.

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Appendix A. Glossary

Calibration factor: Numerical ratio which accounts for differences (jurisdictional and time period) between the sample used for SPF development and the one for which the crash frequency is currently being estimated.

Crash frequency: Number of crashes per unit of time (typically crashes/year).

Countermeasure: A treatment that is applied at a transportation facility to improve safety and reduce the crash frequency.

CMF Clearinghouse: An online database of CMFs hosted by FHWA.

Control site: A location with similar characteristics to the treatment sites that is used for comparison in a cross-sectional study.

Crash Modification Factor (CMF): Numerical ratio which provides the expected change in crash frequency due to the implementation of a countermeasure or a change in a particular site condition.

Cross-sectional study: A method of safety analysis in which the crash performance of treatment sites is compared with the crash performance of control sites (that have not received any treatment).

Empirical Bayes (EB): A before-after study method which uses additional data from reference sites with similar traffic and physical characteristics as the treated sites. Empirical Bayes computes the number of expected crashes using both the observed before period and data from reference sites.

Expected crash frequency: The anticipated future number of crashes per unit of time (typically crashes/year) with consideration of the observed crashes.

Observed crash frequency: The number of crashes which actually occur on a transportation facility during a given period of time (typically crashes/year).

Predicted crash frequency: The anticipated future number of crashes per unit of time (typically crashes/year) without consideration of the observed crashes.

Safety Performance Function (SPF): Regression equation for estimating site-specific average crash frequency (e.g., crashes/year) based on a given set of base conditions.

Treatment site: A location where a particular countermeasure has been implemented that is used for comparison in a cross-sectional study.

Appendix B. Guidelines for Developing High Quality Work Zone CMFs

This section includes some practitioner guidance for developing high quality work zone CMFs. Additional guidance may be found in FHWA (2013), Carter et al. (2012), and Gross et al. (2010).

B.1. Factors to Consider When Developing a Work Zone CMF Study

There are many factors that should be taken into account when designing a work zone CMF study. Some of these factors are described below:

- Are previous studies for the countermeasure available?
- Are sufficient data for the countermeasure available?
- Are the data formatted in a way that allows for crashes to be linked in space and time to specific work zones?
- What steps will be necessary to combine different types of data (such as work zone data, crash data, and traffic data)?
- How should the analysis account for work zones with short length and duration that may not have many crashes?
- Are there appropriate control sites and treatment sites for a cross sectional study?
- Are there enough locations for a before-after study?
- How will traffic volumes be obtained?

B.2. Tips for Building a High Quality Work Zone CMF

There are many considerations for building a high quality work zone CMF. Some of the traits of a high quality work zone CMF are described below (FHWA, 2013):

- Sufficient sample size
- Study includes multiple years of data
- Low standard error
- Potential sources of statistical bias have been taken into account
- Sites are diverse with respect to geographic location and other characteristics
- High level of statistical rigor

B.3. Tips for Documentation of Work Zone CMFs

Documentation of work zone CMFs is important because it allows the practitioner to evaluate the CMF and determine its applicability to a given situation. Documentation that should be included with work zone CMFs is listed below (Carter et al. 2012):

- Name and description of the countermeasure
- CMF values
- CMF standard error
- Previous site characteristics before application of the countermeasure
- Work zone characteristics
- Site characteristics (traffic data, geometric data, speed limit, etc.)
- Crash information (type, severity, etc.)
- CMF study information (methodology, time period of data, sampling criteria, sample characteristics, etc.)
- Criteria for assigning crashes to work zones
- Potential sources of bias