Development and Application of Work Zone Crash Modification Factors (2nd Ed.)

Source: FHWA

Prepared For:

United States Department of Transportation
Federal Highway Administration
Washington, D.C.

U.S. Department of Transportation
Federal Highway Administration

Prepared By:
University of Missouri-Columbia

Technical Report Documentation Page

1. Report No.	**2. Government Accession No.**	**3. Recipient's Catalog No.**

4. Title and Subtitle Development and Application of Work Zone Crash Modification Factors (2nd Edition)	**5. Report Date** October 2020
	6. Performing Organization Code
7. Author(s) Edara, P., Brown, H., Sun, C., Savolainen, P.	**8. Performing Organization Report No.**
9. Performing Organization Name and Address University of Missouri-Columbia C 2640 Lafferre Hall Columbia, MO-65211	**10. Work Unit No. (TRAIS)**
	11. Contract or Grant No.
12. Sponsoring Organization Name and Address United States Department of Transportation Federal Highway Administration HSA Room #E71-324 1200 New Jersey Ave. SE Washington, DC 20590	**13. Type of Report and Period Covered**
	14. Sponsoring Agency Code

15. Supplementary Notes

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. This 2nd Edition includes the addition of information regarding work zone CMF values, existing literature on work zone safety studies, existing agency practices for work zone safety, and more example applications.

17. Key Words Crash modification factor, Work Zones, Safety, Highway Safety Manual, CMF		**18. Distribution Statement** No restrictions.	
19. Security Classification (of this report) Unclassified.	**20. Security Classification (of this page)** Unclassified.	**21. No. of Pages** 69	**22. Price** NA

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

GLOSSARY

Before-after with comparison group: A method for developing CMFs based on comparing untreated sites similar to the treated sites to account for changes in crash frequency due to other factors such as time and volume trends. The CMF is calculated based on the number of observed crashes in the treatment group in the after period, the number of expected crashes in the treatment group in the after period, and the variance of the number of expected crashes in the treatment group in the after period.

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.

Case control: A method for developing CMFs in which sites are selected based on the outcome (crash or no crash), and then the prior treatment is determined within each outcome group. The likelihood of treatment is expressed as the odds ratio between two levels of a variable, which provides a direct estimate of the CMF.

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

Cohort: A method for developing CMFs in which sites are classified into cohorts based on current treatment status and the cohorts are then observed over time with respect to exposure and crash frequency. The relative risk and CMF can then be calculated.

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

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

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

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.

Expert panel: Group of experts convened to critically evaluate findings of published and unpublished research. The panel chooses reliable studies and develops CMFs through consensus.

Full Bayes: A modeling approach that uses distributions instead of point estimates for expected crash frequency.

Meta-analysis: A method of combining knowledge on CMFs from multiple previous studies (including study quality) to develop a final estimate for the CMF and its standard error.

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.

Simple before-after: A method for developing CMFs which assumes that that the crash frequency in the after period without the treatment is same as the crash frequency in the before period. The CMF is calculated as the crash frequency in the after period divided by the crash frequency in the before period with the treatment.

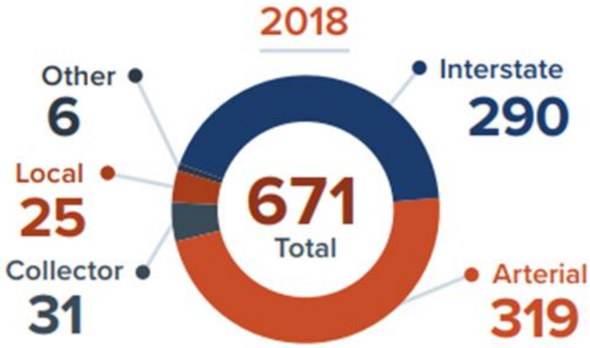
Surrogate measures: Safety performance measures, such as vehicle speeds, stopping behavior, lane change behavior, and traffic conflicts, that can be used in safety studies when sufficient crash data are not available. A CMF can be estimated through the use of a model that relates the observed change in the surrogate measure before and after the treatment with an expected change in crash frequency.

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

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 indicate 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.

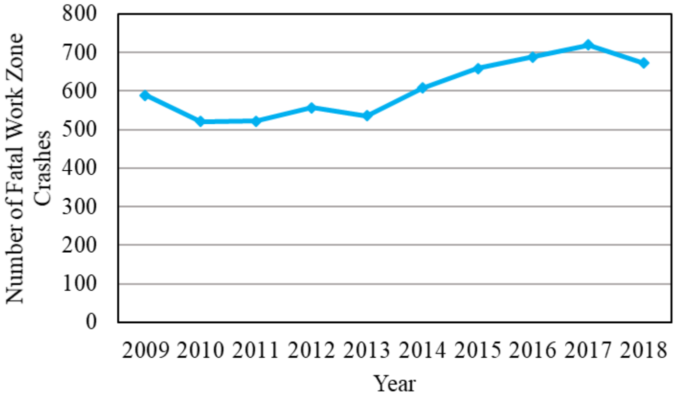
Severe crashes in work zones are a significant challenge. Figure 1.1 shows FHWA statistics for 2018 regarding fatal work zone crashes by type of facility. There were 1.84 fatal work zone crashes per day and 2.1 work zone fatalities per day in 2018 (FHWA, 2020a). Statistics from the American Road and Transportation Builders Association (ARTBA) indicate a work zone crash occurred every 4.3 minutes in 2018 (ARTBA, 2020a).



(FHWA, 2020a)

Figure 1.1. Total fatal work zone crashes by type of facility

As Figure 1.2 shows, the general trend from 2009 to 2018 has shown an increase in the number of fatal work zone crashes per year. Thus, engineering practitioners need additional tools to help improve safety in work zones.



(Data from ARTBA, 2020b)

Figure 1.2. National fatal work zone crashes (2009-2018)

One such tool involves the use of work zone CMFs. CMFs fulfill a specific need to quantify safety benefits of possible work zone countermeasures. By using CMFs, the safety benefits of implementing work zone countermeasures can be weighed against various other tradeoffs such as implementation costs, operational impacts, and public acceptance to assist practitioners in deciding if a work zone countermeasure should be implemented. Thus, CMFs can be used to help answer questions such as whether the work zone shoulder should be widened, an end of queue warning system should be installed, or a contractor should be offered an incentive to complete the project early. In addition, CMFs can help determine which countermeasures are the most cost effective with respect to improving safety. Ultimately, the use of work zone CMFs can help to improve work zone safety by providing practitioners with tools for data-driven decision-making.

Existing practitioner awareness of work zone CMFs appears to be limited. Feedback from engineering practitioners regarding their existing knowledge of work zone CMFs was obtained through a poll adminsitered during a presentation at the 2018 National Work Zone Management Conference. The conference attendees included practitioners from governmental transportation agencies and private companies who are involved with the planning and operation of work zones. As Figure 1.3 shows, almost two thirds of the respondents categorized their level of existing knowledge as low or none, and none of the respondents rated their existing knowledge of work zone CMFs as high. These results suggest that there is a need for greater awareness of work zone CMFs by practitioners.

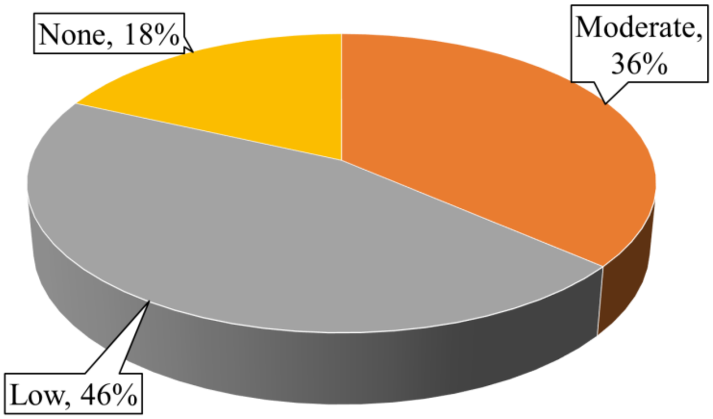


Figure 1.3. Practitioner responses for rating self-knowledge of work zone CMFs during presentation at 2018 National Work Zone Management Conference

2. SAFETY PERFORMANCE FUNCTIONS (SPF) AND CMF OVERVIEW

The Highway Safety Manual (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.

$$N_{predicted} = N_{SPF} * CMF_1 * CMF_2 \ . \ . \ .* C \tag{1}$$

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, 2014). 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** (http://www.cmfclearinghouse.org) which is an online database of CMFs hosted by FHWA (FHWA, 2020b). In addition to the CMF value, the CMF Clearinghouse provides additional information on the CMF, including a star rating (one to five scale), applicability, study reference, and development details. 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):

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

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

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

2.2. Work Zone CMFs in CMF Clearinghouse

The FHWA CMF Clearinghouse (FHWA, 2020b) 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

The HSM includes CMFs for work zone length and duration

7. Two-way two-lane operations in work zones.

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

Figures 2.1 through 2.3 show example screenshots from the CMF Clearinghouse for the CMF for increasing the outside work zone shoulder by one foot. As Figure 2.1 shows, this countermeasure has a CMF value of 0.97 and crash reduction factor (CRF) of 3%. The figure also contains star ratings for each CMF on a scale of 1 (lowest) to 5 (highest). This particular CMF has a star rating value of 3, indicating that the CMF quality is average. The figure also includes information on the crash types, crash severity, and area type. This CMF was developed for all crash types and all crash severity types in an urban area. The CMF Clearinghouse also allows for the comparison of CMFs across countermeasures, subcategories, and categories by checking the box in the "Compare" column. The reference column contains hyperlinks to additional study details, including an abstract and a link to the full report.

Countermeasure: Increasing the inside shoulder width inside the work zone by one foot

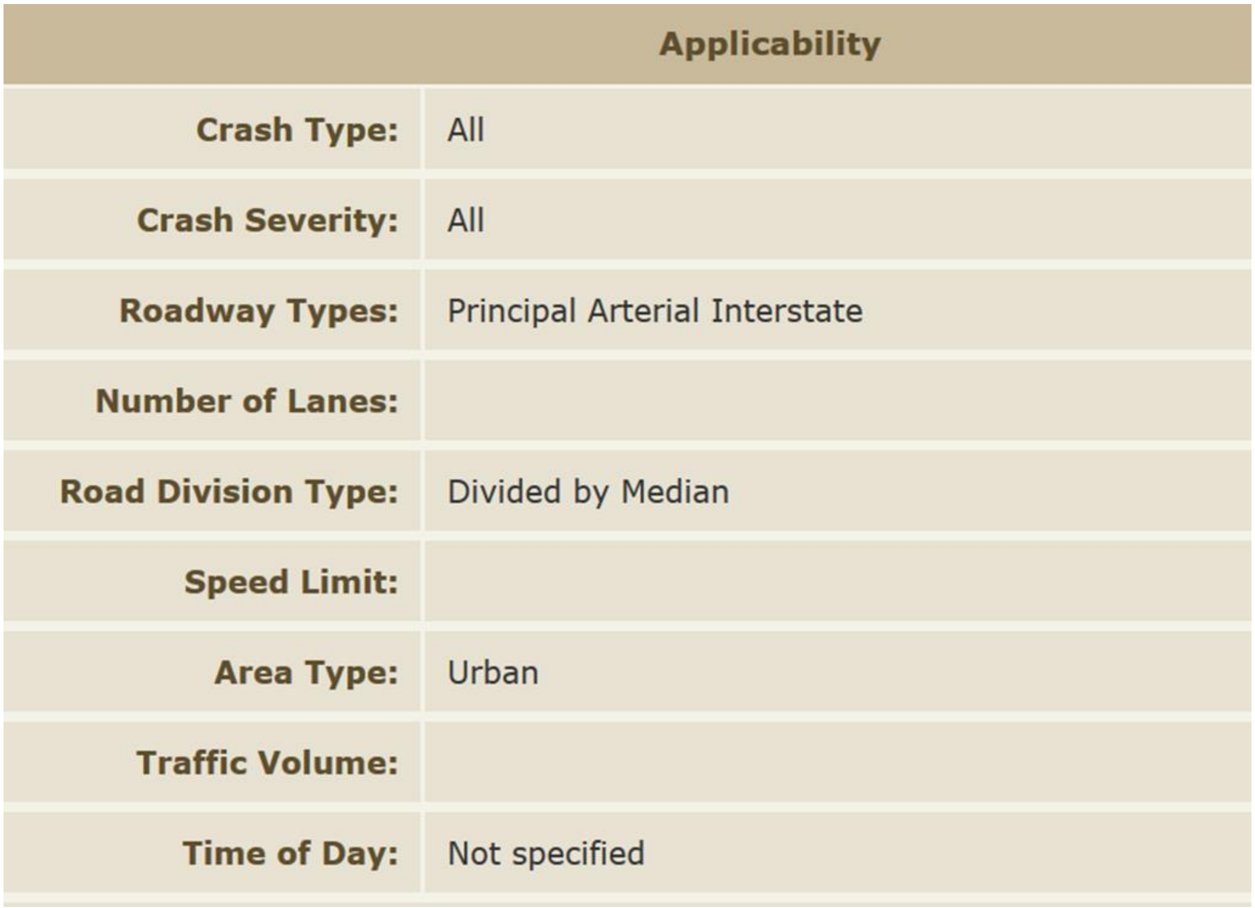
Compare	CMF	CRF(%)	Quality	Crash Type	Crash Severity	Area Type	Reference	Comments
☐	0.97	3	★★★☆☆	All	All	Urban	Tarko, Andrew P.; Bin Islam, Mouyid ; Thomaz, Jose E., 2011	

NOTE: You can compare CMFs across countermeasures, subcategories, and categories.

(FHWA, 2020b)

Figure 2.1. CMF summary for increasing inside shoulder width within the work zone by one foot

The screenshot in Figure 2.2 shows additional details regarding the applicability of the CMF for increasing the inside shoulder width in the work zone by 1 ft. This CMF is applicable to all crash types and crash severities in urban areas. It is applicable to interstates with a divided median. Other fields shown but not specified for this particular CMF include number of lanes, speed limit, traffic volume, and time of day.



	Applicability
Crash Type:	All
Crash Severity:	All
Roadway Types:	Principal Arterial Interstate
Number of Lanes:	
Road Division Type:	Divided by Median
Speed Limit:	
Area Type:	Urban
Traffic Volume:	
Time of Day:	Not specified

(FHWA, 2020b)

Figure 2.2. CMF applicability for increasing inside shoulder width within the work zone by one foot

Figure 2.3 shows development details and other details for the aforementioned CMF. As the figure shows, the CMF was developed using data from 2006 to 2008 in Indianapolis, Indiana. The sample size was 1403 crashes, and the regression cross-section method was used to develop the CMF. The CMF was added to the CMF Clearinghouse in December 2012 and is not included in the Highway Safety Manual. These details can help a practitioner assess whether the CMF is a good fit in a specific situation in a different jurisdiction.

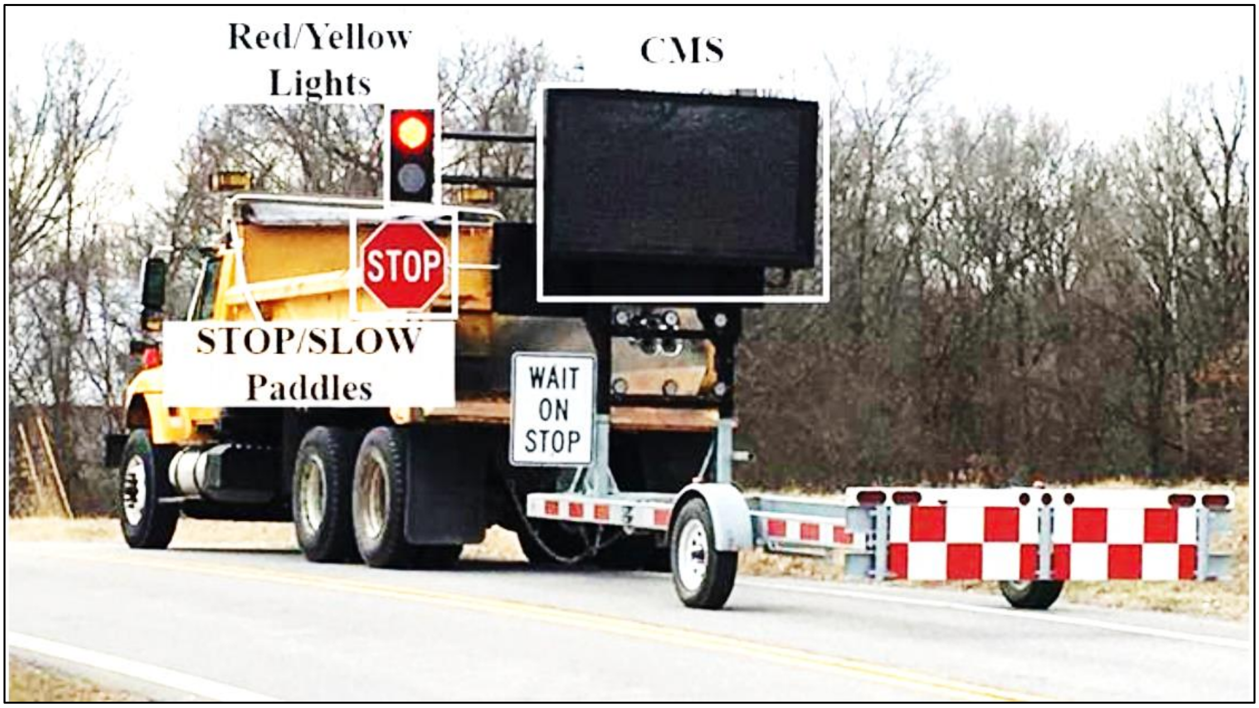
	Development Details
Date Range of Data Used:	2006 to 2008
Municipality:	Indianapolis
State:	IN
Country:	USA
Type of Methodology Used:	Regression cross-section
Sample Size (crashes):	1403 crashes
	Other Details
Included in Highway Safety Manual?	No
Date Added to Clearinghouse:	Dec-06-2012
Comments:	

(FHWA, 2020b)

Figure 2.3. Additional CMF details for increasing inside shoulder width within the work zone by one foot

2.3. Other Work Zone Safety Studies

Other work zone safety studies are discussed in Chapter 3 of this guide. In some instances, these studies led to the development of work zone CMFs which are not in the HSM or CMF Clearinghouse. In addition, some studies use surrogate measures to evaluate work zone safety countermeasures when crash data are not readily available, such as when a new work zone countermeasure is being tested. Example surrogate measures include: vehicle speeds, merging distances, traffic conflicts, lane changes, and driver behavior. Figure 2.4 shows an Automated Flagger Assistance Device (AFAD) mounted on a Truck Mounted Attenuator (TMA) that was evaluated in a feasibility study for Missouri DOT (Brown et al., 2018a). The study collected data on surrogate safety measures such as speeds and braking distances in both field and simulator environments to assess the impacts of the AFAD.



(adapted from Brown et al., 2018a)

Figure 2.4. Automated Flagger Assistance Device (AFAD) evaluated in study for Missouri DOT

3. REVIEW OF EXISTING LITERATURE FOR WORK ZONE SAFETY STUDIES

Work zones are critical aspects of the road network in terms of safety, and they have been an area of concern to many agencies in the recent years. A number of studies have been performed to understand the exact relationship between the presence, design, and operation of work zones with the crash frequency and severity, crash types and other crash characteristics.

A literature review was conducted to gain insight into the state of the existing knowledge regarding work zone Crash Modification Factors (CMFs). Although there are many studies on crash frequency modeling, only a few of them focus on work zone presence.

3.1. Research Studies

One of the first studies on the effect of a lane closure on safety was done by Dudek et al. (1986), which included nine field studies on four-lane divided highways in Texas and Oklahoma to compare single-lane closure in one direction versus a crossover with two-lane, two-way traffic operation (TLTWO). Worker productivity, job duration, construction costs, traffic control device costs, highway-user costs, accidents, conflicts, and capacity were the variables considered in this study. A minimum of one year of before-construction and during-construction data were analyzed (for most of the sites). The analysis showed that the three lane-closure work zones experienced a relatively large increase in accident rate during construction. Based on this study, the TLTWO sites had a better safety performance in general.

Pal and Sinha (1996) conducted a study on Indiana highway work zones and found that crash rates in work zones were significantly higher than non-work zone conditions. This study focused on two lane closure strategies: crossover and partial lane closure. Negative Binomial and Poisson regression and normal regression models were developed in this study. The results indicated that when a large dataset was considered, Negative Binomial and Poisson regression models could be better predictive models for work zones.

Venugopal and Tarko (2000) developed two negative binomial models with duration of work, type of work, AADT, and work zone length as the main variables. The two models were calibrated for the region approaching the work zone and the region containing the work zone. In addition, the cost of work was added to the model as an indicator of the intensity of work. This study showed AADT, work zone length and duration to be major safety-related factors and indicated that a long, single work zone was better than two short work zones.

The current HSM (AASHTO 2014) CMFs for work zones are derived from a negative binomial model using before-and-after data developed by Khattak and Council (2002). In this model, the crash rates for the areas without work zones and with work zones were found to be 0.65 and 0.79 crashes per million vehicle kilometers, respectively. The findings suggested that a higher AADT along with a longer work zone duration and work zone length led to a higher crash rate, which was consistent with previous studies.

Khattak and Targa (2004) studied previous research on multi-vehicle collisions inside work zones and found that multi-vehicle collisions were significant in work zones especially when a large truck was involved in a collision. The study of North Carolina work zones indicated that truck-involved collisions had relatively more fatalities than all work zone crashes (2.48% fatalities versus 1.38% fatalities, respectively). In addition, this kind of collision was more frequent on the divided two-way roadways compared to undivided configurations. Moreover, this study indicated that multi-vehicle crashes were most harmful on two-way undivided or divided but unprotected highways, in situations when a detour to the opposite side was necessary, at locations adjacent to the work area, and in instances when the posted speed limits were higher.

Bryden (2007) studied the effect of category 3 and category 4 work zone safety features, portable traffic signs, and work vehicles and equipment on 461 work zone crashes. Category 3 devices included crash attenuators and temporary traffic barriers, and category 4 devices included trailer-mounted arrow panels, changeable message signs, and light towers. The results of this study showed that category 4 devices and portable signs were involved in a small number of crashes and rarely resulted in injuries while work zone attenuators and temporary barriers were involved in a higher number of crashes and injuries. Based on this study, most of the injured workers were drivers or occupants of vehicles.

A project by Ullman et al. (2008) was initiated to determine how nighttime and daytime work zones affect traffic safety. The researchers found that when work activity is occurring in a work zone with a temporary travel lane closure, the risk of a crash for an individual motorist traveling through the work zone increased by about 66 percent during the day and by 61 percent at night, compared to the expected crash risk that would normally exist at a particular location without the presence of a work zone.

A study by See et al. (2009) indicated that there was approximately a 30 percent reduction in crash rate when the Iowa weave configuration, with the main objective of speeding up the construction progress, was used compared to the conventional right-hand closure. However, the overall number of work zone crashes and the crash severity were not significantly different. The related CMF is equal to 0.54 for all crash severities and 2.24 for fatal and injury and is available in the CMF Clearinghouse (FHWA, 2020b).

Elghamrawy et al. (2010) presented a complete data analysis of 1729 highway construction zone fatal and serious injury crashes in the state of Illinois from 2003 to 2007. Their project's main objectives were to analyze the frequency and severity of work zone crashes and to find the main contributing factors of these crashes. They found that the severity of work zone crashes was affected by the type of collision, the driver’s actions, road surface, type of median and the speed limits of the road. The results showed that more than 37 percent of fatal crashes occurred on roadways with no medians while no fatal crashes occurred on roads with rumble strips and painted medians. In addition, more than half of the fatal crashes occurred on roads that have a speed limit of 50 mph or higher.

Srinivasan et al. (2011) developed negative binomial SPFs for all crashes, injury crashes, and PDOs, and then used the empirical Bayes method to estimate separate CMFs for daytime and nighttime, work status, and temporary traffic control conditions. Data from 64 freeway construction projects were analyzed in this study. The largest CMFs were related to the work activities requiring the temporary closure of one or more travel lanes. Overall total crashes increased by about 66.3 percent during daytime and by 60.9 percent during night time. The lowest increase in crashes occurred when there was no work on the project. The CMFs related to a lane closure did not show a significant difference between daytime and nighttime. Overall, the increase in crash risk was higher for the PDO crashes than for the injury crashes. The result of this study shows that EB method could be useful in assessing how temporal factors affect the road safety.

In a study by Akepati and Dissanayake (2011), characteristics of work zone crashes were examined. The researchers studied the crashes from years 2002 to 2006 from the following states: Iowa, Kansas, Missouri, Nebraska, and Wisconsin. Environmental conditions, vehicles, crashes, drivers, and roadways were the contributory factors that were analyzed for these states. The results of the analysis of percentage-wise distribution showed that most of the work zone crashes occurred under clear environmental conditions as daytime crashes and multiple-vehicle crashes were more predominant than single-vehicle crashes in work zones. The main contributing factors related to vehicle drivers were inattentive driving, following too close for conditions, failure to yield right of way, driving too fast for conditions, and exceeding posted speed limits within work zones. PDO crashes were the main severity type of crashes, and rear-end crashes were the most predominant type of collision in a work zone. The result of this study shows that almost 50 percent of work zone crashes occurred in the activity area where the actual work goes on.

Tarko et al. (2011) studied the spatial differences in crash risks on different roads inside and outside of the work zone and short-term effects of changes in traffic, weather, and traffic management by using advanced econometric models. Based on this study of an urban interstate reconstruction project, rerouting heavy vehicles on other interstate routes was the most successful strategy. In addition, a combination of police enforcement, speed reductions, and other management strategies could be helpful in the improving work zone safety. The results indicated that the segments with wider inside and outside shoulders tend to be safer than other segments. Based on this study the increase in inside and outside shoulder width by one foot may reduce the annual number of work zone crashes by 0.043 and 0.077, respectively. This study could not confirm whether adjusting the number of traffic lanes to traffic volume by using movable barriers could have a positive effect on work zone safety.

Chen and Tarko (2013) focused on evaluating the effect of police enforcement strategies for speed reduction in work zones. In this study different combination of stationary police enforcement with variable message signs were considered in six work zones. The result of a multi level linear model indicated that adding VMS with a relevant message about enforcement greatly increased the effectiveness of the enforcement program. Stationary police enforcement within the work zone reduced the average speed of cars by 2.47 mph and of tractor trailers by 3.61 mph. In this study, traffic conditions (volume, vehicle types, etc.) during the times of enforcement were not available and could not be incorporated into the analysis.

Yang et. al (2013) developed a negative binomial-based model with further temporal adjusted daytime and nighttime traffic volumes using a detailed data collected from 60 work zones in New Jersey. The results indicated that work zone duration, work zone length, and traffic volumes had the most impact on work zone safety.

In a study by Chen and Tarko (2014), researchers made an effort to improve the quality and scope of data and implemented a more advanced modeling technique for highway safety analysis. Many work zone design/management features were identified in this study which had not been available previously. The results indicated that detour signs, lane shifts, and lane splits significantly affected the crash frequency. One of the data improvements in this study was the creation of a monthly data structure, which allowed the researchers to consider the time varying effects. Based on this study the crash frequency in the work zone varies over time. Considering this variability could be useful for better temporal safety treatments such as speed enforcement.

In a research undertaken by Gayah et al. (2014), the researchers assembled a list of CMFs that are consistent with the HSM and are appropriate for use in Pennsylvania in order to integrate the use of CMFs into the existing safety management process. Of the 2,450 CMFs reported in this study, 72 CMFs were related to work zones.

Ozturk et al. (2014) tried to determine whether the presence of a work zone increased the number of crashes. The results of their study on 60 long-term work zones indicated that the average number of crashes and crash rates increased by 18.8 and 24.4 percent respectively under work zone conditions compared to non-work zone conditions. They found that rear-end crash frequency was 8.6 percent higher for work zone conditions, and non-work zone crashes were found to be more severe than work zone crashes. Based on this study, work zone length and traffic exposure significantly affected the crash frequency. In addition, in terms of crash occurrence, the night time condition was found to be less risky compared to the daytime condition.

Clark and Fontaine (2015) reviewed two years crash data of Virginia work zones in order to find the proportion of crashes which happened as the result of the presence of a work zone. The results of their study indicated that only 23 percent of the crashes that happened near a work zone (coded crashes) could be directly related to the work zone. About 24.1% of directly related crashes happened during work zone congestion, and about 15.5% of these crashes were related to changing lanes in a work zone. Their study showed that limited sight distance as the result of the poor placement of work vehicles and equipment at intersections was one of the main reasons for angle crashes. In addition, 10.8% of directly related rear-end crashes were related to flagman control.

Through research undertaken by Eustace et al. (2015), the effects of different variables such as left-and right-side merging, light, roadway pavement, drivers' age and presence of construction work zones on the frequency of crashes were analyzed. In this study, a 6.5-mile section of I-75 that passes through Dayton, Ohio, which has a high traffic volume, was considered. The results of a negative binomial generalized linear model indicated that left side merging and diverging areas are critical in the crashes near ramps on freeways. In addition, wet pavement, snow, ice, darkness, glare, and the presence of a work zone were found to be significant variables in the occurrence of crashes.

In a study by Ullman et al. (2016), researchers analyzed the effect of intelligent transportation system (ITS) technology combined with portable rumble strips (PRS) in nighttime temporary work zones. In this project, the End-of-Queue system was deployed upstream of the nighttime lane closure, where queues were expected to develop. The researchers concluded that the combination of portable End-of-Queue warning system (EOQWS) and PRS resulted in a 44% reduction in crashes. In addition, severe crashes and rear-end crashes both appeared to be reduced. The computed crash modification factor for the EOQ deployment was 0.559 and the level of marginal significance was 0.85. Because the work zones with and without the EOQ system were not necessarily at the same locations, researchers used conditions with-EOQ and without-EOQ for nighttime lane closures as respective treatment and control group data sets. The researchers then compared crashes that occurred during both sets of nights with the crashes expected on those nights if the corridor had not been under construction. One of the limitations of this analysis was that the actual presence or absence of queue during that lane closure was not considered.

Through research undertaken by Brown et al. (2016), a large sample of 20,837 freeway, 8,993 expressway, and 64,476 rural two-lane work zones in Missouri was analyzed in the first step. Then the most appropriate samples of 1,546 freeway, 1,189 expressway, and 6,095 rural two lane work zones longer than 0.1 mile and with a duration of greater than 10 days were used to make 15 different models to predict crashes for work zones on three facility types (freeway, expressway and rural two-lane highways) using Missouri data between 2009 and 2014. All Negative Binomial models developed in this study included the basic variables of AADT, duration, length, urban/rural, and injury. In addition to these basic variables, the freeway models also included the number of closed lanes, the total number of lanes, the number of on-ramps, and the number of off-ramps. The expressway and rural two-lane models both only had one additional variable, which was the number of signalized intersections. In this study, CMFs were determined for work zone length, duration, and AADT.

In a follow up study, additional models were developed to predict work zone crashes on urban multi-lane highways, arterials, ramps, signalized intersections, and unsignalized intersections based on data from Missouri work zones (Brown et al. 2018b). These models were created using several variables, including AADT (on segment, major leg of intersection, or minor leg of intersection), work zone duration, work zone length, and urban or rural classification. The models were incorporated into a spreadsheet-based work zone safety assessment tool that predicts crashes by severity and crash costs for different work zone phasing alternatives.

Rahmani et al. (2016) calibrated the crash modification factors in the HSM for the Midwest. They did a before-after study on a stratified random sample of 162 work zones based on their duration and length. The negative binomial model in this study included the variables of AADT, duration, length, urban/rural, injury, and work zone presence.

The CMF for work zone duration for all crash severities is presented as (Rahmani et al., 2016):

$$CMF_{d,all} = 1.0 + \frac{(\text{\% increase in duration } x \text{ } 1.01)}{100} \tag{4}$$

The CMF for work zone length for all crash severities is presented as (Rahmani et al., 2016):

$$CMF_{l,all} = 1.0 + \frac{(\text{\% increase in length } x \text{ } 0.62)}{100} \tag{5}$$

These equations result in lower values for the CMFs for work zone length and duration than the HSM equations previously shown in Equations 2 and 3. Dissimilarity in geography, driver population, and levels of work zone impact between California data (used in HSM) and Midwest data (used in this study) was the main reason for the differences between the CMFs.

Domenichini et al. (2017) evaluated drivers' behavior in response to nine different configurations of crossover work zones using a driving simulator. In this study, the speed behavior through a typical crossover layout was compared to the other eight alternatives which differed in some characteristics such as a sequence of speed limits, the median opening width, and the lane width. The results indicated that for all configurations the drivers' speed was always higher than the temporary posted speed limit. The study indicated that adopting a wider median opening together with higher speed limits or adopting a traffic calming measures acting on the optical density of the field of view could result in homogeneity of driving speeds.

In a study by La Torre et al. (2017), the empirical Bayes before-and-after method was applied to evaluate the effect of stationary work zones, which are in place for at least 12 hours, on freeway crashes in Italy. In addition, the CMFs were calculated for different layout configurations for four and six-lane median divided freeways. The findings of this research indicated a general increase in crash frequencies due to the installation of work zones. Moreover, the study found that all layout configurations that involved a crossover had the worst safety performance. The highest CMFs were observed for the configurations with only a partial diversion of traffic to the opposite road. Area type, the cross-section through lanes, crash type, and crash severity were the functions which were considered in the predictive model.

A research study by Ullman et al. (2018) evaluated safety impacts of end-of-queue warning systems and portable rumble strips at nighttime. The analysis was performed using field data from lane closures on a highway widening project on a 96-mile corridor of I-35 between Austin and Dallas, Texas. Bluetooth technology was utilized to evaluate the presence of queuing. The following six configurations were assessed:

- Queuing, no safety treatments
- No queuing, no safety treatments
- Queuing, portable rumble strips installed
- No queuing, portable rumble strips installed
- Queuing, end of queue warning system and portable rumble strips installed
- No queuing, end of queue warning system and portable rumble strips installed

The results showed a safety benefit of the portable rumble strips and end of queue warning system, with CMF values ranging from 0.40 to 0.89. In addition to the CMF values, the study generated SPFs to estimate number of crashes on interstate/freeway work zones.

3.2. Work Zone Crash Modification Factors

The work zone CMFs from the literature are summarized in the tables below. Each table may contain the following information:

- Crash Type – e.g. nighttime only

- Crash Severity

- CMF value

A summary table is also found in Appendix B.

Table 3.1. Increase work zone duration (Khattak and Council, 2002)

Crash Type	Crash Severity	CMF
All	All	$CMF = 1 + \frac{\%\, increase\ in\ Duration\ x\ 1.11}{100}$

Table 3.2. Increase work zone length (Khattak and Council, 2002)

Crash Type	Crash Severity	CMF
All	All	$CMF = 1 + \frac{\%\, increase\ in\ length\ in\ miles\ x\ 0.67}{100}$

Table 3.3. Countermeasure: Active work with no lane closure -Compared to no work zone (Ullman et al. 2008)

Crash Type	Crash Severity	CMF
Nighttime	Serious injury, Minor injury	1.41
All	Serious injury, Minor injury	1.19
Nighttime	Property damage only (PDO)	1.67
All	Property damage only (PDO)	1.4
Nighttime	All	1.58
All	All	1.31

Table 3.4. Countermeasure: Active work with Temporary lane closure -Compared to no work zone (Ullman et al., 2008)

Crash Type	Crash Severity	CMF
Nighttime	Serious injury, Minor injury	1.49
All	Serious injury, Minor injury	1.6
Nighttime	Property damage only (PDO)	1.81
All	Property damage only (PDO)	1.9
Nighttime	All	1.65
All	All	1.77

Table 3.5. Countermeasure: No Active work with No lane closure -Compared to no work zone (Ullman et al., 2008)

Crash Type	Crash Severity	CMF
Nighttime	Serious injury, Minor injury	1.11
All	Serious injury, Minor injury	1.11
Nighttime	Property damage only (PDO)	1.33
All	Property damage only (PDO)	1.23
Nighttime	All	1.24
All	All	1.21

Table 3.6. Countermeasure: Implement left-hand merge and downstream lane shift (Iowa Weave) (See et al., 2009)

Crash Type	Crash Severity	CMF
All	All	0.54
All	Fatal, Serious injury, Minor injury	2.24

Table 3.7. Countermeasure: Increase the outside shoulder width inside the WZ by one foot (Tarko et al., 2011)

Crash Type	Crash Severity	CMF
All	All	0.948

Table 3.8. Countermeasure: Increase the inside shoulder width inside the WZ by one foot (Tarko et al., 2011)

Crash Type	Crash Severity	CMF
All	All	0.97

Table 3.9. Countermeasure: Two-way traffic operation-crossover closure (TLTWO) (Dudek et al., 1986)

Crash Type	Crash Severity	CMF
All	All	1

Table 3.10. Countermeasure: Implement mobile automated speed enforcement system (highly enforced sites) (Gayah and Donnell, 2014)

Crash Type	Crash Severity	CMF
All	All	0.83

Table 3.11. Work zone configuration for four-lane median divided freeway (La Torre et al., 2017)

Description	FI	PDO
Closure of the driving lane with traffic diverted to the passing lane	1.62	1.62
Closure of the passing lane with traffic diverted to the driving lane	1.08	1.06
Closure of the shoulder	1.27	1.24
Closure of the driving lane with traffic diverted to the passing lane; closure of the passing lane and total diversion of traffic to the opposite road through a single-lane crossover	2.08	2.42
Closure of the passing lane with traffic diverted to the slow and to the shoulders	1.64	2.18
Closure of the driving lane with traffic diverted to the passing lane; partial diversion of traffic to the opposite road through a single-lane crossover (the driver is allowed to choose whether to stay in the passing lane or move to the opposite road	3.11	3.38

Table 3.12. Work zone configuration for six-lane median divided freeway (La Torre et al., 2017)

Description	FI	PDO
Closure of the driving lane with traffic diverted to the middle lane	1.03	1.89
Closure of the shoulder	1.00	1.34
Closure of the passing lane with traffic diverted to the middle lane	1.49	1.70
Closure of the driving lane with traffic diverted to the middle lane; closure of the middle lane with traffic diverted to the passing lane	1.91	1.68
Closure of the passing lane with traffic diverted to the middle lane; closure of the middle lane with traffic diverted to the driving lane	1.90	2.05
Closure of the driving lane with traffic diverted to the middle lane; closure of the middle lane with traffic diverted to the passing lane; closure of the passing lane and total diversion of traffic to the opposite road through a single-lane crossover	2.15	3.24
Closure of the overtaking with traffic diverted to the middle lane; closure of the middle lane and partial diversion of traffic to the driving lane and to the opposite road through a single-lane crossover (the driver is allowed to choose whether to move to the driving lane or move to the opposite road	2.80	3.21
Closure of the overtaking with traffic diverted to the middle lane; closure of the middle lane with traffic diverted to the driving lane and to the shoulder	0.84	1.60
Closure of the passing lane with traffic diverted to the middle lane, to the driving lane, and to the shoulder	1.51	1.26
Closure of the driving lane with traffic diverted to the middle lane; closure of the road and total diversion of traffic to the opposite side through a dual-lane crossover	1.25	2.50

Table 3.13. Increase work zone duration (Rahmani et al., 2016)

Crash Type	Crash Severity	CMF
All	All	$CMF = 1 + \frac{\%\, increase\ in\ Duration\ x\ 1.01}{100}$

Table 3.14. Increase work zone length (Rahmani et al., 2016)

Crash Type	Crash Severity	CMF
All	All	$CMF = 1 + \frac{\%\ increase\ in\ Length\ x\ 0.62}{100}$

Table 3.15. End of queue warning system (nighttime)* (Ullman et al., 2016)

Crash Type	Crash Severity	CMF
All	All	0.56

* 7 pm to 7 am

Table 3.16. Portable rumble strips - no queue (nighttime)* (Ullman et al., 2018)

Crash Type	Crash Severity	CMF
All	All	0.89

* 7 pm to 7 am

Table 3.17. Portable rumble strips - queued (nighttime)* (Ullman et al., 2018)

Crash Type	Crash Severity	CMF
All	All	0.40

* 7 pm to 7 am

Table 3.18. End of queue warning system and portable rumble strips - no queue (nighttime)* (Ullman et al., 2018)

Crash Type	Crash Severity	CMF
All	All	0.72

* 7 pm to 7 am

Table 3.19. End of queue warning system and portable rumble strips - queued (nighttime)* (Ullman et al., 2018)

Crash Type	Crash Severity	CMF
All	All	0.47

* 7 pm to 7 am

3.3. Summary of Literature Review

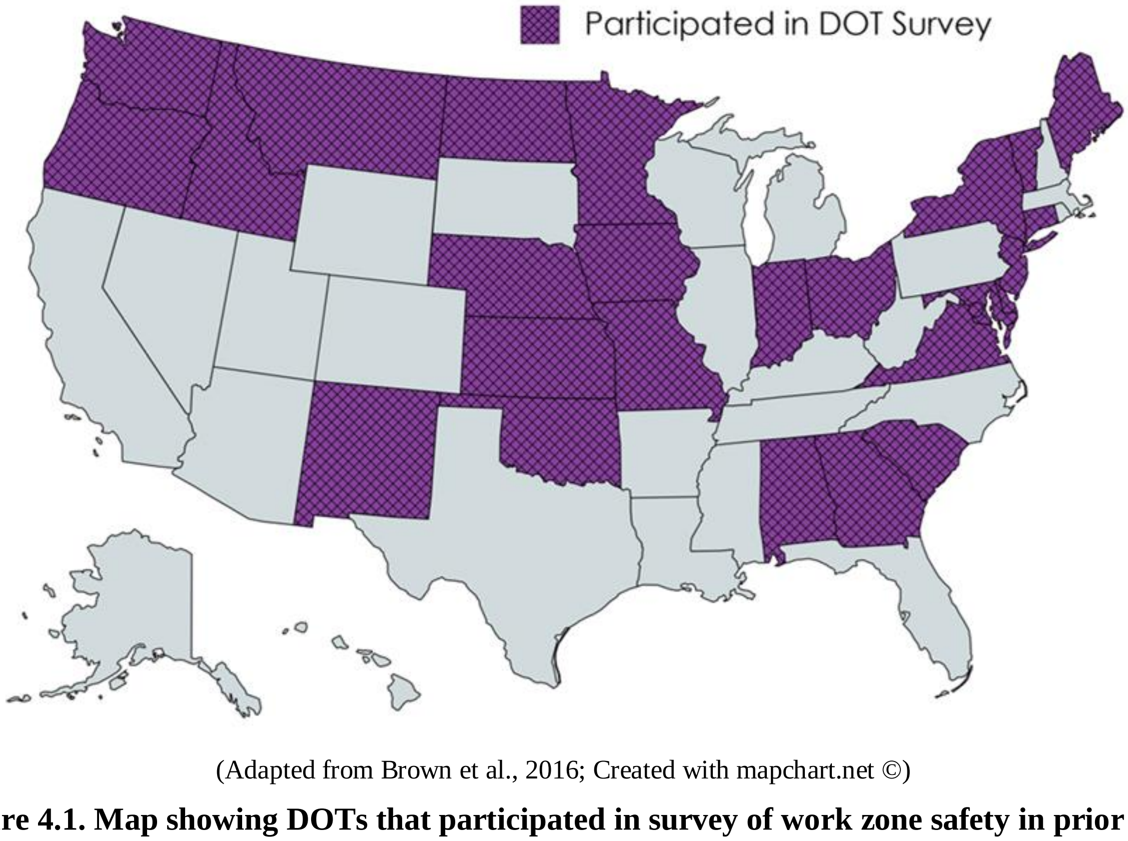
In general, the results from the literature review demonstrate the need for additional work zone safety research and work zone CMFs. The CMF Clearinghouse only contains a small number of work zone CMFs, and there have only been a few recent work zone safety studies. Many of the previous work zone safety studies did not directly generate CMFs. The most recent study by La Torre et al. (2017) that generated work zone CMFs analyzed data from Italy, and the transferability of the CMFs generated to the United States is questionable. There is also a need for greater awareness of existing work zone CMFs by practitioners. The generation of new work zone CMFs and increased awareness of existing work zone CMFs will give practitioners more tools to assess work zone countermeasures and evaluate work zone safety.

4. EXISTING AGENCY PRACTICES REGARDING WORK ZONE SAFETY AND WORK ZONE CMFS

This chapter provides an overview of existing agency practices regarding work zone safety and work zone CMFs. The information presented in this chapter is based primarily on two sources: a prior research study to develop a work zone safety assessment tool and phone interviews conducted with DOTs and one local agency.

4.1. Prior Study for Work Zone Safety Assessment Tool

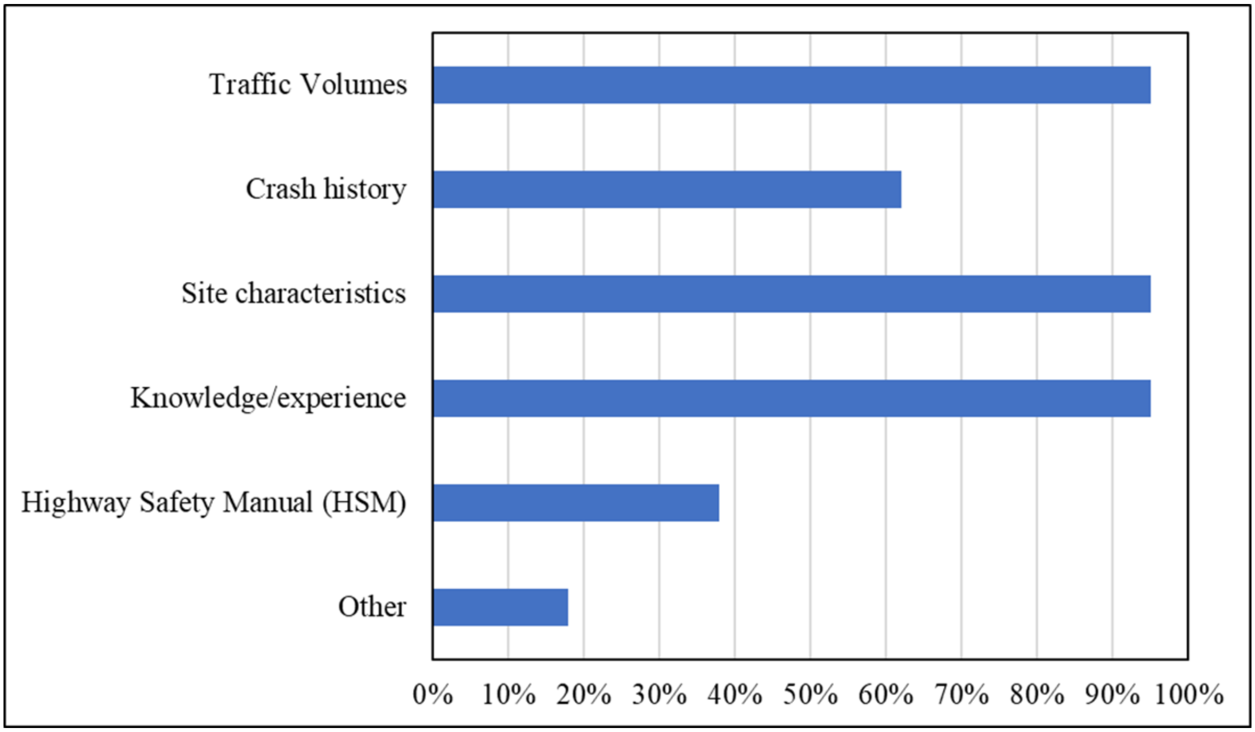
A prior study to develop a work zone safety assessment tool, funded by a FHWA pooled fund known as the Smart Work Zone Deployment Initiative (or SWZDI), included a survey of DOTs and contractors regarding their perceptions of work zone safety and DOT practices (Brown et al., 2016). Two versions of the survey were administered; one to DOTs and FHWA representatives and another to contractors. The survey respondents included 27 representatives from state DOTs, 2 representatives from FHWA, and 7 representative contractors. Figure 4.1 shows a U.S. map with states that participated in the DOT survey. Example results from the survey are presented in the following paragraphs, with the focus mostly on the DOT survey.



(Adapted from Brown et al., 2016; Created with mapchart.net ©)

Figure 4.1. Map showing DOTs that participated in survey of work zone safety in prior study

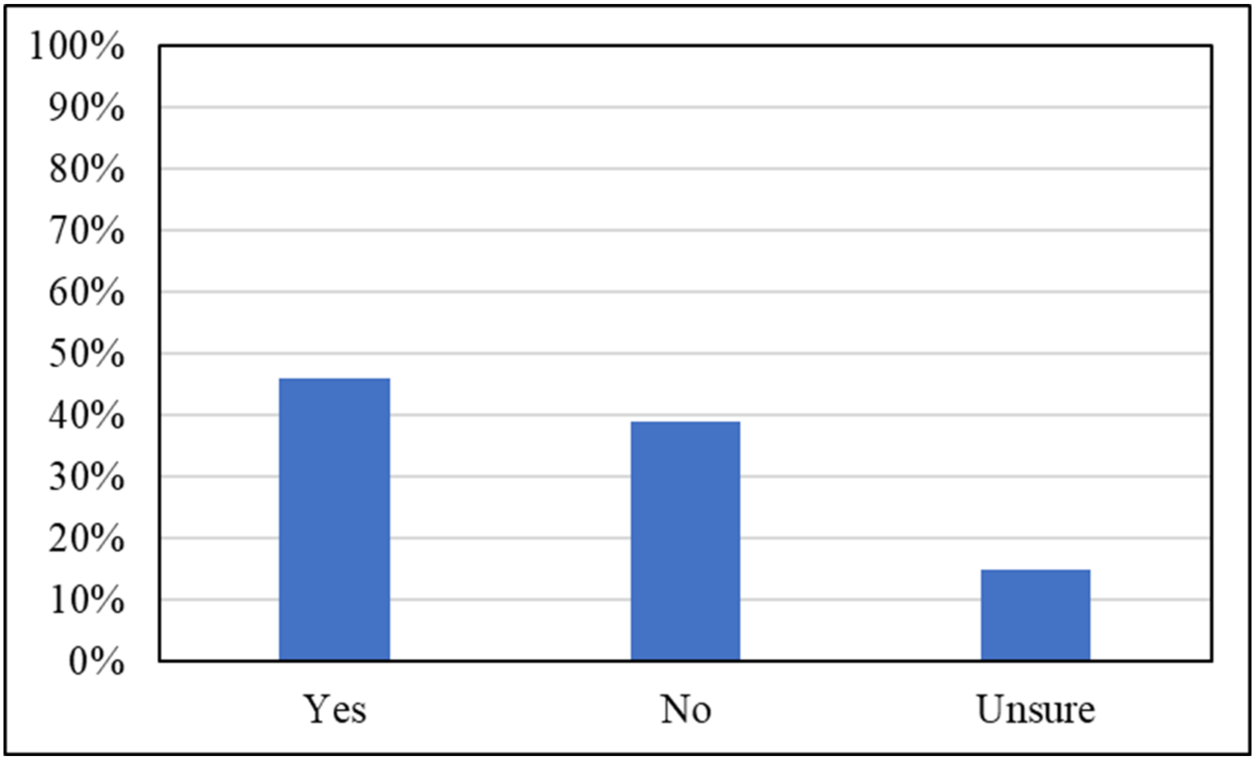
Respondents were asked about factors and resources used in work zone planning and design, and the results from the DOT survey are shown in Figure 4.2. The figure shows DOT respondents most often considered traffic volumes, site characteristics, and their own knowledge and experience when accounting for safety in work zone planning and design. Another notable finding from this survey is that the Highway Safety Manual does not seem to be applied often to work zone safety analyses.



(Adapted from Brown et al., 2016)

Figure 4.2. Factors and resources used by DOTs in considering safety in work zone planning and design

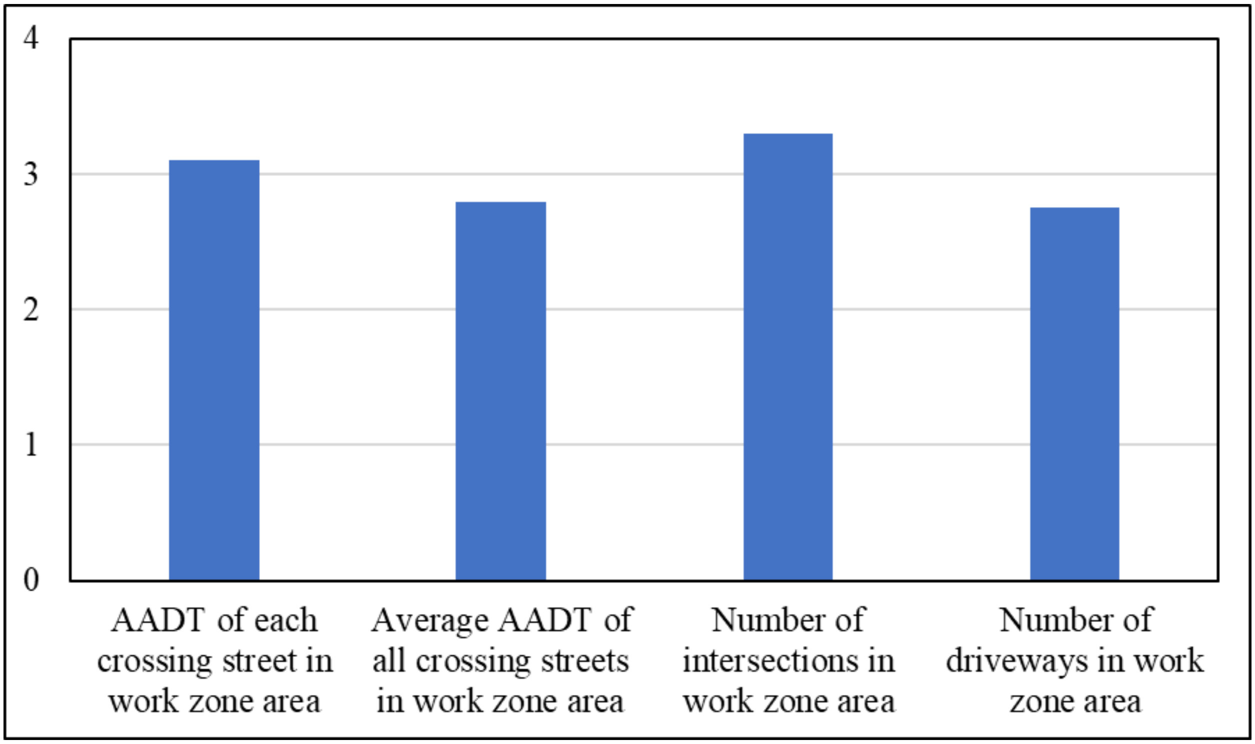
Respondents were asked if they generally believed that the presence of work zones increases the crash frequency. As Figure 4.3 shows, 43% of DOT respondents believed work zones increase the frequency of crashes, 39% did not believe that work zones increase crash frequency, and 18% were unsure. The results clearly indicate that there is no uniform consensus among DOT practitioners regarding the effect of work zone presence on crash frequency.



(Adapted from Brown et al., 2016)

Figure 4.3. DOT survey responses for effects of work zones on crash frequency

In addition to asking about general perceptions regarding the impacts of work zones on safety, respondents were also asked about the extent to which they believed additional factors impacted safety of work zones on facilities with at-grade intersections. Figure 4.4 shows the averaged DOT survey results on a scale of 1 to 4, with 1 being not important and 4 being highly important. The results show the Number of Intersections in the Work Zone Area had the highest score at 3.3, followed by the AADT of Each Crossing Street at 3.1. The lowest score at 2.8 was shared by the Average AADT of all Crossing Streets and the Number of Driveways in the Work Zone Area. Overall, the results show that practitioners believe that all four factors are important to safety of work zones, although the number of intersections in the work zone area was reported as the most important factor contributing to safety.



(Adapted from Brown et al., 2016)

Figure 4.4. DOT survey responses for effects of additional factors on safety of work zones with at-grade intersections

An additional survey question inquired about the extent to which participants believed that various factors, such as AADT, lane closure, etc., impacted work zone safety on freeways. Table 4.1 shows both the DOT and contractor results. Again, the results are averaged on a scale of 1 to 4, with 1 being not important and 4 being highly important. The answers provided by both groups demonstrate that AADT was regarded as the most important factor affecting work zone safety on freeways, with DOT mean score of 3.6 and contractor mean score of 3.4. The following additional factors were rated as 3 or higher by both groups: the Existence of a Lane Closure, Work Zone Warning Signs, Moving Work Zones, Urban vs. Rural Setting, Speed Decrease, and Lane Shift/Crossover. Both DOTs and contractors rated the Cost per Mile per Duration as having the lowest impact on work zone safety on freeways with a score of 2 and under. Generally, the results between the DOTs and contractors are consistent. However, DOTs felt that Work Zone Duration, Number of On-Off Ramps, and Work Zone Length had more impact than contractors, while contractors believed that Terrain and Contract Incentives or Disincentives had a greater impact.

Table 4.1. Respondent beliefs on factors affecting work zone safety on freeways (adapted from Brown et al., 2016)

Answer Options	Rating Average (DOT)	Rating Average (Contractors)
AADT	3.58	3.38
Lane closure	3.23	3.00
Work zone warning signs	3.19	3.13
Moving WZ	3.15	3.25
Duration	3.12	2.50
Number of on-off ramps	3.08	2.75
Urban versus rural	3.04	3.13
Speed decrease	3.04	3.13
Lane shift/crossover	3.00	3.00
Length	2.85	2.25
Work on shoulder	2.58	2.63
Terrain (flat, rolling)	2.54	2.75
Incentive/disincentives, cost + time	2.19	2.50
Cost per mile per duration	1.96	2.00

4.2. Agency Interviews

In addition to the literature review conducted in the process of updating this guide, phone interviews were conducted with DOTs and one local agency to determine the current state of the practice regarding work zone safety and the use of work zone CMFs. The interviewees included: participants from a prior survey on work zone safety as part of a FHWA pooled fund project to develop a work zone safety assessment tool (Brown et al., 2016), and members of a NCHRP panel for a project to develop implementation materials for the second edition of the Highway Safety Manual. The phone interviews were conducted with the following agencies:

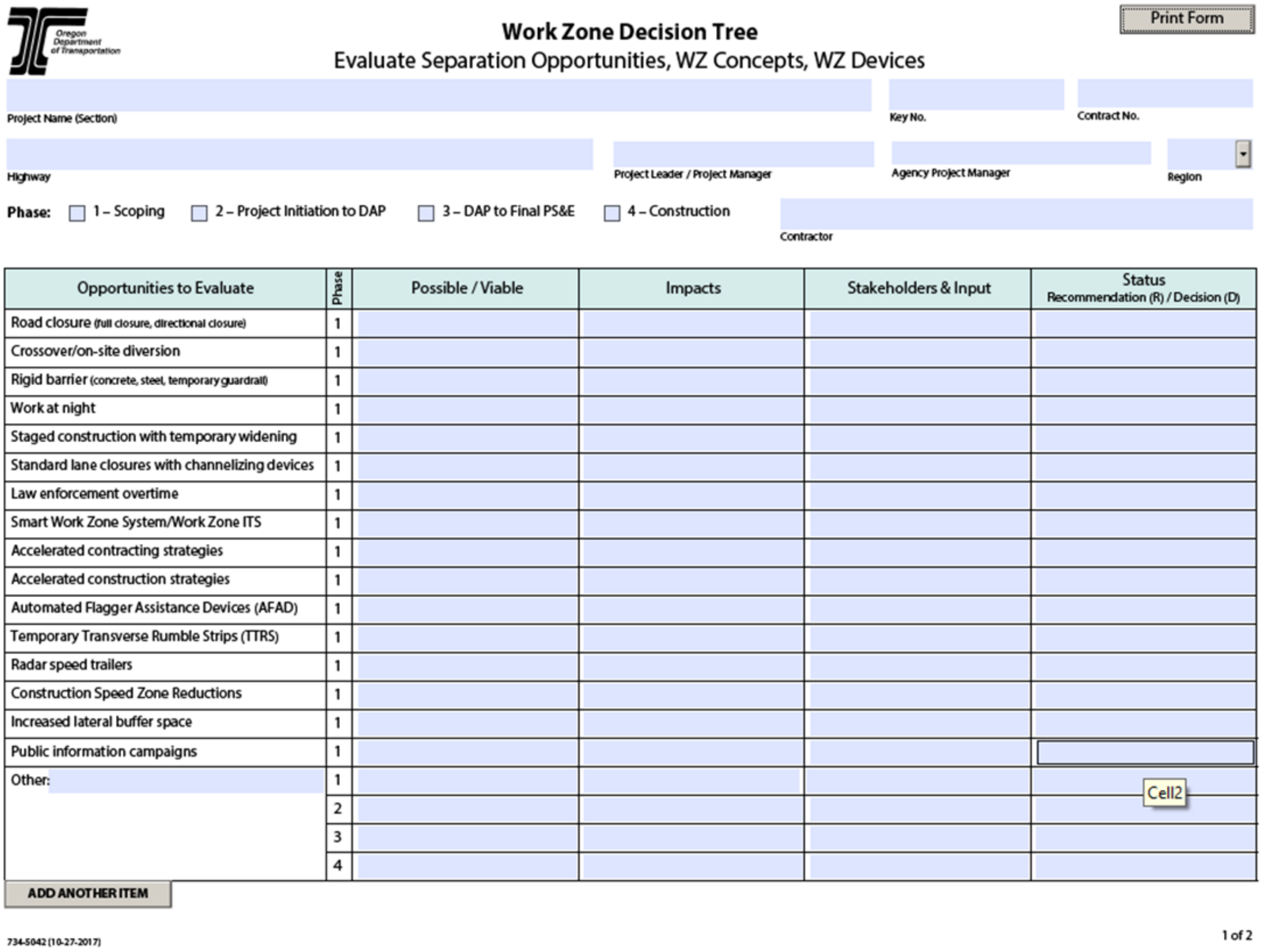
- Arizona DOT
- Delaware DOT
- District of Columbia DOT
- Florida DOT
- Iowa DOT
- Kansas DOT

- Massachusetts DOT
- Minnesota DOT
- Missouri DOT
- Ohio DOT
- Oregon DOT
- Texas DOT
- Virginia DOT
- Wisconsin DOT
- Washington County, Minnesota

Agencies were asked about many aspects of work zone safety, including their current practices for evaluating work zone safety, their use of work zone CMFs, their wish list for new work zone CMFs, and challenges that they experience in trying to keep work zones safe.

4.2.1. Current Practices Regarding Work Zone Safety

The agencies indicated they use many different approaches to evaluate work zone safety. Many agencies do not have a formal process, but instead rely on engineering judgment and look at projects on a case-by-case basis. Crash history often drives future decisions regarding work zone configurations and potential countermeasures. For example, if a work zone location has a large number of crashes, an agency may investigate and make changes to future work zones. Some states try to mitigate congestion impacts of work zones because they have found that many of their work zone crashes are related to congestion. Some states do have a more formalized process for evaluating work zone phasing alternatives. For example, Oregon uses a decision tree form (Figure 4.5) to document which work zone phasing options were explored. The form focuses on positive protection and incorporates considerations for pedestrians.



Work Zone Decision Tree
Evaluate Separation Opportunities, WZ Concepts, WZ Devices

Project Name (Section)
Key No.
Contract No.
Highway
Project Leader / Project Manager
Agency Project Manager
Region

Phase: ☐ 1 – Scoping ☐ 2 – Project Initiation to DAP ☐ 3 – DAP to Final PS&E ☐ 4 – Construction

Contractor

Opportunities to Evaluate	Phase	Possible / Viable	Impacts	Stakeholders & Input	Status Recommendation (R) / Decision (D)
Road closure (full closure, directional closure)	1				
Crossover/on-site diversion	1				
Rigid barrier (concrete, steel, temporary guardrail)	1				
Work at night	1				
Staged construction with temporary widening	1				
Standard lane closures with channelizing devices	1				
Law enforcement overtime	1				
Smart Work Zone System/Work Zone ITS	1				
Accelerated contracting strategies	1				
Accelerated construction strategies	1				
Automated Flagger Assistance Devices (AFAD)	1				
Temporary Transverse Rumble Strips (TTRS)	1				
Radar speed trailers	1				
Construction Speed Zone Reductions	1				
Increased lateral buffer space	1				
Public information campaigns	1				
Other:	1				
	2				
	3				
	4				

734-5042 (10-27-2017)

1 of 2

(Adapted from Oregon DOT, 2017)

Figure 4.5. Oregon Decision Tree Form (Oregon DOT, 2017)

Ohio utilizes a maintenance of traffic (MOT) Alternatives Analysis Form in the planning stage to evaluate different work zone scenarios. The form is used to look at different options such as partial width closure versus a crossover, and incorporates factors such as decision sight distance, lane width, and distance to barrier. An excerpt from the form is shown in Table 4.2.

Table 4.2. Excerpt from Ohio MOT Alternatives Analysis Form (Ohio DOT, 2004)

	Work Zone Alternatives	
Constraint	Part Width Construction	Crossover Construction
Ability to meet Work Zone Policy		
Ability to maintain all accesses		
Ability to provide required on-ramp merge decision sight distance		
Right-of-way impacts		
Environmental impacts		
Final bridge widths		
Significant impacts for construction duration and/or construction costs		
Significant impacts to earthwork, retaining walls, pier clearances, profile differences; etc.		
Ability to maintain existing drainage and lighting systems		
Constructability and construction equipment access		
Location of crossovers (e.g., Can crossovers be located near the project?)		

The District of Columbia utilizes a customized tool to predict traffic impacts when project plans are 65 percent completed. Some states such as Missouri and Kansas are considering using a work zone safety assessment tool that was completed in a prior FHWA pooled fund project (Brown et al., 2016). The spreadsheet tool predicts crashes and crash costs for work zones on freeways, rural two-lane highways, and expressways based on input variables such as length, AADT, number of intersections, and number of ramps.

Agencies indicated they also employ other strategies to help keep work zones safe. For example, Arizona requires an emergency vehicle access plan in the contract special provisions. Virginia recently implemented a lane closure system that records the days and times for all lane closures.

Iowa would like to develop a lane closure approval process and a work zone app to document lane closures. Virginia is developing specifications for nighttime lighting. Some agencies include construction audits for the review of work zones. Agencies have implemented various work zone safety countermeasures including the use of TMAs at lane closures, smart work zones to notify drivers of delays and alternate routes, temporary rumble strips, speed enforcement, chevrons, movable barriers, and end of queue warning systems.

4.2.2. Use of Work Zone CMFs

The agencies were also asked about their practices regarding the use of work zone CMFs. Although some of the agencies have used non-work zone CMFs, all of the agencies indicated that they have not used work zone CMFs. Some of reasons provided for not using work zone CMFs are as follows:

- Lack of availability of CMFs for work zones
- Concerns about CMF reliability and transferability to other jurisdictions and traffic control setups
- Lack of guidance regarding use of work zone CMFs
- Unsure of need for work zone CMFs
- Lack of time or staffing
- Unsure of how to apply the work zone CMFs
- Find using CMFs to be overwhelming based on their experience with non-work zone CMFs
- Believe that the use of CMFs is hard to sell to public.

Some agencies expressed an interest in potentially using work zone CMFs in the future. For example, Ohio indicated that the work zone CMFs could be incorporated into its MOT Alternatives Analysis Form in the future. The District of Columbia DOT is in the process of a reorganization and may look at work zone CMFs once the reorganization is completed. Oregon currently uses qualitative analyses for work zone safety, but would like to apply a quantitative approach.

4.2.3. Wish List of Work Zone CMFs

The agencies were asked about which work zone CMFs they would like to see developed in the future. The most common response concerned work zone ITS solutions, such as end of queue detection systems and systems to provide travelers with work zone information. Several agencies were interested in the end of queue detection systems because many of their work zone crashes are related to congestion. Other countermeasures for which agencies are interested in seeing work zone CMFs developed are as follows:

- Weaving sections
- Temporary raised rumble strips
- Divided highway crossover versus lane closures
- Lane width and shoulder width
- 3, 2, or 1 cone procedures for flagger operations
- Steel barrier versus concrete barrier
- Shy distance to barrier
- Use of tubular marker versus drums for lane closure
- Road closure with detour versus staged construction (1 lane closed)
- Early lane merge, late lane merge, zipper merge
- Temporary portable signal versus 24-hour flagging
- Presence of law enforcement
- Automated speed enforcement
- Work zone intrusion alarms
- Traffic sensor message board to say when construction vehicle entering or leaving site
- Wrong way driving prevention.

4.2.4. Challenges to Work Zone Safety

Agencies were also asked to identify some of the challenges that they face in keeping work zones safe. Some of the challenges identified are as follows:

- Keeping motorists informed
- Older drivers
- Distracted driving
- Need to bolster driver expectancy of work zone through communication of information
- Construction phasing often gets changed from the design plans in the field
- Ensuring that work zones meet specifications
- Variability in the work zone on a day to day basis
- Sloppy work zones
- Contractors move things around in the field but do not put them back
- Need to keep contractors and inspectors accountable
- Variability in work zone design within the agency
- Need for training and education for contractors and the agency
- Providing for the safe ingress and egress of vehicles in and out of the work zone
- Nighttime work zones (ensuring visibility of work zone at night)
- Work zone intrusions
- Need for positive protection
- Difficulty in maintaining local access during reconstruction
- Construction worker safety

- Speed management
- Getting data for work zone analysis
- Difficulty in linking work zones to crashes
- Reliance on crash report to determine if a crash was work zone related

4.3. Other Practitioner Feedback

Additional feedback from engineering practitioners regarding work zone challenges and the need for additional CMFs was obtained through a poll adminsitered during a presentation at the 2018 National Work Zone Management Conference. As Figure 4.4 shows, almost 80% of poll participants agreed that distracted driving posed the greatest challenge to work zone safety.

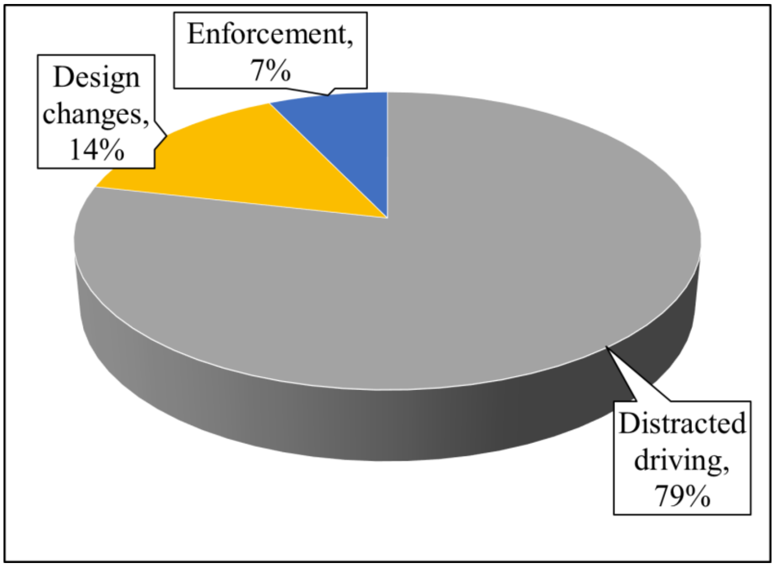


Figure 4.6. Practitioner responses for greatest challenges to work zone safety from 2018 National Work Zone Management Conference

When asked about general categories for new work zone CMFs to be developed, participants indicated that work zone CMFs were most needed for work zone configurations (61%) and positive protection (31%) (Figure 4.5).

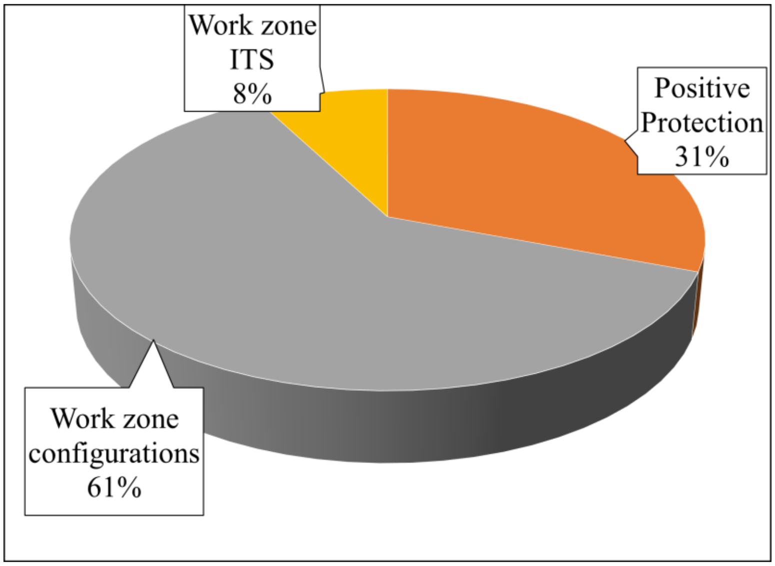


Figure 4.7. Practitioner responses for greatest work zone CMF needs from 2018 National Work Zone Management Conference

4.4. Summary of Agency Practices for Work Zone Safety

In general, DOTs rely on engineering judgment in evaluating work zone safety. The results from the interviews demonstrate the need for practitioner guidance regarding work zone CMFs and the need for additional work zone CMFs to be generated. A perceived lack of existing guidance was one of the reasons cited by the interviewees for not using work zone CMFs. The development of additional guidance and training materials for the use of work zone CMFs will facilitate the use of work zone CMFs to evaluate work zone countermeasures. Many states are currently using a qualitative and reactive approach to work zone safety. The increased use of work zone CMFs to evaluate countermeasures can help to develop a more quantitative and proactive approach to work zone safety. The interview results also support the need to develop additional work zone CMFs for a wide range of work zone countermeasures.

5. PROCEDURE FOR EVALUATING WORK ZONE COUNTERMEASURES USING EXISTING CMFS

The existing CMFs can be used to evaluate the safety effectiveness of work zone **countermeasures**. The steps for this procedure are shown in Figure 5.1. 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.

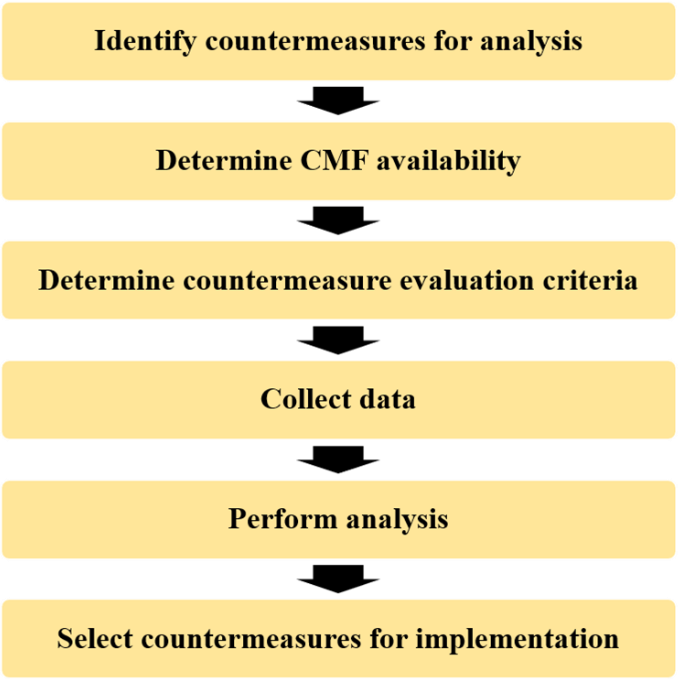


Figure 5.1. Procedure for evaluation of work zone countermeasures using existing CMFs

5.1. 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.

5.2. Determine CMF Availability

The availability of existing CMFs for the countermeasures under consideration is investigated next. As described previously in Chapter 2, there are CMFs for work zone length and duration in the HSM and a limited selection of other work zone CMFs in 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.

5.3. 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.

5.4. Collect Data

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.

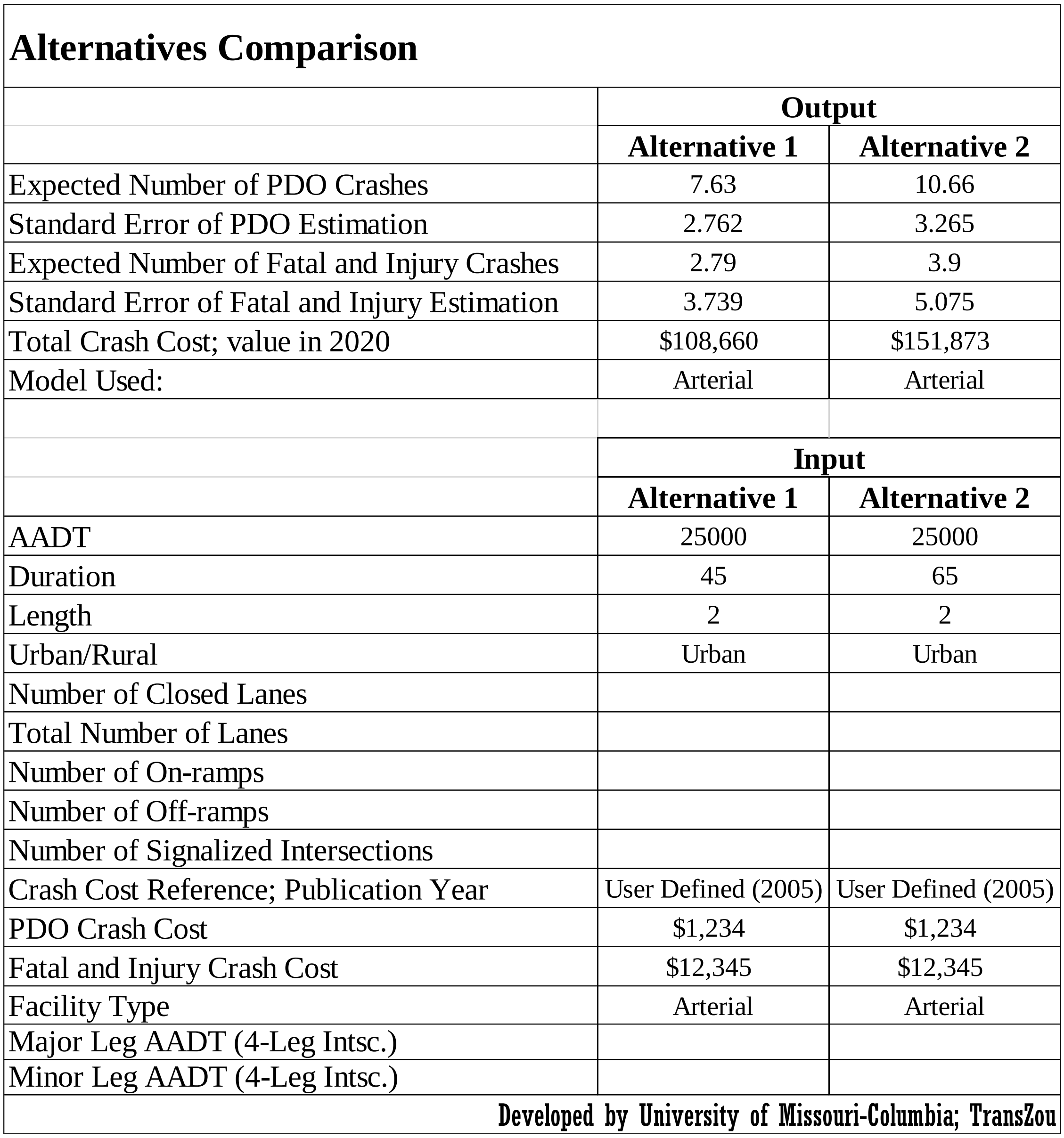
5.5. Perform Analysis

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.

As part of the analysis, the expected change in crashes associated with the work zone countermeasure needs to be calculated. The expected number of crashes with the countermeasure is found by multiplying the expected number of crashes without the countermeasure by the CMF. The expected change in the number of crashes is the number of crashes with the countermeasure minus the expected number of crashes without the countermeasure.

There are several ways to calculate the expected number of work zone crashes without the countermeasure (i.e. a baseline estimate). These include engineering judgment, a work zone safety assessment tool, and other work zone safety models in the literature such as models for work zone crashes on 4-lane and 6-lane freeways (Ullman et al., 2018). CMFs that account for work zone presence may also be used.

The work zone safety assessment tool is a spreadsheet tool that was developed during two research studies sponsored by the Smart Work Zone Deployment Initiative (SWZDI), a FHWA pooled fund study (Brown et al., 2016; Brown et al., 2018b). The tool calculates the expected number of work zone crashes by severity and crash costs for different work zone phasing alternatives. The tool covers work zones for a wide variety of facility types, including: arterials, expressways, ramps, rural two-lane highways, signalized intersections, unsignalized intersections, and multi-lane highways. A screenshot showing example output (along with input data echo) for two arterial alternatives is shown in Figure 5.2.



Alternatives Comparison

	Output	
	Alternative 1	**Alternative 2**
Expected Number of PDO Crashes	7.63	10.66
Standard Error of PDO Estimation	2.762	3.265
Expected Number of Fatal and Injury Crashes	2.79	3.9
Standard Error of Fatal and Injury Estimation	3.739	5.075
Total Crash Cost; value in 2020	$108,660	$151,873
Model Used:	Arterial	Arterial
	Input	
	Alternative 1	**Alternative 2**
AADT	25000	25000
Duration	45	65
Length	2	2
Urban/Rural	Urban	Urban
Number of Closed Lanes		
Total Number of Lanes		
Number of On-ramps		
Number of Off-ramps		
Number of Signalized Intersections		
Crash Cost Reference; Publication Year	User Defined (2005)	User Defined (2005)
PDO Crash Cost	$1,234	$1,234
Fatal and Injury Crash Cost	$12,345	$12,345
Facility Type	Arterial	Arterial
Major Leg AADT (4-Leg Intsc.)		
Minor Leg AADT (4-Leg Intsc.)		

Developed by University of Missouri-Columbia; TransZou

(Adapted from Brown et al., 2018b)

Figure 5.2. Example output from work zone safety assessment tool

The tool collects input data such as Annual Average Daily Traffic (AADT), work zone duration, work zone length, number of closed lanes, and unit crash costs. Unit crash costs by severity from the Highway Safety Manual may be used, or the user may define their own crash costs. The output summarizes the expected number of crashes by severity (Property Damage Only, Fatal and Injury) and total crash costs for each alternative being studied. The tool is available for download at:

https://swzdi.intrans.iastate.edu/research/completed/extension-of-safety-assessment-tool-for-construction-work-zone-phasing-plans/.

5.6. 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.

5.7. Example Applications of Work Zone CMFs

Two examples of applying work zone CMFs are described in the following sections. The first example examines shoulder widening while the second example concerns the use of portable rumble strips.

5.7.1. Example 1: Work Zone Outside Shoulder Width

In this example, a highway agency would like to assess the benefits of increasing the work zone outside shoulder width (Figure 5.3) by 1 ft on a two-mile section of urban interstate.

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

Figure 5.3. Freeway outside shoulder in work zone

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, 2020b) indicates that a CMF is available for this countermeasure. The CMF value is 0.95, indicating a 5 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 1.5.

Step 4: Collect Data

The estimated cost of the improvement is $3,000 per mile, and the expected number of total crashes in this work zone without the countermeasure is eight crashes. The anticipated cost of each crash is $86,000.

Step 5: Perform Analysis

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

The expected number of crashes with the countermeasure is 0.95 * 8 = 7.60 crashes.

The change in expected number of crashes is 7.60 – 8 = -0.40 crashes (decrease).

The estimated crash cost savings is 0.40 crashes * $86,000 per crash = $34,400.

The benefit-cost ratio is calculated as $34,400/$6,000 = 5.73.

Step 6: Select Countermeasures for Implementation

In this example, the agency chooses to implement the countermeasure because the benefit-cost ratio is 5.73 which is greater than 1.5.

5.7.2. Example 2: Portable Rumble Strips

In this example, a highway agency would like to investigate the use of portable rumble strips (Figure 5.4) in a long-term nighttime work zone without queuing.

(Source: https://safety.fhwa.dot.gov/newsletter/safetycompass/2013/spring/)

Figure 5.4. Portable rumble strips

Step 1: Identify Countermeasures for Analysis

The countermeasure to be investigated involves implementation of portable rumble strips with no queue during nighttime.

Step 2: Determine CMF Availability

A CMF value of 0.89 for this countermeasure is available in a research study by Ullman et al (2018). This CMF value may also be found in Appendix B.

Step 3: Determine Countermeasure Evaluation Criteria

The agency has determined that the countermeasure will be implemented if the benefit-cost ratio is greater than 2.0.

Step 4: Collect Data

The estimated cost of the improvement is $25,000, and the expected number of total crashes in this work zone without the countermeasure is four crashes. This long-term work zone will be in place for more than one year. The anticipated cost of each crash is $86,000.

Step 5: Perform Analysis

The total estimated cost of the improvement is $25,000.

The expected number of crashes with the countermeasure is 0.89 * 4 = 3.56 crashes.

The change in expected number of crashes is 3.56 – 4 = -0.44 crashes (decrease).

The estimated crash cost savings is 0.44 crashes * $86,000 per crash = $37,840.

The benefit-cost ratio is calculated as $37,840/$25,000 = 1.51.

Step 6: Select Countermeasures for Implementation

In this example, the agency chooses not to implement the countermeasure because the benefit-cost ratio is 1.51 which is less than 2.0.

6. 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 6.1. These steps are described in further detail in the following sections.

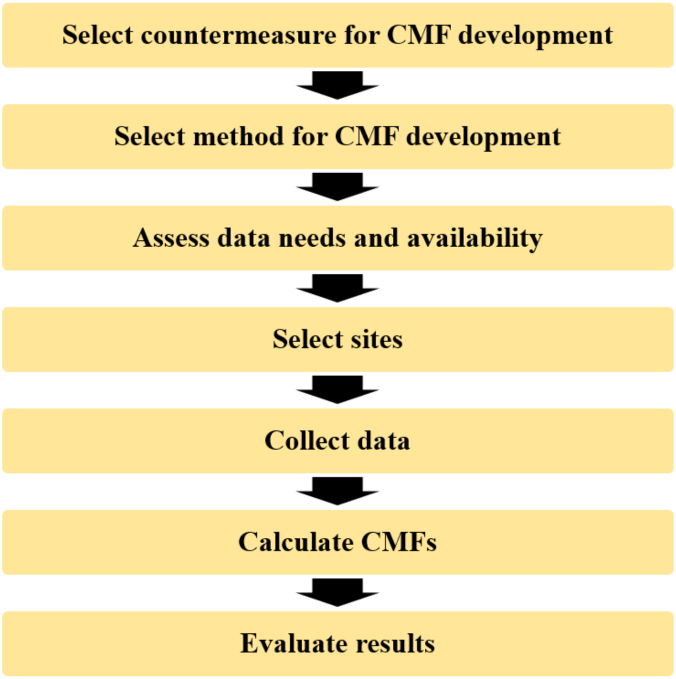


Figure 6.1. Procedure for development of work zone CMFs

6.1. 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 5.1.

6.2. 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. Other methods for generating CMFs include **simple before-after study**, **before-after study with comparison group**, **Full Bayes**, **case control**, **cohort**, **meta-analysis**, **expert panel**, and **surrogate safety measures**.

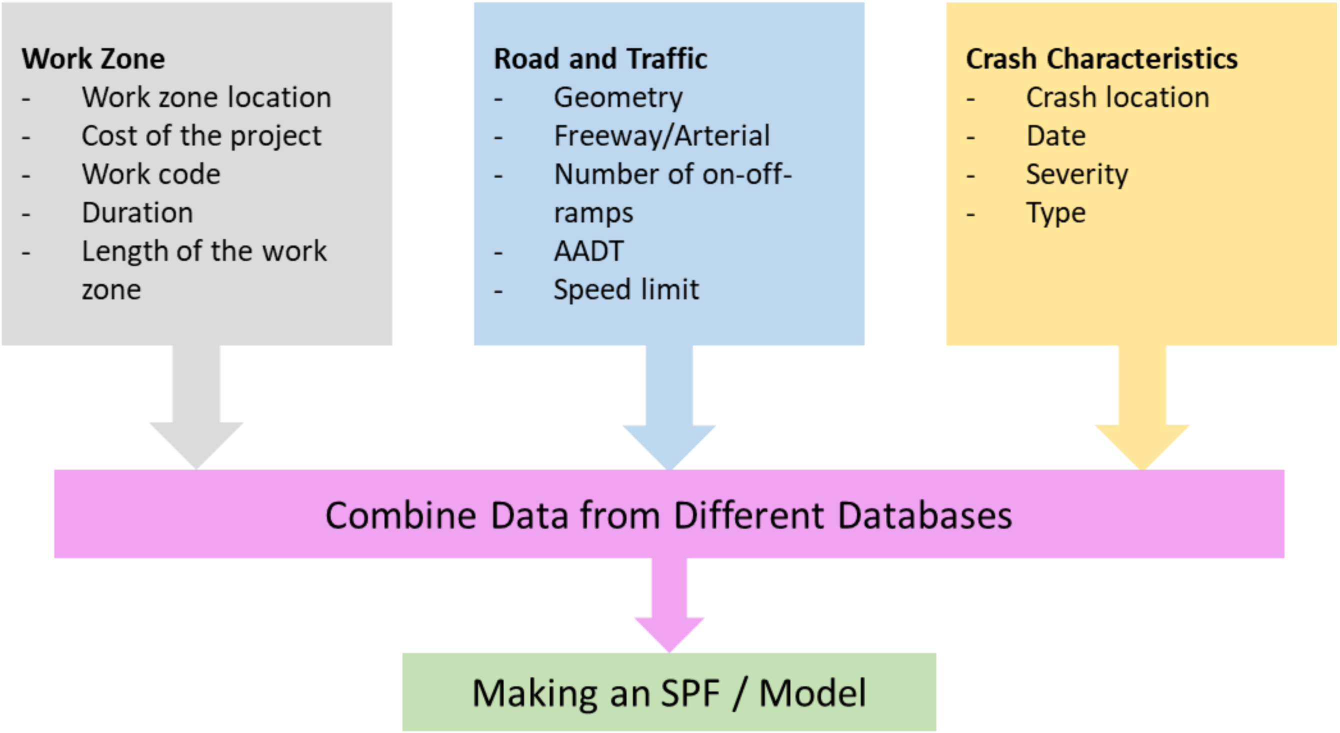
The best method for use in a given situation depends on many factors, such as the availability of data during the before and after periods and the availability of control sites. One instance where a cross-sectional study is recommended is when there are few treatment sites. A flow chart in the FHWA CMF Guide (Gross et al., 2010) shows the process used to select the appropriate method for a specific study.

There are some special considerations for developing CMFs for work zones. First, obtaining a sufficient sample size of crashes for work zone CMF studies may be challenging because crashes are rare events, and work zones typically have short lengths and durations. The availability of sufficient sites for a before and after study may also be limited due to the short duration and length of work zones. Thus, a cross sectional method using linear regression may be more appropriate for work zone CMF development. Surrogate safety measures may be useful in cases where an innovative work zone countermeasure is being developed and there is not enough crash history to perform an analysis using crash data. However, use of the surrogate method requires the analyst to obtain a model that relates the observed change in the surrogate measure before and after the treatment with an expected change in crash frequency, which can be a major challenge. Finally, there is a lack of existing work zone CMFs which makes the use of Meta-Analysis or Expert Panel methods, which evaluate findings of multiple previous studies, less likely for work zone CMF studies. The different CMF development techniques involve various tradeoffs, and agencies are encouraged to pursue the technique that best meets their needs and resources.

6.3. 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. As Figure 6.2 shows, these can include work zone data (e.g. work zone location, cost, work zone duration, and work zone length), road and traffic data (e.g. geometry, traffic counts, speed limit), and crash data (e.g. crash location, date, severity, type).

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



(Brown et al., 2016)

Figure 6.2. Data fusion process for work zone CMF studies

There are several challenges related to obtaining the data necessary for developing work zone CMFs. These challenges are separated into four categories:

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. A manual review of more than 12,000 freeway interchange crash reports in Missouri found that 69% of the crashes had errors regarding the crash location (Sun et al. 2017). In a research study from Bai et al. (2006), 157 reports for fatal crashes in work zones from 1992 to 2004 were reviewed to compile data in a spreadsheet format (one row per crash) suitable for further analysis by statistical software. The crash data were analyzed to identify crash characteristics, risk factors, and safety improvements for work zones.

6.4. 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).

6.5. Collect Data

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.

6.6. 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.

6.7. 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 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. Considerations for the documentation of work zone CMFs are summarized in Appendix A, which also includes factors to consider when developing a work zone CMF study and tips for building a high-quality work zone CMF. The calculated CMF can then be used to evaluate countermeasures using the procedures described in Section 3 of this implementation guide.

Developed CMFs should be reasonable in their effects on crashes

6.8. 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.

6.8.1. 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: Collect Data

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 6.1.

Table 6.1. 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 (4), (5), and (6).

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

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

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

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 (4), (5), and (6) 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.

6.8.2. 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: Collect Data

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, 2020b).

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.

7. 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. The use of work zone CMFs can help to enhance work zone safety by providing practitioners with a tool to quantitatively evaluate the benefits of work zone safety countermeasures for use in data-driven decision-making.

8. REFERENCES

AASHTO. 2014. *Highway Safety Manual*. First Edition with 2014 Supplement. Washington, D.C.

Akepati, S. R., and Dissanayake, S. 2011. "Characteristics of the Work Zone Crashes." In *Transportation and Development Institute Congress 2011: Integrated Transportation and Development for a Better Tomorrow*, pp. 1286-1295.

American Road and Transportation Builders Association (ARTBA). 2020a. "National Estimates of Total and Injury Work Zone Crashes." <https://www.workzonesafety.org/crash-information/work-zone-injuries-injury-property-damage-crashes/>, Accessed July 3, 2020.

American Road and Transportation Builders Association (ARTBA). 2020b. "Work Zone Fatal Crashes and Fatalities." <https://www.workzonesafety.org/crash-information/work-zone-fatal-crashes-fatalities/#national>, Accessed July 3, 2020.

Bai, Y., and Li, Y. 2006. *Determining the Major Causes of Highway Work Zone Accidents in Kansas*. Report No. K-TRAN: KU-05-1. Kansas Department of Transportation. Topeka, Kansas.

Brown, H., Sun, C., Edara, P., and Rahmani, R. 2016. *Safety Assessment Tool for Construction Zone Work Phasing Plans*. InTrans Project 15-535. Smart Work Zone Deployment Initiative. Ames, Iowa.

Brown, H., Sun, C., Zhang, S., and Qing, Z. 2018a. *Evaluation of Automated Flagger Assistance Devices*. Report No. cmr 18-004. Missouri Department of Transportation. Jefferson City, Missouri.

Brown, H., Sun, C., Edara, P., and Rahmani, R. 2018b. *Extension of Safety Assessment Tool for Construction Work Zone Phasing Plans*. InTrans Project 18-535. Smart Work Zone Deployment Initiative. Ames, Iowa.

Bryden, J. 2007. "Work Zone Crashes Involving Traffic Control Devices, Safety Features, and Work Vehicles and Equipment." *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2015, No. 1, pp. 64-70.

Carter, D., Srinivasan, R., Gross, F., and Council, F. 2012. *Recommended Protocols for Developing Crash Modification Factors*. NCHRP Project 20-07, Task 314. National Cooperative Highway Research Program. Washington, D.C.

Chen, E., and Tarko, A. 2013. "Police Enforcement Strategies and Speed Reduction in Work Zones." In *92nd Annual Meeting of the Transportation Research Board*. Washington D.C.

Chen, E., and Tarko, A.P. 2014. "Modeling safety of highway work zones with random parameters and random effects models." *Analytic Methods in Accident Research*, Vol. 1, pp. 86-95.

Clark, J. B., and Fontaine, M. D. 2015. "Exploration of Work Zone Crash Causes and Implications for Safety Performance Measurement Programs." *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2485, No. 1, pp. 61-69.

Domenichini, L., La Torre, F., Branzi, V., and Nocentini, A. 2017. "Speed Behavior in Work Zone Crossovers. A Driving Simulator Study." *Accident Analysis and Prevention*, Vol. 98, pp. 10-24.

Dudek, C. L., Richards, S. H., and Buffington, J. L. 1986. "Some Effects of Traffic Control on Four-Lane Divided Highways." *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 1086, No. 1, pp. 20-30.

Elghamrawy, T., El-Rayes, K., and Liu, L. 2010. "Analysis of Injury and Fatal Crashes in Highway Construction Zones." In *Construction Research Congress 2010: Innovation for Reshaping Construction Practice*, pp. 568-577.

Eustace, D., Aylo, A., and Mergia, W. Y. 2015. Crash Frequency Analysis of Left Side Merging and Diverging Areas on Urban Freeway Segments–A Case Study of I-75 Through Downtown Dayton, Ohio. *Transportation Research Part C: Emerging Technologies*, Vol. 50, pp. 78-85.

Federal Highway Administration. (FHWA). 2009. *Manual on Uniform Traffic Control Devices for Streets and Highways*. 2009 Edition Including Revisions 1 and 2. Washington, D.C.

Federal Highway Administration (FHWA). 2013. "Better CMFs, safer roadways: Tips for building high-quality CMFs." <http://www.cmfclearinghouse.org/collateral/HighQualityCMFs.pdf>, Accessed March 29, 2016.

Federal Highway Administration (FHWA). 2020a. "National Work Zone Awareness Week." <https://ops.fhwa.dot.gov/wz/outreach/nwzaw_factsheet_2020/nwzaw_factsheet_2020.pdf>, Accessed July 3, 2020.

Federal Highway Administration (FHWA). 2020b. "CMF Clearinghouse." <http://www.cmfclearinghouse.org/ >, Accessed July 6, 2020.

Gayah, V.V., and Donnell, E.T. 2014. *Establishing Crash Modification Factors and Their Use*. Report No. FHWA-PA-2014-005-PSU WO 6. Pennsylvania Department of Transportation, Harrisburg, Pennsylvania.

Gross, F., Persaud, B., and Lyon, C. 2010. *A Guide to Developing Quality Crash Modification Factors*. Report No. FHWA-SA-10-032. Federal Highway Administration. Washington, D.C.

Khattak, A. J., and Council, F.M. 2002. "Effects of Work Zone Presence on Injury and Non-Injury Crashes." *Accident Analysis and Prevention*, Vol. 34, pp. 19-29.

Khattak, A., and Targa, F. 2004. "Injury Severity and Total Harm in Truck-Involved Work Zone Crashes." *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 1877, No. 1, pp. 106-116.

La Torre, F., Domenichini, L., and Nocentini, A. 2017. "Effects of Stationary Work Zones on Motorway Crashes." *Safety Science*, Vol. 92, pp. 148-159.

Ohio Department of Transportation. 2004. Maintenance of Traffic Alternative Analysis (Section 630-5). In *Traffic Engineering Manual*. Columbus, Ohio.

Oregon Department of Transportation. 2016. *Traffic Control Plans Design Manual*. Salem, Oregon.

Ozturk, O., Ozbay, K., and Yang, H. 2014. "Estimating the Impact of Work Zones on Highway

Safety." In *93rd Annual Meeting of the Transportation Research Board*. Washington, D.C.

Pal, R., and Sinha, K.C. 1996. "Analysis of Crash Rates at Interstate Work Zones in Indiana." *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 1529, No. 1, pp. 43-53.

Rahmani, R., Sun, C., Edara, P., Brown, H., and Zhu, Z. 2016. "Freeway Work Zone Crash Prediction Models Using Missouri Data." In *95th Annual Meeting of the Transportation Research Board*. Washington D.C.

See, C.F., Schrock, S.D., and McClure, K. 2009. "Crash Analysis of Work Zone Lane Closures with Left-Hand Merge and Downstream Lane Shift." In *88th Annual Meeting of the Transportation Research Board*. Washington, D.C.

Srinivasan, R., Ullman, G.L., Finley, M.D., and Council, F.M. 2011. "Use of Empirical Bayesian Methods to Estimate Temporal-Based Crash Modification Factors for Construction Zones." In *90th Annual Meeting of the Transportation Research Board*. Washington, D.C.

Sun, C., Edara, P., Claros, B., Khezerzadeh, A., Brown, H., and Nemmers, C. 2017. *Crash Location Correction for Freeway Interchange Modeling*. Report No. cmr 16-010. Missouri Department of Transportation. Jefferson City, Missouri.

Tarko, A., Islam, M.B., and Thomaz, J. 2011. *Improving Safety in High-Speed Work Zones: A Super 70 Study*. Report No. FHWA/IN/JTRP-2011/09. Joint Transportation Research Program, Purdue University. West Lafayette, IN.

Ullman, G. L., Finley, M. D., Bryden, J. E., Srinivasan, R., and Council, F. M. 2008. *Traffic Safety Evaluation of Nighttime and Daytime Work Zones*. NCHRP Report 627. National Cooperative Highway Research Program. Washington, D.C.

Ullman, G. L., Iragavarapu, V., and Brydia, R. E. (2016). "Safety Effects of Portable End-of-Queue Warning System Deployments at Texas Work Zones." *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2555, No. 1, pp. 46-52.

Ullman, G. L., Pratt, M., Fontaine, M.D., Porter, R.J., and Medina, J. 2018. *Analysis of Work Zone Crash Characteristics and Countermeasures*. NCHRP Web-Only Document 240. National Cooperative Highway Research Program. Washington, D.C.

Venugopal, S., and Tarko, A. 2000. "Safety Models for Rural Freeway Work Zones." *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 1715, No. 1, pp. 1-9.

Yang, H., Ozbay, K., Ozturk, O., and Yildirimoglu, M. 2013. "Modeling Work Zone Crash Frequency by Quantifying Measurement Errors in Work Zone Length." *Accident Analysis and Prevention*, Vol. 55, pp. 192-201.

APPENDIX A. 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).

A.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?

A.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 characteristics 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

A.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

APPENDIX B. SUMMARY OF WORK ZONE CMF VALUES

Table B.1. Work zone CMF values

Description	Fatal	Serious Injury	Minor Injury	PDO	All	CMF
Increase Work Zone Duration	-	-	-	-	✓	$1+\frac{\%\ increase\ in\ Duration\ x\ 1.11}{100}$
Increase Work Zone Length	-	-	-	-	✓	$1+\frac{\%\ increase\ in\ length\ \ x\ 0.67}{100}$
Active Work with no Lane Closure (Daytime)*	✓	✓	✓	-	-	1.17
Active Work with no Lane Closure (Daytime)*	-	-	-	✓	-	1.40
Active Work with no Lane Closure (Daytime)*	-	-	-	-	✓	1.31
Active Work with no Lane Closure (Nighttime)**	✓	✓	✓	-	-	1.41
Active Work with no Lane Closure (Nighttime)**	-	-	-	✓	-	1.67
Active Work with no Lane Closure (Nighttime)**	-	-	-	-	✓	1.58
Active Work with Temporary Lane Closure (Daytime)*	✓	✓	✓	-	-	1.46
Active Work with Temporary Lane Closure (Daytime)*	-	-	-	✓	-	1.81
Active Work with Temporary Lane Closure (Daytime)*	-	-	-	-	✓	1.66
Active Work with Temporary Lane Closure (Nighttime)**	✓	✓	✓	-	-	1.42
Active Work with Temporary Lane Closure (Nighttime)**	-	-	-	✓	-	1.75
Active Work with Temporary Lane Closure (Nighttime)**	-	-	-	-	✓	1.61
No Active Work with No Lane Closure (Daytime)*	✓	✓	✓	-	-	1.02
No Active Work with No Lane Closure (Daytime)*	-	-	-	✓	-	1.20
No Active Work with No Lane Closure (Daytime)*	-	-	-	-	✓	1.13

Description	Fatal	Serious Injury	Minor Injury	PDO	All	CMF
No Active Work with No Lane Closure (Nighttime)**	✓	✓	✓	-	-	1.11
No Active Work with No Lane Closure (Nighttime)**	-	-	-	✓	-	1.33
No Active Work with No Lane Closure (Nighttime)**	-	-	-	-	✓	1.24
Implement left-hand merge and downstream lane shift	✓	✓	✓	-	-	2.24
Implement left-hand merge and downstream lane shift	-	-	-	-	✓	0.54
Increase the outside shoulder width inside the WZ by one foot	-	-	-	-	✓	0.95
Increase the inside shoulder width inside the WZ by one foot	-	-	-	-	✓	0.97
Two-way traffic operation-crossover closure	-	-	-	-	✓	1.00
Implement mobile automated speed enforcement system[#]	✓	✓	✓	-	-	0.83
End of Queue Warning System (Nighttime)[+]	-	-	-	-	✓	0.56
Portable Rumble Strips - No Queue (Nighttime)[+]	-	-	-	-	✓	0.89
Portable Rumble Strips - Queued (Nighttime)[+]	-	-	-	-	✓	0.40
EOQ Warning System and Portable Rumble Strips - No Queue (Nighttime)[+]	-	-	-	-	✓	0.72
EOQ Warning System and Portable Rumble Strips - Queued (Nighttime)[+]	-	-	-	-	✓	0.47

*Daytime : 6 am to 7 pm **Nighttime : 7 pm to 6 am [+] Nighttime : 7 pm to 7 am [#] CMF based on non-work zone data