Texas Department of Transportation

Highway Safety Improvement Program (HSIP)

Combining Work Codes

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LIST OF ABBREVIATIONS / ACRONYMS

Acronym	Definition
AASHTO	American Association of State Highway and Transportation Officials
AADT	Annual Average Daily Traffic
ADT	Average Daily Traffic
AMF	Accident Modification Factor
CMF	Crash Modification Factor
CRF	Crash Reduction Factor
CRIS	Crash Records Information System
CSRS	Continuous Shoulder Rumble Strips
DOT	Department of Transportation
EB	Empirical Bayes
EPDO	Equivalent Property Damage Only
FHWA	Federal Highway Administration
FYA	Flashing Yellow Arrow
F+I	Fatal and Injury Crashes
HAWK	High-Intensity Activated Crosswalk
HSIS	Highway Safety Information System
IHSDM	Interactive Highway Safety Design Model
ITE	Institute of Transportation Engineers
LED	Light-Emitting Diode
NCHRP	National Cooperative Highway Research Program
NCDOT	North Carolina Department of Transportation
OD	Opposing Direction (crash)
PDO	Property Damage Only (crash)
PRPMs	Permanent Raised Pavement Markers
SD	Same Direction (crash)
SKARP	Skid Accident Reduction Program
SPF	Safety Performance Function
SRS	Shoulder Rumble Strips
SV	Single Vehicle (crash)
TMUTCD	Texas Manual on Uniform Traffic Control Devices
TxDOT	Texas Department of Transportation
TWLTL	Two-Way Left-Turn Lane
U	Union
WC	Work Code

CHAPTER 1. INTRODUCTION

Currently, the Texas Department of Transportation (TxDOT) uses a variety of safety countermeasures in an effort to reduce crashes. It is important to know how effective these countermeasures are in reducing total crashes as well as injury and fatal crashes. At this time, TxDOT has compiled crash reduction factors (CRFs) that estimate the percent reduction of crashes. These estimates are represented by a list of work codes (WCs) that also include supplemental information regarding the candidate countermeasure. In many instances, however, there is a need to combine candidate countermeasures. When this occurs, TxDOT needs a reliable way to combine the values of the WCs to adequately represent the estimated crash reduction of the combined countermeasure configuration.

This report, therefore, reviews the existing TxDOT WCs and compares them to the available published literature (Chapter 2). Chapter 3 of this effort then summarizes the statistical evaluation for how to best combine work codes. Included in Chapter 3 is a recommended procedure supplemented by a database tool that will help automate the process for TxDOT decision makers. The report ends with conclusions and recommendations (Chapter 4) and a list of references cited in the document (Chapter 5).

A large number of abbreviations or acronyms are used throughout this report; therefore, Page ix includes a summary of these definitions.

CHAPTER 2. LITERATURE REVIEW

This chapter includes a comprehensive review of published literature that is aligned with the TxDOT WCs. These WCs are currently used to estimate the approximate crash reduction associated with a given type of countermeasure. These crash reductions are associated with countermeasures for the following five categories: signing and signals, roadside obstacles and barriers, resurfacing and roadway lighting, pavement markings, and roadway work. This review summarizes published research efforts where researchers evaluated similar treatments as those in the TxDOT WC list. Where available, this chapter identified crash reduction information associated with collision types, crash severity, study locations, sample size, study methodology, and quality of fit to the studied data.

The following summaries are organized so that first the TxDOT WCs are individually defined. Each summary includes a table that first depicts the TxDOT value and then summarizes findings from other studies (where identified). Additional supplemental study information is summarized for studies identified in the treatment table for a WC.

SIGNING AND SIGNALS

There are a variety of TxDOT WCs for signing and signals. This section identifies this information and then reviews the associated published literature. The WCs addressed in this section are summarized in Table 1.

Table 1. TxDOT Signing and Signal Work Codes.

Texas Work Code Number	Work Code Name	Report Page Number
101	Install Warning / Guide Signs	4
102	Install STOP Signs	4
104	Improve Advance Warning Signals	6*
105	Install Intersection Flashing Beacon	7
106	Modernize Intersection Flashing Beacon	9
107	Install Traffic Signal	9
108	Improve Traffic Signals	11
110	Install Pedestrian Signal	13
111	Interconnect Signals	13
112	Overheight Warning System	14*
113	Install Delineators	14
114	Install School Zones	15
118	Replace Flashing Beacon with a Traffic Signal	15*
119	Install Overhead Guide Signs	16
121	Convert 2-way STOP Signs to 4-way STOP Signs	16
122	Install Advance Warning Signals (Intersection – Existing Signal, Flashing Beacon or STOP Signs)	18*
123	Install Advance Warning Signals (Curve)	18*
124	Install Advance Warning Signals and Signs (Intersection – Existing Signal, Flashing Beacon or STOP Signs)	19*
125	Install Advance Warning Signals and Signs (Curve)	19
126	Install Advance Warning Signals and/or Signs (Intersection – Uncontrolled; No Existing Advance Warning)	20*
127	Install Advance Warning Signals (Intersection – Existing Warning Signs)	21*
128	Install Advance Warning Signs (Intersection – Existing Warning Signals)	21*
129	Install Advance Warning Signals (Curve – Existing Warning Signs)	22*
130	Install Advance Warning Signs (Curve – Existing Warning Signals)	22*
131	Improve Pedestrian Signals	23
132	Install Advance Warning Signals and Signs	24
133	Improve School Zone	25*
136	Install LED Flashing Chevrons (Curve)	25
137	Install Chevrons (Curve)	26
138	Install Flashing Yellow Arrow	27

* Additional information could not be located in the published literature.

WC 101: Install Warning/Guide Signs

Definition: Provide advance signing for unusual or unexpected roadway features where no signing existed previously.

Table 2. Estimated Effects for Installing Warning/Guide Signs.

<table>
<tr><th>Study</th><th>Crash Type</th><th>Percent Crash Reduction (%)</th><th colspan="2">Study Details</th></tr>
<tr><td>Texas</td><td>Head-on, Rear-end, Sideswipe and Road departure crashes</td><td>20</td><td colspan="2">Service Life (years): 6
Preventable Crash: (Vehicle Movements/Manner of Collision = 20–22 or 30) or (Roadway Related = 2, 3 or 4)</td></tr>
<tr><td rowspan="4">Agent et al. (1996)</td><td rowspan="2">Total crashes</td><td>23</td><td rowspan="2">Warning Signs</td><td>From surveys for 12 states</td></tr>
<tr><td>30</td><td>Based on review of 11 studies</td></tr>
<tr><td rowspan="2">Total crashes</td><td>14</td><td rowspan="2">Guide Signs</td><td>From surveys for 9 states</td></tr>
<tr><td>15</td><td>Based on review of 3 studies</td></tr>
</table>

<u>Review of Supplemental Studies for WC 101:</u>

Agent et al. (1996) collected data for crash reduction factors from 43 states and the District of Columbia. The researchers distributed a user survey via mail to identify various safety improvements and the treatment's level of effectiveness. They also performed a literature review. As noted in the table, their identified crash reductions applied to total crashes and ranged from 14 up to 30 percent crash reduction for guide and warning signs.

WC 102: Install STOP Signs

Definition: Provide STOP signs where none existed previously.

Table 3. Estimated Effects for Installing STOP Signs.

Study	Crash	Percent Crash Reduction (%)	Study Details
Texas	Total crashes	20	Service Life (years): 6 Preventable Crash: Intersection Related = 1 or 2
Main (1984)	Total crashes	24	Location: Urban areas in the City of Hamilton, Ontario, Canada Methodology: Simple before-after study with 3 years of data
Lovell and Hauer (1986)	Total crashes	43	Location: 222 urban intersections in Philadelphia, only intersections converted from one-way streets to all-way stop control Methodology: Simple before-after study with 2 years of data
	Right-angle crashes	77	
	Injury crash	73	
Laplante and Kropidlowski (1992)	Total crashes	88	Locations: 9 low-volume intersections in a neighborhood of Chicago, Illinois. Methodology: Simple before-after study with 3 years of data Note: traffic volume increased by 11% in average
Polanis (2003)	Total crashes	70	Locations: 15 intersections in Winston Salem, NC Methodology: Simple before-after study
	Right-angle crashes	81	
Simpson and Hummer (2009)	Total crashes	67 (76)	Locations: 18 locations in North Carolina Methodology: Simple before-and-after analysis with a linear adjustment for traffic volumes Notes: unpublished *(*): denotes value for intersections without flashing beacons (value for intersection with flashing beacons)
	Frontal-impact crashes	79 (80)	
	Injury crashes	82 (83)	

Review of Supplemental Studies for WC 102:

Main (1984) studied the effects of safety treatments for urban grid street systems. The City of Hamilton in Ontario, Canada adjusted and implemented stop control in different neighborhoods in an effort to develop a regular pattern of stop control. Only four-approach intersections with stop control were selected for this treatment and study locations were characterized by having motorists stop on the local or collector grid street system at two-block intervals. The authors used a simple before-and-after methodology based on crash data for a period of three years.

Lovell and Hauer (1986) studied operational and crash data for 222 urban intersections in Philadelphia. During a period from 1968 to 1975, the intersections were converted from one-way streets to all-way stop control. Lovell and Hauer applied a before-and-after methodology with a time frame of two years.

Laplante and Kropidlowski (1992) evaluated traffic control methods for nine intersections that were changed from uncontrolled to two-way stop control in a Chicago, Illinois neighborhood. These intersections, however, did not meet the United States warrants. After the installation of the stop signs, the motorists could travel no more than two blocks without encountering a stop sign. A three-year before–and-after study demonstrated a crash reduction of 88 percent while traffic volumes increased, on average, by 11 percent during the three year study period.

Polanis (2003) evaluated crash data for 15 Winston Salem, North Carolina, intersection locations (11 in residential areas, two in commercial areas, and two in areas that had both residential and commercial land use). At the study locations, the city installed multi-way stop control based on observed crash patterns. Following installation, the stop signs yielded an average reduction in right-angle crashes of 80.6 percent, with statistically significant crash reductions at seven of the intersections.

Simpson and Hummer (2009) performed a study for the North Carolina Department of Transportation (DOT) Safety Evaluation Group. The researchers evaluated the crash history for 18 all-way stop intersections (a mix of urban, suburban, and rural intersections). The intersections were improved with all-way stop control with or without flashing beacons. Simpson and Hummer used a simple before-and-after analysis with a linear adjustment for traffic volumes.

Upon review of the summary crash reductions shown in Table 3, the installation of STOP signs can be estimated to reduce the total number of crashes from 24 up to 88 percent. This value can be contrasted with the TxDOT value of 20 percent reduction in total crashes. In addition, injury crashes may be reduced by values ranging from 73 up to 82 percent.

WC 104: Improve Advance Warning Signals

Definition: Bring existing flasher units into conformance with current design standards. Refer to WC 106 for modernization of intersection flashing beacons.

Table 4. Estimated Effects for Improving Advance Warning Signals.

Study	Crash Type	Percent Crash Reduction (%)	Study Details
Texas	Total	To be defined.	Service Life (years): 10 Preventable Crash: Will be determined from supplied diagram

Currently, the value for WC 104 has not yet been quantified. In addition, There do not appear to be any studies in the published literature that directly quantify crash reductions for this treatment.

WC 105: Install Intersection Flashing Beacon

Definition: Provide a flashing beacon at an intersection where a beacon did not exist previously.

Review of Supplemental Studies for WC 105:

In 1970, Cribbins and Walton investigated 14 rural North Carolina intersections where flashing beacons were installed after 1965. The researchers evaluated crash data for at least one year before-after the installment and computed the equivalent property damage only (EPDO) rates. The researchers developed crash reduction conclusions based on the severity level of each crash and associated traffic volumes.

Vogt and Bared (1998) noted a 12 percent decrease in total crashes for a safety study of 170 intersections after installing flashing beacons in North Carolina. The researchers used the Empirical Bayes (EB) method with an assumption of a linear increase in traffic volume.

Pant et al. (1999) compared six stop-controlled intersections to seven stop-controlled intersections with beacons and evaluated crash rates for fatal, injury, property damage only (PDO), and right-angle crashes. Beacon-controlled intersections had higher mean rates for most crash types than stop-controlled intersections without a beacon. Seven beacon-controlled sites were analyzed with a before-after study. The rate of fatal, serious visible injury, and angle crashes decreased after installing beacons; however, based on a chi-square test, the reductions were determined to not be statistically significant.

Table 5. Estimated Effects for Installing Intersection Flashing Beacon.

Study	Crash	Percent Crash Reduction (%)	Study Details
Texas	Total crashes	35	Service Life (years): 10 Maintenance Cost: $2,100 (overhead) $1,300 (roadside mounted) Preventable Crash: Intersection Related = 1 or 2
Cribbins and Walton (1970)	EPDO Rate (all crashes)	48 (EPDO rate)	Location: 14 rural intersections in North Carolina Methodology: Before-after study Results: Statistically significant at the 0.01 level, based on paired t-test
Vogt and Bared (1998)	Total crashes	12	Locations: 170 intersections in North Carolina Methodology: EB method
	Injury crashes	9	
	Severe injury crashes	40	
	Frontal impact crashes	9	
	Failure-to-stop crashes	26	
Pant et al. (1999)	Fatal	3.1	Location: 7 intersections in Ohio Methodology: Before-after study without a control group Results: Not statistically significant at the 0.05 level (based on Chi Square test)
	Injury	3.4	
Murphy and Hummer (2007)	Total crashes	10	Locations: 34 four-leg intersections in North Carolina (no turn lanes, 2-way stop control) Methodology: Simple before-after analysis, before-after analysis using a safety performance function, and the EB method
	Injury crashes	15	
	Severe injury crashes	66	
	Frontal impact crashes	11	
	Ran STOP sign crashes	50	
Srinivasan et al. (2008)	Angle Crashes	13.3	Locations: 64 stop-controlled intersections in North Carolina and 42 stop-controlled intersections in South Carolina Methodology: Before-after analysis incorporated with the EB method Goodness of Fit: SE=0.046 for angle crashes and 0.048 for F+I crashes.
	Fatal and Injury (F+I) Crashes	10.2	

Murphy and Hummer (2007) studied the safety impacts of flashing beacons at 34 North Carolina locations. The four-leg intersections included in the study had two-way stop control and no turn lanes. They used three types of analysis -- simple before-after analysis, before-after analysis using a safety performance function (resulting in a “predicted” crash), and the EB method (resulting in “expected” crashes).

Srinivasan et al. (2008) evaluated 106 stop-controlled intersection locations (64 in North Carolina and 42 in South Carolina) where flashing beacons were installed during the study scope phase of the project. To evaluate the safety effectiveness, the researchers used a before-and-after analysis that incorporated EB methods.

They observed a statistically significant reduction in total, angle, and injury plus fatal crashes for the North Carolina locations, but did not have statistically significant results for the South Carolina sites.

As noted in Table 5, the reduction in total crashes due to installing an intersection flashing beacon, as indicated in the literature, is 10 to 12 percent (contrasted to the Texas value of 35 percent); however, severe crashes can be expected to be reduced from 40 to 66 percent.

WC 106: Modernize Intersection Flashing Beacon

Definition: Improve an existing overhead flashing beacon, located at an intersection, to current design standards. Refer to WC 104 for improving advance warning signals including non-intersection flashing beacon.

Table 6. Estimated Effects for Modernizing Intersection Flashing Beacon.

Study	Crash Type	Percent Crash Reduction (%)	Study Details
Texas	Total	10	Service Life (years): 10 Preventable Crash: Intersection Related = 1 or 2
Ermer and Sinha (1991)	Total	9	Methodology: Before-after Study

Review of Supplemental Study for WC 106:

Ermer and Sinha (1991) performed a research study for the Indiana DOT and determined a crash reduction factor of 0.09 (i.e. nine percent reduction in crashes) for upgrading an existing flasher. The Indiana study considered crash data for three years before-after. Prior to computing the crash reduction factor using regression analysis, Ermer and Sinha accounted for biases by adjusting the crashes using the traffic volumes rather than statewide growth factors. The TxDOT and Indiana percent crash reductions are similar for this treatment.

WC 107: Install Traffic Signal

Definition: Provide a traffic signal where none existed previously.

Table 7. Estimated Effects for Installing Traffic Signal.

Study	Crash Type	Percent Crash Reduction (%)	Study Details
Texas	Total	35	Service Life (years): 10 Maintenance Cost: $3,400 (Isolated) $3,900 (Interconnected) $5,400 (Diamond Interchange) Preventable Crash: [(Intersection Related = 1 or 2) and (Vehicle Movements/Manner of Collision = 10–39)] or (First Harmful Event = 1 or 5)
Ermer and Sinha (1991)	Total	-3	Number of sites: 137 Number of crashes: 3865
	PDO	-3	
	Injury	-3	
	Fatal	77	
McGee et al. (2003)	Total crashes	14	Type: Three-Leg Intersections Number of improved sites: 22
	Right-Angle Crashes	34	
	Rear-End Crashes	-50	
	Total crashes	23	Type: Four-Leg Intersections Number of improved sites: 100
	Right-Angle Crashes	67	
	Rear-End Crashes	-38	
Harkey et al. (2008)	Total Crashes	44	Location: 45 sites located in Minnesota and California Methodology: EB before-and-after studies
	Right-Angle Crashes	77	
	Rear-End Crashes	-58	
	Left- Turn Crashes	60	
	Total Crashes	27	Methodology: EB before-and-after studies Number of sites: 16

<u>Review of Supplemental Studies for WC 107:</u>

The Ermer and Sinha (1991) study is summarized in the previous WC 106 section. They noted a very slight increase in most crashes following traffic signal installation; however, they observed a significant reduction in fatal crashes (possibly due to the low number of fatal crashes before the treatment).

McGee et al. (2003) evaluated crash data for intersections located in five states (California, Florida, Maryland, Virginia, and Wisconsin) plus Toronto. The study intersections were converted from stop-control to signal control. For three-leg intersection data, 22 treatment sites were included with 118 reference group sites (99 stop-controlled and 19 signalized intersections). Four-leg intersection data included 100 treatment sites with 295 reference group sites (96 stop-controlled and 199 signalized intersections). The authors developed an additional reference group using Highway Safety Information System (HSIS) California urban data. This data set included 1,418 stop-controlled and 799 signalized intersections. Traffic volumes at the treatment sites ranged from 911 to 3952 vpd for the minor street. The major street traffic volumes ranged from 11,739 up to 24,584 vpd.

Harkey et al. (2008) used HSIS data to evaluate 45 sites in Minnesota and California. For three-leg intersection data, they included six treatment sites with 1927 reference group sites (stop-controlled intersections). Four-leg intersection data included 39 treatment sites with 1661 reference group sites (96 stop-controlled and 199 signalized intersections). The researchers also developed a reference group set using 84 signalized intersections. Traffic volumes in the treatment sites ranged from 101 to 10,300 vpd for the minor street. The major street traffic volumes ranged from 3261 up to 29,926 vpd.

Based on the published literature, the installation of a traffic signal can be expected to affect total crashes from -3 up to 44 percent. As expected, the installation of the traffic signal can be directly associated with an increase in rear-end crashes (ranging from 38 up to 58 percent) and a decrease in the more severe right-angle crashes (from 34 up to 77 percent reduction in these angle crashes).

WC 108: Improve Traffic Signals

Definition: Modernize existing intersection signals to current design standards. Refer to WC 106 for modernization of intersection flashing beacons.

<u>Review of Supplemental Studies for WC 108:</u>

The Ermer and Sinha (1991) study is summarized in the previous WC 106 section. As noted in Table 8, they determined an approximate 11 percent reduction in total crashes as a result of improving traffic signals. Similarly the 1996 study by Agent et al. is described in the previous WC 101 section. Agent et al. noted a 23 to 24 percent crash reduction following improvement of traffic signals.

Table 8. Estimated Effects for Improving Traffic Signals.

Study	Crash Type	Percent Crash Reduction (%)	Study Details
Texas	Total	50	Service Life (years): 10 Preventable Crash: [(Intersection Related =1 or 2) and (Vehicle Movements/Manner of Collision = 10–39)] or (First Harmful Event = 1 or 5)
Ermer and Sinha (1991)	Total	11	Number of sites: 110
Agent et al. (1996)	Total	24	From 21 state surveys Improvements include 12-inch lens, pretimed to actuated control, backplates, optical lenses.
		23	From a review of 18 studies Improvements include 12-inch lens, pretimed to actuated control, backplates, optical lenses.
Retting et al., (2002)	Reportable crashes	8	Modifying the duration of traffic signal change intervals to conform with values associated with a proposed recommended practice published by the Institute of Transportation (ITE) Before-after studies with 51 experimental sites and 71 control sites 3-year period following implementation of signal timing changes
	Injury crashes	12	
	Pedestrian and bicycle crashes	37	

Retting et al. (2002) studied the safety effects of modifying the duration of traffic signal change intervals to conform to values associated with a proposed recommended practice published by ITE. They randomly selected 122 intersections and assigned them to experimental and control groups. For the eligible experimental sites, 40 out of 51 needed the signal timing changes so as to comply with the ITE values. Retting et al. noted that the modifications to signal timing could be expected to reduce reportable crashes, injury crashes, and pedestrian and bicycle crashes (from 8 up to 37 percent).

As shown in Table 8, the TxDOT estimated crash reduction for total crashes is 50%, a much larger value than identified in other studies (where values ranged from 11 up to 24 percent for total crashes).

WC 110: Install Pedestrian Signal

Definition: Provide a pedestrian signal at an existing signalized location where no pedestrian phase exists, but pedestrian crosswalks are existing. Refer to WC 403 for installation of pedestrian crosswalks.

Table 9. Estimated Effects for Installing Pedestrian Signal.

Study	Crash	Percent Crash Reduction (%)	Study Details
Texas	Total crashes	15	Service Life (years): 10 Preventable Crash: First Harmful Event = 1
Agent et al. (1996)	Total	23	Data from surveys of 14 states
		24	From a review of 6 studies
	Pedestrian	47	Data from surveys of 7 states
		60	From a review of 3 studies

Review of Supplemental Studies for WC 110:

The 1996 study by Agent et al. is described in the previous WC 101 section. Agent et al. noted a 23 to 24 percent crash reduction in total crashes, but the installation of pedestrian signals reduced crashes with pedestrians 47 to 60 percent. These findings, though dated, indicated greater crash reductions than currently assumed by the TxDOT WC 110 15 percent value.

WC 111: Interconnect Signals

Definition: Provide a communication link between two or more adjacent signals in a corridor. Specify all signalized intersections to be included in the interconnection.

Table 10. Estimated Effects for Interconnecting Signals.

Study	Crash	Percent Crash Reduction (%)	Study Details
Texas	Total crashes	10	Service Life (years): 10 Preventable Crash: All
Agent et al. (1996)	Total Crashes	15	Data from survey of 9 states
		17	From a review of 3 studies

Review of Supplemental Studies for WC 111:

Agent et al. (1996), as described in the previous WC 101 section, evaluated the safety effects of interconnecting traffic signals. They noted a 15 to 17 percent estimated total crash reduction. This is similar to the TxDOT value of 10 percent.

WC 112: Overheight Warning System

Definition: Install electronic devices to detect over-height loads.

Table 11. Estimated Effects for Over-height Warning System.

Study	Crash	Percent Crash Reduction (%)	Study Details
Texas	Total crashes	65	Service Life (years): 10 Preventable Crash: Object Struck = 43

There do not appear to be any additional studies in the published literature that directly address the safety effects of an overheight warning system.

WC 113: Install Delineators

Definition: Install post-mounted delineators to provide guidance.

Table 12. Estimated Effects for Installing Post-Mounted Delineators

Study	Crash Type	Percent Crash Reduction (%)	Study Details
Texas	Total Crashes	65	Service Life (years): 10 Preventable Crash: Object Struck = 43
Choi et al. (2013)	Total Crashes	-10	Location: Five Korean expressways Methodology: EB method Goodness of Fit: SE=0.1364 crashes Number of crashes (before-after): 433

Review of Supplemental Studies for WC 113:

Choi et al. (2013) performed an assessment of post-mounted delineators for five Korean expressways and determined that they actually were associated with an increase in crashes of 10 percent. The authors used the EB method so as to reduce any potential bias due to regression-to-the-mean. Because this study was not in the United States, it is likely that the device implementation was not consistent with typical installations in the United States.

WC 114: School Zone

Definition: Place school zones to include flashers, signing, and/or pavement markings where none existed previously. Refer to WC 403 for pedestrian crosswalk markings.

Table 13. Estimated Effects for School Zone.

Study	Crash Type	Percent Crash Reduction (%)	Study Details
Texas	Total Crashes	20	Service Life (years): 5 Preventable Crash: All
Agent et al. (1996)	Total Crashes	14	Treatment: Installation of signs indicating 'School Zone' Data from surveys of 3 states
Feldman et al. (2010)	Total Crashes	37	Treatment: high-visibility school (yellow, continental-style) crosswalks Location: 108 intersections in San Francisco Methodology: EB Method Goodness of Fit: 95% confidence interval is (13%, 60%)

Review of Supplemental Studies for WC 114:

Agent et al. (1996), as described in the previous WC 101 section, summarized the safety effects of adding a school zone and estimated a 14 percent total crash reduction. This is similar to the TxDOT value of 20 percent.

Feldman et al. (2010) performed post hoc tests to evaluate the effectiveness of high-visibility school (yellow, continental-style) crosswalks at 54 treated intersections in City of San Francisco, California. Feldman et al. applied the EB method to predict the number of collisions for the after period had the school crosswalks not been installed. The researchers also included 54 control intersections in the study, each of which was similar to a treated intersection geographically. They estimated a reduction in total crashes of 37 percent.

WC 118: Replace Flashing Beacon with a Traffic Signal

Definition: Replace an existing flashing beacon at an intersection with a traffic signal.

Table 14. Estimated Effects for Replacing Flashing Beacon with a Traffic Signal.

Study	Crash Type	Crash Severity	Percent Crash Reduction (%)	Study Details
Texas	Total Crashes	Total crashes	25	Service Life (years): 10 Maintenance Cost: $1,300 Preventable Crash: [(Intersection Related = 1 or 2) and (Vehicle Movements/Manner of Collision = 10–39)] or (First Harmful Event = 1 or 5)

There do not appear to be any additional studies in the published literature that directly address the safety effects of replacing a flashing beacon with a traffic signal.

WC 119: Install Overhead Guide Signs

Definition: Install overhead advance signing for unusual or unexpected roadway features where no signing existed previously.

Table 15. Estimated Effects for Installing Overhead Guide Signs.

Study	Crash Type	Crash Severity	Percent Crash Reduction (%)	Study Details
Texas	Total Crashes	Total crashes	20	Service Life (years): 6 Preventable Crash: Vehicle Movements/Manner of Collision = 20–29

There do not appear to be any additional studies in the published literature that directly address the safety effects of installing overhead advance signing for unusual or unexpected roadway features.

WC 121 : Convert Two-Way (without Flashing Beacons) to All-Way Stop Control (without Flashing Beacons)

Definition: Provide four-way STOP signs where two-way STOP signs existed previously.

Table 16. Estimated Effects for Converting Two-Way (without Flashing Beacons) to All-Way Stop Control (without Flashing Beacons).

Study	Crash	Percent Crash Reduction (%)	Study Details
Texas	Total crashes	15	Service Life (years): 6 Preventable Crash: Intersection/Intersection Related = 1 or 2
Lovell and Hauer (1986)	Total crashes	47	Location: 360 intersections in San Francisco, Philadelphia, Michigan, and Toronto. Methodology: Before-after analysis with likelihood functions Goodness of Fit: SD=0.03 for right-angle crashes, 0.13 for rear-end crashes, 0.52 for left-turn crashes, 0.08=pedestrian crashes, and 0.06 for injury crashes.
	Right-Angle Crashes	72	
	Rear-end Crashes	13	
	Left-turn Crashes	20	
	Pedestrian Crashes	39	
	Injury Crashes	71	
Simpson and Hummer (2010)	Total Crashes	68	Location: 53 treatment sites located in urban, suburban, and rural areas in North Carolina Methodology: EB Method
	Injury Crashes	77	
	Frontal- Impact Crashes	75	
	Ran-stop-sign Crashes	15	

Review of Supplemental Studies for WC 121:

Lovell and Hauer (1986) evaluated primarily urban treatments and also re-analyzed data from three previous safety studies in San Francisco, Philadelphia, and Michigan. They also included a new data set from Toronto. At the study sites, intersections which were two-way stop control or one-way streets were treated with all-way stop control. The San Francisco data consisted of 49 urban intersections, Philadelphia data included 222 urban intersections, Toronto data consisted of 79 urban intersections, and Michigan data included 10 low-volumes, high-speed rural intersections. The results showed consistent safety effectiveness for all-way stop conversion. The crash reductions identified in this study were also documented in the subsequent National Cooperative Highway Research Program (NCHRP) Digest 299, the interim report to NCHRP Report 617: *Accident Modification Factors for Traffic Engineering and ITS Improvements* (Harkey et al., 2008). The findings were also included as part of the interactive highway safety design model (IHSDM) developed by the Federal Highway Administration (FHWA).

Simpson and Hummer (2010) analyzed 53 treatment sites (urban, suburban, and rural). The sites were separated into three groups based upon presence of an overhead and/or sign mounted flashing beacon. This included intersections without flashing beacons, intersections with flashing beacons in the before-after period, and intersections where the flashing beacon was installed with the all-way stop control. The researchers used the EB method to evaluate the resulting data.

As shown in Table 16, the published literature indicates that converting a two-way to an all-way stop-control (when flashing beacons are not present) can result in a reduction in total crashes ranging from 47 to 68 percent. The TxDOT value for this treatment is assumed to result in a total crash reduction of 15 percent (a considerably lower value).

WC 122: Install Advance Warning Signals (Intersection — Existing Signal, Flashing Beacon or STOP Signs)

Definition: Provide flasher units in advance of an intersection where none previously existed.

Table 17. Estimated Effects for Installing Advance Warning Signals (Intersection — Existing Signal, Flashing Beacon or STOP Signs).

Study	Crash Type	Percent Crash Reduction (%)	Study Details
Texas	Head-on, Rear-end, Sideswipe, Angle and Road departure crashes	10	Service Life (years): 10 Maintenance Cost: $1300 per Approach Preventable Crash: Intersection Related = 1 or 2

There do not appear to be any additional studies in the published literature that directly address the safety effects of sideswipe, angle, or road departure crashes of new installations of advance warning flasher units at intersection locations.

WC 123: Install Advance Warning Signals (Curve)

Definition: Provide flasher units in advance of a curve where none previously existed.

Table 18. Estimated Effects for Installing Advance Warning Signals (Curve).

Study	Crash Type	Percent Crash Reduction (%)	Study Details
Texas	Head-on, Rear-end, Sideswipe, Angle and Road departure crashes	10	Service Life (years): 10 Maintenance Cost: $1300 per Approach Preventable Crash: (Roadway Related = 2, 3 or 4) or (Vehicle Movements/Manner of Collison = 20–24 or 30)

There do not appear to be any additional studies in the published literature that directly address the safety effects of providing flasher units in advance of a curve.

WC 124: Install Advance Warning Signals and Signs (Intersection — Existing Signal, Flashing Beacon or STOP Signs)

Definition: Provide flasher units and signs in advance of an intersection where none previously existed.

Table 19. Estimated Effects for Installing Advance Warning Signals and Signs (Intersection — Existing Signal, Flashing Beacon or STOP Signs).

Study	Crash Type	Percent Crash Reduction (%)	Study Details
Texas	Intersection and Intersection-related crashes	15	Service Life (years): 10 Maintenance Cost: $1300 per Approach

There do not appear to be any additional studies in the published literature that directly address the intersection-related crash type safety effects of providing flasher units and signs in advance of an intersection where none previously existed.

WC 125: Install Advance Warning Signals and Signs (Curve)

Definition: Provide flasher units and signs in advance of a curve where none previously existed.

Table 20. Estimated Effects for Installing Advance Warning Signals and Signs.

Study	Crash Type	Percent Crash Reduction (%)	Study Details
Texas	Head-on, Rear-end, Sideswipe, Angle and Road departure crashes	15	Service Life (years): 10 Maintenance Cost: $1300 per Approach
Montella (2009)	Total crashes	39.4	Location: 15 curves in Italy Methodology: EB before-after study with 2 years of after period data Results: Statistically significant crash reductions in total, nighttime, daytime, rainy, non-rainy, run-off-road, and property-damage-only crashes. Treatment effectiveness is greater for curves with radius less than or equal to 300 m and for curves with deflection angle greater than 60 gon (100 gon = 90°)
	Injury crashes	19.1	
	PDO crashes	49	
	ROR	41.5	
	Rainy	47.1	

Review of Supplemental Studies for WC 125:

Montella (2009) evaluated 15 curves located on the A16 motorway in Naples–Canosa. This motorway was a four-way divided highway in southern Italy. Montella found that installing advance warning signs and signals was more effective for curves with radii less than or equal to 300 m, or with deflection angles greater than 54 degrees. The most effective treatment in this study was the installation of curve warning signs, chevron signs, and sequential flashing beacons along the curve. Because this alternative study is located in Italy, it is possible that sign placement and road design may differ from that of Texas facilities and so the crash reduction values should be considered with this potential difference in mind.

WC 126: Install Advance Warning Signals and/or Signs (Intersection - Uncontrolled; No Existing Advance Warning)

Definition: Provide flasher units and/or signs in advance of an uncontrolled intersection where none previously existed.

Table 21. Estimated Effects for Installing Advance Warning Signals and/or Signs (Intersection - Uncontrolled; No Existing Advance Warning).

Study	Crash Type	Percent Crash Reduction (%)	Study Details
Texas	Intersection and Intersection-related crashes	20	Service Life (years): 10 Maintenance Cost: $1300 per Approach

There do not appear to be any additional studies in the published literature that directly address the safety effects of providing flasher units and/or signs in advance of an uncontrolled intersection where devices were not already present.

WC 127: Install Advance Warning Signals (Intersection - Existing Warning Signs)

Definition: Provide flasher units in advance of an intersection where none previously existed. Advance warning signs already exist.

Table 22. Estimated Effects for Installing Advance Warning Signals (Intersection - Existing Warning Signs).

Study	Crash Type	Percent Crash Reduction (%)	Study Details
Texas	Intersection and Intersection-related crashes	10	Service Life (years): 10 Maintenance Cost: $1300 per Approach

There do not appear to be any additional studies in the published literature that directly address the safety effects of installing advance warning signals for intersections locations where warning signs previously existed.

WC 128 : Install Advance Warning Signs (Intersection - Existing Warning Signals)

Definition: Provide signs in advance of an intersection where none previously existed. Advance warning signals already exist.

Table 23. Estimated Effects for Installing Advance Warning Signs (Intersection - Existing Warning Signals).

Study	Crash Type	Percent Crash Reduction (%)	Study Details
Texas	Intersection and Intersection-related crashes	5	Service Life (years): 6

There do not appear to be any additional studies in the published literature that directly address the safety effects of installing advance warning signs for intersections locations where warning signals previously existed.

WC 129 : Install Advance Warning Signals (Curve-Existing Warning Signs)

Definition: Provide flasher units in advance of a curve where none previously existed. Advance warning signs already exist.

Table 24. Estimated Effects for Installing Advance Warning Signals (Curve-Existing Warning Signs).

Study	Crash Type	Percent Crash Reduction (%)	Study Details
Texas	Head-on, Rear-end, Sideswipe, Angle and Road departure crashes	10	Service Life (years): 10 Maintenance Cost: $1300 per Approach

There do not appear to be any additional studies in the published literature that directly address the safety effects of installing advance warning signals for curve locations where warning signs previously existed.

WC 130 : Install Advance Warning Signs (Curve — Existing Warning Signals)

Definition: Provide signs in advance of a curve where none previously existed.

Table 25. Estimated Effects for Installing Advance Warning Signs (Curve — Existing Warning Signals).

Study	Crash Type	Percent Crash Reduction (%)	Study Details
Texas	Head-on, Rear-end, Sideswipe, Angle and Road departure crashes	5	Service Life (years): 6

There do not appear to be any additional studies in the published literature that directly address the safety effects of installing advance warning signs for curve locations where warning signals previously existed.

WC 131 : Improve Pedestrian Signals

Definition: Bring existing pedestrian signal units into conformance with current standards.

Table 26. Estimated Effects for Improving Pedestrian Signals.

Study	Crash Type	Percent Crash Reduction (%)	Study Details
Texas	Pedestrian crashes	10	Service Life (years): 10
Feldman et al. (2010)	Pedestrian crashes	37	Location: 54 sites in San Francisco, California Methodology: EB Before-after study with 3 years of after data Results: A statistically significant reduction in the numbers of collisions occurred with the installation of high-visibility school crosswalks. Treatment likely contributes to a sense of pedestrian comfort and overall design amenity.
Fitzpatrick et al. (2012)	Total crashes	29	Location: 21intersections in Tucson, Arizona Methodology: EB before-after Study with 3 years of after data Note: Separate analysis using aggregated and disaggregated before-after data. The result related to severe crashes is not statistically significant.
	Severe crashes	15	
	Pedestrian crashes	69	
Huitema et al. (2014)	Pedestrian crashes	70	Location: City of Detroit, Michigan Methodology: Before-after study with a control group Results: No correlation between crashes and traffic volume

Review of Supplemental Studies for WC 131:

Details of the study by Feldman et al. (2010) were previously reviewed in the WC 114 review of studies. They determined that improving pedestrian signals can result in pedestrian crash reductions as high as 37 percent (note that the Texas value is a 10 percent reduction in pedestrian crashes).

Fitzpatrick et al. (2012) assessed the safety effects of the high-intensity activated crosswalk (HAWK) pedestrian beacons. They evaluated crash data at 21 locations in Tucson, Arizona where the HAWK had been deployed. The researchers also included a reference group of 102 un-signalized intersections. The treatment group and reference group shared similar roadway characteristics. The researchers analyzed the data using aggregated data over the entire study period as well as disaggregated data for crash counts representing the before-after period for each intersection.

Huitema et al. (2014) evaluated the safety effects of the pedestrian countdown timer (PCT). The researchers used a before-after study for a set of studied intersections in Detroit, Michigan. They determined that PCTs can be expected to yield the largest effects in locations with very poor pedestrian safety compliance prior to installation.

Overall, improved pedestrian signals can be expected to reduce pedestrian crashes from 37 up to 70 percent (a considerably higher reduction than that currently assumed for the TxDOT value of 10 percent.

WC 132: Install Advance Warning Signals and Signs

Definition: Provide flasher units and signs in advance of hazard where none previously existed.

Table 27. Estimated Effects for Installing Advance Warning Signals and Signs.

Study	Crash Type	Percent Crash Reduction (%)	Study Details
Texas	Depends on the Treatment Type	10	Service Life (years): 10 Maintenance Cost: $1300 per Approach Preventable Crash: Intersection Related = 1 or 2
Huijser et al. (2009)	Reported collisions with large mammals or large mammal road mortalities	42.4	Location: One animal detection system in Montana Methodology: Before-after study with a control section and 1 year of after period data Note: No statistical test performed

<u>Review of Supplemental Studies for WC 132:</u>

Huijser et al. (2009) evaluated the effectiveness of Animal-Vehicle Crash Mitigation system on reducing the number of collisions with large wild animals. Though the researchers did not perform a statistical test, they did conduct a simple before-after evaluation to determine a crash reduction of approximately 42 percent for animal crashes.

WC 133: Improve School Zone

Definition: Improve an existing school zone by upgrading signing, pavement markings, or signals.

Table 28. Estimated Effects for Improving School Zone.

Study	Crash	Percent Crash Reduction (%)	Study Details
Texas	Total crashes	5	Service Life (years): 5 Preventable Crash: All

There do not appear to be any additional studies in the published literature that directly address the safety effects of improving an existing school zone by upgrading signing, pavement markings, or signals.

WC 136: Install Light-Emitting Diode (LED) Flashing Chevrons (Curve)

Definition: Install LED flashing chevrons on curve to provide guidance.

Table 29. Estimated Effects for Installing LED Flashing Chevrons (Curve).

Study	Crash	Percent Crash Reduction (%)	Study Details
Texas	Total crashes	35	Service Life (years): 10 Preventable Crash: (Roadway Related = 2, 3, or 4) or (Vehicle Movements/Manner of Collision = 20 – 24, or 30)
Montella (2009)	Total crashes	47.6	Locations: 15 curves of the motorway A16 Naples–Canosa in Italy Methodology: EB before-after study Goodness of Fit: SE=0.09 for total crashes, 0.14 for Injury crashes, and 0.11 for PDO crashes
	Injury crashes	38.2	
	PDO crashes	56.2	

Review of Supplemental Studies for WC 136:

The Montella (2009) study is summarized in the previous WC 125 section. They determined that a reduction in total crashes of approximately 48 percent could be expected when installing LED flashing chevrons. This is slightly greater than the Texas value of 35 percent.

WC 137: Install Chevrons (Curve)

Definition: Install chevrons on curve to provide guidance.

Table 30. Estimated Effects for Installing Chevrons (Curve)

Study	Crash	Percent Crash Reduction (%)	Study Details
Texas	Total crashes	25	Service Life (years): 10 Preventable Crash: (Roadway Related = 2, 3, or 4) or (Vehicle Movements/Manner of Collision = 20 – 24, or 30)
Tarko et al. (2000)	Total crashes	35	Countermeasure: Install chevron alignment signs on horizontal curves.
Shen et al. (2004)	Total crashes	35	Countermeasure: Install chevron alignment signs on horizontal curves. Location: Missouri
Srinivasan et al. (2009)	Non-intersection crashes	4.3	Locations: 89 treated curves in Connecticut 139 treated curves in Washington Methodology: EB before-after analysis Goodness of fit: SE=8.9 for non-intersection crashes, 8.8 for non-intersection lane departure crashes, 10.4 for F+I crashes, 9.5 for non-intersection crashes during dark conditions, and 10.1 for non-intersection lane departure crashes on curves during dark conditions.
	Non-intersection lane departure crashes	5.9	
	F+I crashes	16.4	
	Non-intersection crashes during dark conditions	24.5	
	Non-intersection lane departure crashes on curves during dark conditions	22.1	

Review of Supplemental Studies for WC 137:

Tarko et al. (2000) developed crash reduction values for installing chevrons at curves and reported these findings in the Indiana *Guidelines for Roadway Safety Improvements*. They determined that a 35 percent reduction in crashes can be expected following the installation of chevrons.

Shen et al. (2004) performed a similar study in Missouri and also determined an estimated 35 percent reduction in crashes.

Srinivasan et al. (2009) acquired geometric, traffic, and crash data for 89 treated curves in Connecticut and 139 treated curves in Washington to use for evaluating safety effectiveness of improved curve delineation. The selected sites were on two-lane rural roads. The treatments included a variety of new chevrons, horizontal arrows, advance warning signs, and the improvement of existing signs using fluorescent yellow sheeting and varied between sites. The researchers performed an EB before-and-after analysis and determined that curve delineation contributed to larger crash reductions at sharper curves (curve radius less than 492 ft), locations with higher traffic volumes, or sites with more hazardous roadsides (roadside hazard rating of 5 or higher).

WC 138: Install Flashing Yellow Arrow

Definition: Modernize existing intersection signals by adding a flashing yellow arrow indication. Refer to WC 108 for improvement of traffic signal.

Review of Supplemental Studies for WC 138:

Srinivasan et al. (2011) evaluated five sites in Kennewich, Washington, 15 sites in Beaverton, Oregon, six sites in Gresham, Oregon, three sites in Oregon City, Oregon, 10 sites in Portland, Oregon, and 16 sites in urban areas from North Carolina. For the Washington sites, the major road annual average daily traffic (AADT) in the before period was, on average, 18,568 vpd (minimum was 11,443 and maximum was 22,756) and the average minor road AADT was 6,729 (minimum was 3,020 and maximum was 11,765). For the sites from Oregon, the average major road AADT in the before period was 22,490 (minimum was 8,260 and maximum was 32,350) and the average minor road AADT in the before period was 3,455 (minimum was 780 and maximum was 10,620). For the sites from North Carolina, the average major road AADT in the before period was 24,206 (minimum was 9,100 and maximum was 43,000), and the average minor road AADT in the before period was 5,048 (minimum was 660 and maximum was 11,350).

The researchers used the EB before-after method with a comparison group. The sample for the conversion from permissive or permissive/protected to FYA is limited. These results should be cautiously considered. As noted in Table 31, the observed reductions in crashes ranged widely.

Table 31. Estimated Effects for Installing Flashing Yellow Arrow.

Study	Crash	Percent Crash Reduction (%)	Study Details
Texas	Total crashes	15	Service Life (years): 10 Preventable Crash: (Intersection Related = 1 or 2) and (Vehicle Movements/Manner of Collision = 34)
Srinivasan et al. (2011)	Total intersection crashes	24.7	Countermeasure: Changing left turn phasing from at least one permissive approach to flashing yellow arrow (FYA) Locations: 55 sites in North Carolina, Oregon and Washington Methodology: Combination of EB before-after and Comparison Group Goodness of fit: SE=9.4 for intersection crashes, 12.6 for intersection left-turn crashes.
	Intersection left-turn crashes	36.5	
	Total intersection crashes	-33.8	Countermeasure: Changing left turn phasing from protected to FYA Locations: 55 sites in North Carolina, Oregon and Washington Methodology: Combination of EB before-after and Comparison Group Goodness of fit: SE=9.7 for intersection crashes, 27.6 for intersection left-turn crashes.
	Intersection left-turn crashes	-124.2	
	Total intersection crashes	7.8	Countermeasure: Changing left turn phasing from protected-permissive to FYA Locations: 55 sites in North Carolina, Oregon and Washington Methodology: Combination of EB before-after and Comparison Group Goodness of fit: SE=10.4 for intersection crashes, 14.6 for intersection left-turn crashes.
	Intersection left-turn crashes	19.4	

ROADSIDE OBSTACLES AND BARRIERS

This section reviews the published literature related to crash reduction factors for roadside obstacles and barriers. The WCs addressed in this section are summarized in Table 32.

Table 32. TxDOT Roadside Obstacles and Barriers Work Codes.

Texas Work Code Number	Work Code Name	Report Page Number
201	Install Median Barrier	29
202	Convert Median Barrier	32*
203	Install Raised Median	33
204	Flatten Side Slope	34
206	Improve Guardrail to Design Standards	35
207	Install Protection	36
209	Safety Treat Fixed Objects	37
217	Install Impact Attenuation System	38

* Additional information could not be located in the published literature.

WC 201: Install Median Barrier

Definition: Construct a metal, concrete, or cable safety system median barrier where none existed previously.

Review of Supplemental Studies for WC 201:

Hauer (2000) evaluated the installation of beam guardrails on medians for a divided highway. Though PDO and injury crashes increased, the fatal crashes decreased by 87 percent.

Elvik and Vaa (2004) conducted a meta-analysis for a variety of median treatment types including cable, steel, and concrete options. This study showed a decrease in fatal and injury crashes and an increase in crashes for all severities following the installation of a variety of median barrier types. The details are shown in the Table 34.

Table 33. Estimated Effects for Installing Median Barrier.

Study	Crash	Percent Crash Reduction (%)	Study Details
Texas	Total crashes	55	Service Life (years): 20 Preventable Crash: Vehicle Movements/Manner of Collision = 30
Hauer (2000)	Fatal	87	Countermeasure: Install beam guardrails on median of divided highway Locations: Principal Arterial Other Freeways and Expressways
	Serious injury, Minor injury	-18	
	PDO	-40	
	Total Crashes	78	
Elvik and Vaa (2004)	Total Crashes	-24	Countermeasure: Any type of Median Barrier Locations: Unspecified (Multi-lane divided highways) Methodology: Meta-analysis Goodness of fit: SE=3 for all crashes, 6 for fatal crashes, and 10 for serious injury and minor injury.
	Fatal	43	
	Serious injury and minor injury	30	
	Serious injury and minor injury	29	Countermeasure: Install cable median barrier Locations: Unspecified (Multi-lane divided highways) Methodology: Meta-analysis Goodness of fit: SE=11 for serious injury and minor injury crashes
	Serious injury and minor injury	35	Countermeasure: Install steel median barrier Locations: Unspecified (Multi-lane divided highways) Methodology: Meta-analysis Goodness of fit: SE=8 for serious injury and minor injury crashes
	Serious injury and minor injury	-15	Countermeasure: Install concrete barrier in median Locations: Unspecified (Multi-lane divided highways) Methodology: Meta-analysis Goodness of fit: SE=36 for serious injury and minor injury crashes
Hovey and Chowdhury (2005)	Total Crashes	86	Locations: 8 sites in Ohio Methodology: EB method Goodness of fit: SE=2.9 for all crashes, 5.2 for injured and fatality crashes.
	Injured and fatality Crashes	88	
Tarko, et al. (2008)	Single vehicle crashes	-120	Locations: 1127 Miles in rural areas in Colorado, Illinois, Indiana, Missouri, New York, Ohio, Oregon, Washington Methodology: EB before-after method Goodness of fit: SE=113 for single vehicle crashes, 37.4 for sideswipe crashes
	Sideswipe crashes	20	
	Cross median, Frontal and opposing direction sideswipe, Head on crashes	100	

Table 33. Estimated Effects for Installing Median Barrier. (continued)

Study	Crash	Percent Crash Reduction (%)	Study Details
Villwock et al. (2009)	Fixed object, Run-off-road, Single vehicle	-72	Locations: 113 Miles in rural areas Indiana Methodology: EB before-after method Goodness of fit: SE=58 for fixed object, run off road and single vehicle crashes, 63 for rear end and sideswipe crashes, and 6 for cross median, frontal and opposing direction sideswipe, head on crashes.
	Rear end, Sideswipe	-8	
	Cross median, Frontal and opposing direction sideswipe, Head on crashes	96	
Olsen et al.(2011)	Total Crashes	62	Locations: 42 sites in Utah Methodology: EB before-after method Goodness of fit: SE=10 for all crashes and 10 for injury and fatality crashes.
	Fatal and Serious injury	44	

Table 34. Potential Crash Effects of Installing a Median Barrier.

Treatment	Setting (Road Type)	Traffic Volume	Crash Type (Severity)	CMF*	Std. Error
Install any type of median barrier	Unspecified (Multi-lane divided highways)	AADT of 20,000 to 60,000	All types (Fatal)	0.57	0.1
			All types (Injury)	0.70	0.06
			All types (All Severity)	1.24	0.03
Install steel median barrier			All types (Injury)	0.65	0.08
Install cable median barrier				0.71	0.10

* CMF refers to a Crash Modification Factor

Base Condition: Absence of a median barrier.
Based on US studies: Billion 1956; Moskowitz and Scheafer 1960; Beaton, Field and Moskowitz 1962; Billion and Parsons 1962; Billion, Taragin and Cross 1962; Sacks 1962; Johnson 1966; Williston 1969; Galati 1970; Tye 1975; Ricker, Banks Brenner, Brown and Hall 1977; Hunter, Steward and Council 1993; Sposito and Johnson 1999; Hancock and Ray 2000; Hunter et al 2001; and International studies: Moore and Jehu 1968; Good and Joubert 1971; Anderson 1977; Johnson 1980; Statens vagverk 1980; Martin et al 1998; Nilsson and Ljungblad 2000.

Source: Adapted from Elvik and Vaa, 2004

Hovey and Chowdhury (2005) used the EB methodology to analyze the data collected from Ohio. The researchers developed crash reduction factors for the following improvement categories: adding a two-way left turn lane, installing a median barrier, flattening slope and removing guardrail, removing or relocating a fixed object, flattening vertical curve, providing highway lighting and closing median opening. They determined that median barrier is statistically effective in reducing both injury and fatal crashes.

Tarko, et al. (2008) the safety impact of median designs based on data collected in eight participating states (Colorado, Illinois, Indiana, Missouri, New York, Ohio, Oregon, and Washington). They analyzed the data using negative binomial regression and before-after studies methods. The crashes were divided into three categories: single vehicle (SV), multiple vehicle same direction (SD), and multiple vehicle opposing direction (OD). The researchers used a logit model approach to study the impact on crash severity. The results indicated that reducing the median width without adding barriers would increase the severity of crashes (particularly OD crashes). Furthermore, installation of concrete barriers after reducing the median helped to reduce the OD crashes but doubled the frequency of SV crashes

Villwock et al. (2009) investigated the safety impact of high-tensioned cable barriers based on data collected in eight participating states. They used negative binomial regression, before-after studies, and logistic regression to analyze the data obtained from 113 miles of road sections in rural areas, Indiana. The crashes were divided into the SV, SD, and OD categories.

Olsen et al. (2011) performed a before-after study using hierarchical Bayesian modeling to evaluate the effect of cable barriers on Utah highways.

WC 202: Convert Median Barrier

Definition: Remove an existing metal median barrier system and install a concrete or cable safety system median barrier.

Table 35. Estimated Effects for Converting Median Barrier.

Study	Crash	Percent Crash Reduction (%)	Study Details
Texas	Total crashes	40	Service Life (years): 15 Preventable Crash: (Roadway related = 4) and (Object struck= 23, 39, 56, 62, or 63)] or (Vehicle Movements/Manner of Collision = 30))

There do not appear to be any additional studies in the published literature that directly address the safety effects of removing a metal median barrier and installing a concrete or cable safety system.

WC 203: Install Raised Median

Definition: Install a roadway divider using barrier curb.

Table 36. Estimated Effects for Installing Raised Median.

Study	Crash	Percent Crash Reduction (%)	Study Details
Texas	Total crashes	25	Service Life (years): 20 Preventable Crash: (Part of Roadway No. 1 Involved = 1) and (Vehicle Movements/Manner of Collision = 10, 14, 20–22, 24, 26, 28–30, 34 or 38)
Gattis et al. (2005)	Total crashes	13	With right shoulder Locations: Several rural and suburban four-lane highways in Arkansas
		43	With right curb Locations: Several rural and suburban four-lane highways in Arkansas
Eisele et al. (2005)	Total crashes	60	Crash rates reduced from 4.3 to 1.8 crashes per million vehicle miles of travel In the first year of this 2-year project Study corridor in Texas
	Total crashes	31	From either a TWLTL or an undivided roadway to a raised median. Five specific corridors or segments of the corridors were studied before-after the raised median installation.
Schultz et al. (2011)	Total crashes	39	Locations: Several sites at which raised medians have been installed in the past 10 years in Utah. Methodology: Using a hierarchical Bayesian model
	Severe crashes	44	

Review of Supplemental Studies for WC 203:

Gattis et al. (2005) evaluated three years of crash data for four-lane highways located in rural and suburban Arkansas. Their goal was to assess the safety effects of median treatments and access density. They excluded roadways with posted speeds lower than 40 mph and fully controlled access roadways. The crash rate decreased with increased median width, but increased with increased access density.

Eisele et al. (2005) investigated the operational and safety impact of raised medians and driveway consolidation. They studied 11 test corridors and estimated relationships between crash rates and median types (raised medians or two-way left-turn lanes (TWLTLs)). They observed that crash rates increase with the increase of access point density regardless of the median type. Crash rate decreased after the installation of raised median.

Schultz et al. (2011) applied a hierarchical Bayesian model to the analysis of the effect of raised medians in Utah. They used crash data from several sites where raised medians had been installed in the previous 10 year period.

WC 204: Flatten Side Slope

Definition: Provide an embankment side slope of 6:1 or flatter.

Table 37. Estimated Effects for Flattening Side Slope.

Study	Crash	Percent Crash Reduction (%)	Study Details
Texas	Total crashes	46	Service Life (years): 20 Preventable Crash: Roadway Related = 3
Hovey and Chowdhury (2005)	Total crashes	42	Locations: 8 sites in Ohio Methodology: EB method Goodness of fit: SE=57.5 for all crashes.
Harkey et al. (2008)	Single vehicle crashes	12	Treatment: The value of 12 and 7 are the CRFs for sideslope of 1:4 in before condition and 1:6 in after condition, more values can be found in Table 38 Locations: Rural two-lane roads Methodology: Log linear regression models
	Total crashes	7	

Review of Supplemental Studies for WC 204:

Hovey and Chowdhury (2005) applied the EB methodology to analyze data collected from Ohio for the following improvement categories: adding a TWLTL, installing a median barrier, flattening slope and removing guardrail, removing or relocating a fixed object, flattening vertical curve, providing highway lighting and closing median opening. They estimated a 42.4 percent reduction in crashes after flattening slopes and removing guardrail. The standard error of estimate is 0.575. Because there were not any injury or fatality crashes reported during the study, they did not compute the crash reduction percentage for injury and fatality crashes.

Harkey et al. (2008) documented findings from an original study by Zegeer et al. (1988). They used loglinear regression models to develop estimates of the effects of sideslope on single-vehicle crashes and total crashes on rural two-lane roads. The NCHRP Projects17-25/17-29 expert panel on rural multilane highways concluded that the CMFs derived were valid and the best available for both rural two-lane roads and rural multilane highways. The CMF detailes are shown in Table 38 and Table 39.

Table 38. CMFs of Single Vehicle Crashes

Sideslope in Before Condition	Sideslope in After Condition			
	1:4	1:5	1:6	1:7
1:2	10	15	21	27
1:3	8	14	19	26
1:4	-	6	12	19
1:5	-	-	6	14
1:6	-	-	-	8

Source: Adapted from Harkey et al., 2008

Table 39. CMFs of Total Crashes

Sideslope in Before Condition	Sideslope in After Condition			
	1:4	1:5	1:6	1:7
1:2	6	9	12	15
1:3	5	8	11	15
1:4	-	3	7	11
1:5	-	-	3	8
1:6	-	-	-	5

Source: Adapted from Harkey et al., 2008

WC 206: Improve Guardrail to Design Standards

Definition: Bring existing substandard guardrail into conformance with current design standards.

Table 40. Estimated Effects for Improving Guardrail to Design Standards.

Study	Crash	Percent Crash Reduction (%)	Study Details
Texas	Total crashes	35	Service Life (years): 10 Preventable Crash: (Roadway Related = 2, 3 or 4) or (Object Struck = 20–26, 29–36, 40–42, 56–58, 60, 62, or 63)
Elvik and Vaa (2004)	Fatal injury crashes	44	Locations: 20 studies were evaluated, including 12 U.S. studies (6 of which were conducted in 1982 or later). Methodology: Meta-analysis
	All injury crashes	47	

Review of Supplemental Studies for WC 206:

Elvik and Vaa (2004) investigated the safety effects of guardrail installations along an embankment. The studies included in the meta-analysis were not differentiated by roadway class. The researchers determined that the changes in the crash rate were not statistically significant.

WC 207: Install Protection

Definition: Install guardrail or concrete traffic barrier where none existed previously. Refer to WC 209 if using guardrail to safety treat a fixed object or drainage structures.

Table 41. Estimated Effects for Installing Protection.

Study	Crash	Percent Crash Reduction (%)	Study Details
Texas	Total crashes	30	Service Life (years): 10 Preventable Crash: (Roadway Related = 2, 3 or 4) or (Object Struck = 20–26, 29–36, 40–42, 56–58, 60, 62, or 63)
Elvik and Vaa (2004)	Serious injury and minor injury	35	Countermeasure: Install steel median barrier Locations: Unspecified (Multi-lane divided highways) Methodology: Meta-analysis Goodness of fit: SE=8 for serious injury and minor injury crashes
	Serious injury and minor injury	-15	Countermeasure: Install concrete guardrail in median Locations: Unspecified (Multi-lane divided highways) Methodology: Meta-analysis Goodness of fit: SE=36 for serious injury and minor injury crashes
Tarko et al. (2008)	Single vehicle crashes	-120	Locations: 1127 Miles in rural areas in Colorado, Illinois, Indiana, Missouri, New York, Ohio, Oregon, and Washington Methodology: EB before-after method Goodness of fit: SE=113 for single vehicle crashes, 37.4 for sideswipe crashes
	Sideswipe crashes	20	
	Cross median, Frontal and opposing direction sideswipe, Head on crashes	100	

Review of Supplemental Studies for WC 207:

The 2004 study by Elvik and Vaa is described in the previous WC 201 section. They noted an increase of 15 percent in serious and minor injury crashes when installing a concrete barrier, and a decrease of 35 percent for the same crash type when installing a steel barrier.

Similarly, the 2008 Tarko et al. study is also described in the WC 201 section. They noted an increase of 120 percent in single vehicle crashes but a decrease of from 20 to 100 percent for sideswipe and opposing direction crashes, respectively.

WC 209: Safety Treat Fixed Objects

Definition: Remove, relocate or safety treat all fixed objects including the installation of guardrail for safety treatment of a fixed object or drainage structures within the project limits, to include both point and continuous objects.

Table 42. Estimated Effects for Safety Treat Fixed Objects.

Study	Crash	Percent Crash Reduction (%)	Study Details	
Texas	Total crashes	50	Service Life (years): 20 Preventable Crash: (Roadway Related = 2, 3 or 4) or (Object Struck = 20–26, 29–36, 40–42, 56–58, 60, 62, or 63)	
Agent et al. (1996)	Total crashes	32	Remove fixed objects	Data from survey of 15 states
		22		From a review of 10 studies
	Fatal	50		Data from survey of 8 states
		53		From a review of 3 studies
	Injury	17		Data from survey of 8 states
		17		From a review of 3 studies
	Off road	55		Data from survey of 2 states
	Total crashes	41	Relocate fixed objects	Data from survey of 10 states
		42		From a review of 2 studies
	Fatal	40		Data from survey of 4 states
		40		From a review of 2 studies
	Injury	15		Data from survey of 4 states
		15		From a review of 2 studies
	Off road	55		Data from survey of 2 states
Elvik and Vaa (2004)	Serious injury and minor injury	-15	Countermeasure: Install concrete barrier in median Locations: Unspecified (Multi-lane divided highways) Methodology: Meta-analysis Goodness of fit: SE=36 for serious injury and minor injury crashes	

<u>Review of Supplemental Studies for WC 209:</u>

The details of the Agent et al. (1996) study are described in the WC 101 section. The 2004 meta-analysis study by Elvik and Vaa is described in the WC 201 section. Elvik and Vaa noted an increase in injury crashes of 15 percent following the installation of a concrete median barrier. Agent et al., however, only noted crash reductions ranging from 15 up to 55 percent.

WC 217: Install Impact Attenuation System

Definition: Provide any of a variety of impact attenuators where none existed previously.

For Countermeasure: Install crash cushions at fixed roadside features

Table 43. Estimated Effects for Installing Impact Attenuation System.

Study	Crash	Percent Crash Reduction (%)	Study Details
Texas	Total crashes	50	Service Life (years): 20 Preventable Crash: (Roadway Related = 2, 3 or 4) or (Object Struck = 20–26, 29–36, 40–42, 56–58, 60, 62, or 63)
Elvik and Vaa (2004)	Fixed Object Serious injury and minor injury crashes	69	Countermeasure: Install crash cushions at fixed roadside features Locations: Unspecified (Multi-lane divided highways) Methodology: Meta-analysis Goodness of fit: SE=28 for fixed object (serious injury and minor injury) crashes, 10 for fixed Object (fatal) crashes, and 30 for fixed Object PDO crashes.
	Fixed Object fatal crashes	69	
	Fixed Object PDO crashes	46	

<u>Review of Supplemental Studies for WC 217:</u>

Details of the 2004 study by Elvik and Vaa are described in the WC 201 section. Their meta-analysis assessed the installation of crash cushions at fixed roadside features determined a 46 to 69 percent reduction in crashes. This is consistent with the TxDOT value of 50 percent.

RESURFACING AND ROADWAY LIGHTING

This section reviews the published literature related to estimated crash reductions for resurfacing and roadway lighting countermeasures. The WCs addressed in this section are summarized in Table 44.

Table 44. TxDOT Resurfacing and Roadway Lighting Work Codes.

Texas Work Code Number	Work Code Name	Report Page Number
303	Resurfacing	39
304	Safety Lighting (Roadway)	40
305	Safety Lighting at Intersection	41
306	High Friction Surface Treatment (Curve)	42
307	High Friction Surface Treatment (Intersection)	43

WC 303: Resurfacing

Definition: Provide a new roadway surface to increase pavement skid numbers on all the lanes.

Table 45. Estimated Effects for Resurfacing.

Study	Crash	Percent Crash Reduction (%)	Study Details
Texas	Total crashes	30	Service Life (years): 10 Preventable Crash: Surface Condition = 2 or 4 (Skid Value must be less than 20)
Agent et al. (1996)	Total crashes	26	Data from survey of 14 states
Agent et al. (1996)	Total crashes	27	From a review of 8 studies
Agent et al. (1996)	Wet	41	Data from survey of 7 states
Agent et al. (1996)	Wet	45	From a review of 3 studies
Erwin and Tighe (2008)	All crashes (AADT<2999/lane)	14	Countermeasure: Refinish pavement with resurfacing treatment Locations: 84 sites in Region of York, Canada Methodology: Simple before-after analysis Goodness of fit: SE= 75.73 for all crashes (AADT<2999/lane), SE=8 for all crashes (3000<AADT<6999/lane), SE=12.62 for all crashes (AADT>7000/lane).
Erwin and Tighe (2008)	All crashes (3000 < AADT < 6999 per lane)	26	
Erwin and Tighe (2008)	All crashes (AADT > 7000 per lane)	-6	
Erwin and Tighe (2008)	Wet Road crashes (3000 < AADT < 6999 per lane)	51	
Erwin and Tighe (2008)	Rear end crashes (3000<AADT<6999/lane)	33	
Abdel-Aty et al. (2009)	Total crashes	-0.6	Locations: 2780 continuous roadway sections of multilane arterials having the same number of lanes and speed limit from the state of Florida Countermeasure: resurface treatment Methodology: EB Before-after method Goodness of fit: SE=1.6 for total crashes, SE=4.5 for fatal and serious injury crashes, and SE=2.6 for rear-end crashes
Abdel-Aty et al. (2009)	Fatal and serious injury crashes	4.6	
Abdel-Aty et al. (2009)	Rear-end crashes	0.8	

Review of Supplemental Studies for WC 303:

The details of the Agent et al. (1996) study are described in the WC 101 section. They noted a crash reduction similar to the 30 percent used by TxDOT; however, the observed a greater reduction of crashes during wet weather (41 to 45 percent) than observed for all crashes (26 to 27 percent).

Erwin and Tighe (2008) conducted a before-after study to evaluate safety effects of resurfacing and remedying pavements with microsurfacing treatments. They obtained data from the York Region, in Toronto, Canada. Their results indicated that the influence on crashes, due to the resurfacing, were sensitive to the treatment year date and average AADT per lane. They concluded that microsurfacing, in general, has a positive safety effect under the following conditions: regular occurrence of wet or slick (not dry) road surface conditions, a trend toward severe crashes, frequent intersection-related crashes, and a high occurrence of rear-end crashes.

Abdel-Aty et al. (2009) conducted an EB before-after study to assess the safety effects of resurfacing projects on multilane arterials with partially limited access. The results revealed widely varying (moderate) safety effects.

WC 304 : Safety Lighting (Roadway)

Definition: Provide roadway lighting, either partial or continuous, where either none existed previously or major improvements are being made.

Review of Supplemental Studies for WC 304:

The details of the Agent et al. (1996) study are described in the WC 101 section. As shown in Table 46, they found lighting resulted in a night time crash reduction from 38 to 42 percent with a total crash reduction of 19 to 28 percent.

Table 46. Estimated Effects for Safety Lighting (Roadway)

Study	Crash	Percent Crash Reduction (%)	Study Details
Texas	Total crashes	40	Service Life (years): 15 Maintenance Cost: $100 per Luminaire Preventable Crash: Light Condition = 3, 4 or 6
Agent et al. (1996)	All-New Roadway	28	Data from survey of 10 states
		19	From a review of 7 studies
	Night-New Roadway	45	Data from survey of 12 states
		38	From a review of 5 studies
	Night-upgrade Roadway	42	Data from survey of 2 states
Elvik and Vaa (2004); Harkey et al. (2008)	Nighttime crashes (all crashes)	20	Locations: 38 studies as part of the meta-analysis, including 14 United States studies. Methodology: Meta-analysis / expert Panel
	Nighttime crashes (all injury crashes)	19	
	Total crashes	6	
	All crashes (all injury crashes)	8	

Elvik and Vaa (2004) and Harkey et al. (2008) further evaluated the crash reductions due to adding roadway lighting. They obtained the distributions of crashes by injury severity and time of day from the HSIS data for Minnesota and Michigan. The meta-analysis results produced CMF estimates for reductions in fatal, injury and property-damage-only crashes of 0.36, 0.72, and 0.83, respectively. This is equivalent to crash reductions of 64, 38, and 17 percent. The NCHRP 17-25/17-26 expert panel on urban/suburban arterials recommended that the meta-analysis results be applied to roadway segments and that the fatal and injury results be combined into a single CMF for all levels of injury. The NCHRP 17-26 Final Report includes a distribution of crashes by time of day and injury severity for several roadway classes. The resulting crash reductions represent the mean estimates for all roadway classes and were derived on the basis of these distributions and the meta-analysis.

WC 305 : Safety Lighting at Intersection

Definition: Install lighting at an intersection where either none existed previously or major improvements are proposed.

Table 47. Estimated Effects for Safety Lighting at Intersection.

Study	Crash	Percent Crash Reduction (%)	Study Details
Texas	Total crashes	45	Service Life (years): 15 Maintenance Cost: $100 per Luminaire Preventable Crash: Light Condition = 3, 4 or 6 and Intersection Related = 1 or 2
Agent et al. (1996)	All (new intersection)	31	Data from survey of 8 states
		25	From a review of 1 study
	Night (new intersection)	49	Data from survey of 12 states
		64	From a review of 6 studies
	All (upgrade intersection)	38	Data from survey of 2 states
	Night (upgrade intersection)	50	Data from survey of 1 states
		50	From a review of 2 studies
Elvik and Vaa (2004); Harkey et al. (2008)	Nighttime crashes (all crashes)	21	Locations: 38 studies were evaluated as part of the meta-analysis, including 14 U.S. studies. Methodology: Meta-analysis / expert Panel
	Nighttime crashes (all injury crashes)	29	
	Total crashes	4	
	All crashes (all injury crashes)	6	

<u>Review of Supplemental Studies for WC 305:</u>

The details of the Agent et al. (1996) study are described in the WC 101 section. As shown in Table 47, installing lighting at an intersection can reduce night time crashes from 49 to 64 percent and all crashes from 25 to 38 percent.

The details of Elvik and Vaa (2004) and Harkey et al. (2008) are described in the previous WC 304 section. They determined a much lower 4 to 6 percent crash reduction for all crashes, but found a 21 to 29 percent reduction in night time crashes.

When contrasted to both studies, the TxDOT percent reduction for total crashes of 45 percent appears to more close align with estimated night time crash reductions for other studies.

WC 306 : High Friction Surface Treatment (Curve)

Definition: Provide a high friction surface treatment on a curve.

Table 48. Estimated Effects for High Friction Surface Treatment (Curve).

Study	Crash	Percent Crash Reduction (%)	Study Details
Texas	Total crashes	45	Service Life (years): 5 Preventable Crash: (Roadway Related = 2, 3, or 4) or (Surface Condition = 2 or 4)
Bray (2001) and Harkey et al. (2008)	Total crashes	24	Locations: Data collected from New York State for 36.3 miles of treated segments and 1,242.4 miles of reference segments. Locations in both urban and rural locations. Methodology: EB Before-After Goodness of Fit: SE=2 for all crashes, 2 for wet-road crashes, 4 for rear-end crashes, 6 for rear-end wet-road crashes and 4 for single-vehicle crashes
	Wet-Road crashes	57	
	Rear-end crashes	17	
	Rear-end Wet-road crashes	42	
	Single vehicle crashes	93	

Review of Supplemental Studies for WC 306:

Bray (2001) and Harkey et al. (2008) evaluated this treatment using the Skid Accident Reduction Program (SKARP) developed by NY State DOT in 1995. The analysis was based on data collected from New York State for 36.3 miles of treated segments and 1,242.4 miles of reference segments. Locations were in both urban and rural locations. The segments are in close proximity to treated intersections, which are the primary targets of the treatment. The agency selected study sites for treatment based on both a high proportion of wet-road crashes and low friction numbers. The treatment generally involved a 1.5-in. resurfacing or a 0.5-in. microsurfacing using non-carbonate aggregates. The researchers observed crash reductions ranging from 17 up to 93 percent with a total crash reduction estimated as 14 percent.

The Texas estimated crash reductions are greater than those suggested by Bray (2001) and Harkey et al. (2008), but similar to the wet road conditions values they observed.

WC 307: High Friction Surface Treatment (Intersection)

Definition: Provide a high friction surface treatment at an intersection approach.

Table 49. Estimated Effects for High Friction Surface Treatment (Intersection).

Study	Crash	Percent Crash Reduction (%)	Study Details
Texas	Total crashes	20	Service Life (years): 5 Preventable Crash: Intersection Related = 1 or 2
Bray (2001); Harkey et al. (2008)	Wet-Road crashes	57	Locations: 256 treated intersections and 3993 reference intersections (urban and rural) Methodology: EB before-after method Goodness of Fit: SE=3 for all crashes, 3 for wet-road crashes, 3 for rear-end crashes, 5 for dry-road Crashes and 4 for rear-end wet-road crashes
	Rear-end crashes	42	
	Dry-Road Crashes	-15	
	Rear-end Wet-road crashes	68	

Review of Supplemental Studies for WC 307:

The details of the Bray (2001) and Harkey et al. (2008) analysis are reviewed in the previous WC 306 section. The researchers collected data for 256 treated intersections and 3993 reference intersections. For the treated sites, 73 were signal-controlled, 176 were stop-controlled, and 7 were yield-controlled. Fifty-seven were four-leg and 199 were three-leg intersections. The agency selected study sites for treatment based on both a high proportion of wet-road crashes and low friction numbers. The treatment generally involved a 1.5-inch resurfacing or a 0.5-inch microsurfacing using non-carbonate aggregates. The researchers determined that wet road crashes can be estimated to reduce from 57 to 68 percent with the use of the improved pavement friction.

PAVEMENT MARKINGS

This section reviews the published literature related to estimated crash reduction for pavement markings. The WCs addressed in this section are summarized in Table 53.

Table 50. TxDOT Pavement Marking Work Codes.

Texas Work Code Number	Work Code Name	Report Page Number
401	Install Pavement Markings	45
402	Install Edge Markings	46
403	Install Pedestrian Crosswalk	47
404	Install Centerline Striping	49
407	Install Sidewalks	50

WC 401 : Install Pavement Markings

Definition: Place complete pavement markings, excluding crosswalks, in accordance with the Texas Manual on Uniform Traffic Control Devices (TMUTCD) where either no markings or nonstandard markings exist. Refer to WC 402 for edge marking, WC 403 for pedestrian crosswalks, and WC 404 for centerline striping.

Table 51. Estimated Effects for Installing Pavement Markings.

Study	Crash	Percent Crash Reduction (%)	Study Details
Texas	Total crashes	20	Service Life (years): 2 Preventable Crash: (Roadway Related = 2, 3 or 4) or (Vehicle Movements/Manner of Collision = 21 or 30) or (First Harmful Event = 3)
Al-Masaeid and Sinha (1994)	Total crashes	13.5	Locations: 100 sites on rural roads in Indiana Methodology: Bayesian approach Goodness of Fit: the expected range of 6.5% and 21.5% corresponding to 10% and 90% probability levels, respectively
Elvik and Vaa (2004)	Injury crashes	-1	Countermeasure: Place centerline markings Locations: Unspecified (Multi-lane divided highways) Methodology: Meta-analysis Goodness of fit: SE=6 for injury crashes and 5 for PDO crashes.
	PDO crashes	1	

Review of Supplemental Studies for WC 401:

Al-Masaeid and Sinha (1994) evaluated the safety effectiveness of pavement marking on undivided rural roads with traffic volumes ranging from 1000 to 4000 vehicles per day. The study was based on 100 rural roads randomly selected in Indiana where the pavement markings were placed in 1987. The researchers used a Bayesian approach so as to eliminate the effect of regression to the mean bias. They found approximately a 14 percent crash reduction for total crashes.

The details of Elvik and Vaa (2004) are described in the previous WC 201 section. Using a meta-analysis approach, they found negligible results due to the pavement marking.

The TxDOT total crash reduction value of 20 percent is larger than those identified in these companion research efforts.

WC 402 : Install Edge Marking

Definition: Place edge lines where none existed previously.

Review of Supplemental Studies for WC 402:

The details of the Agent et al. (1996) study are described in the WC 101 section. As shown in Table 52, installing edge lines where none previously existed can be estimated to reduce total crashes by 15 to 20 percent and run-off-road crashes from 25 to 36 percent.

The details of the Elvik and Vaa (2004) study are described in the WC 201 section. They determined that installing edge markings in conjunction with centerline markings has a greater expected influence on crash reductions then just the edge marking installation.

The TxDOT estimated crash reduction of 25 percent for total crashes is slightly higher than that observed in the published literature (where total crash reduction values range from 15 to 20 percent.

Table 52. Estimated Effects for Installing Edge Marking.

Study	Crash	Percent Crash Reduction (%)	Study Details
Texas	Total crashes	25	Service Life (years): 2 Preventable Crash: Roadway Related = 2, 3 or 4
Agent et al. (1996)	Total crashes	20	Data from surveys of 19 states
		15	From a review of 11 studies
	Off road	25	Data from surveys of 2 states
		36	From a review of 3 studies
Elvik and Vaa (2004)	Injury crashes	24	Countermeasure: Place edgeline and centerline markings Locations: Unspecified (Multi-lane divided highways) Methodology: Meta-analysis Goodness of fit: SE=11 for injury crashes
	Injury crashes	3	Countermeasure: Place standard edgeline marking (4-6 in) Locations: Unspecified (Multi-lane divided highways) Methodology: Meta-analysis Goodness of fit: SE=4 for injury crashes and 11 for PDO crashes.
	PDO crashes	3	
	Injury crashes	-5	Countermeasure: Place wide (8 inches) edgeline markings Locations: Unspecified (Multi-lane divided highways) Methodology: Meta-analysis Goodness of fit: SE=8 for injury crashes and 15 for PDO crashes.
	PDO crashes	1	
	Injury crashes	19	Countermeasure: Placing edgelines and background/ directional markings on horizontal curves Locations: Unspecified (Multi-lane divided highways) Methodology: Meta-analysis Goodness of fit: SE=31 for injury crashes

WC 403: Install Pedestrian Crosswalk

Definition: Place pedestrian crosswalk markings where none existed previously. Refer to WC 114 for school zones and WC 110 for pedestrian signal.

Table 53. Estimated Effects for Installing Pedestrian Crosswalk.

Study	Crash	Percent Crash Reduction (%)	Study Details
Texas	Total crashes	10	Service Life (years): 2 Preventable Crash: First Harmful Event = 1
Agent et al. (1996)	Total crashes	10	Data from survey of 2 states
	Pedestrian	18	From a review of 2 studies
Haleem and Abdel-Aty (2011)	Total crashes	65	Countermeasure: Install pedestrian crosswalk on one minor approach Locations: 1735 unsignalized intersections in Florida Methodology: Regression cross-section
Chen et al. (2012)	Vehicle/pedestrian crashes	40	Countermeasure: Install high-visibility crosswalk Locations: Urban areas in New York Methodology: Simple before-after
	Angle, Head-on, Left-turn, Rear-end, Rear-to-rear, Right-turn, and Sideswipe crashes	19	

Review of Supplemental Studies for WC 403:

The details of the Agent et al. (1996) study are described in the WC 101 section. As shown in Table 53, installing a pedestrian crosswalk where one did not previously exist can be estimated to reduce total crashes by 10 percent and pedestrian crashes by 18 percent.

Haleem and Abdel-Aty (2011) obtained data for 2475 unsignalized intersections and used the least absolute shrinkage and selection operator technique to identify the significant factors affecting safety of unsignalized intersections. According to this analysis, the significant predictors were traffic volume on the major road, the upstream and downstream distances to the nearest signalized intersection, median type on major and minor approaches, and type of land use.

Chen et al. (2012) evaluated the relative effectiveness of five countermeasures with regard to pedestrian safety in New York City: 1) increasing the total cycle length, 2) Barnes Dance all-pedestrian phase, 3) split phase timing, 4) signal installation, and 5) high visibility crosswalk. They determined that the four signal-related countermeasures were more effective in reducing crashes than the high visibility crosswalks in a large urban area.

WC 404: Install Centerline Striping

Definition: Provide centerline striping where either no markings or nonstandard markings existed previously. Refer to WC 401 for complete pavement markings.

Table 54. Estimated Effects for Installing Centerline Striping.

Study	Crash	Percent Crash Reduction (%)	Study Details
Texas	Total crashes	65	Service Life (years): 2 Preventable Crash: Vehicle Movements/Manner of Collision = 30
Persaud et al. (2003)	All severities (total crashes)	14	Countermeasure: Add Centerline Rumble Strips Locations: 98 treatment sites, consisting of 210 miles, where centerline rumble strips had been installed on rural two-lane roads in the states of California, Colorado, Delaware, Maryland, Minnesota, Oregon, and Washington. Methodology: EB Before-After Goodness of fit: SE=5for all severity crashes, SE=12 for all severities (frontal/opposing-direction sideswipe crashes), SE=8 for injury crashes (all crashes), and SE=15 injury crashes (frontal/opposing-direction sideswipe
	All severities (frontal/opposing-direction sideswipe crashes)	21	
	Injury crashes	15	
	Injury crashes (frontal/opposing-direction sideswipe crashes)	25	
	PDO crashes	1	

<u>Review of Supplemental Studies for WC 404:</u>

Persaud et al. (2003) collected crash and traffic volume data for 98 treatment sites, consisting of 210 miles, where centerline rumble strips had been installed on rural two-lane roads in the states of California, Colorado, Delaware, Maryland, Minnesota, Oregon, and Washington. The average length of the treatment sites was two miles, and the traffic volumes ranged from 5,000 to 22,000 vpd. The reference group of sites was developed from HSIS data for the states of California, Washington, and Minnesota. The researchers also acquired additional data from Colorado for safety performance function (SPF) calibration for the Colorado sites.

The authors noted that the results covered a wide range of geometric conditions, including curved and tangent sections and sections with and without grades. The results included all rumble strip designs (milled-in, rolled-in, formed, and raised thermo-plastic) and placements (continuous versus intermittent) that were present. Though their focus was on the centerline rumble strip, some of the benefits may have been due to the marking itself.

The application of a solitary centerline application is widespread and so research studies that addressed the single application of centerline markings where they did not exist before does not appear to be available in the published literature.

WC 407: Install Sidewalks

Table 55. Estimated Effects for Installing Sidewalks.

Study	Crash	Percent Crash Reduction (%)	Study Details
Texas	Total crashes	20	Service Life (years): 10 Preventable Crash: First Harmful Event = 1 or 5
Agent et al. (1996)	Pedestrians	68	Data from survey of 2 states
Bahar et al. (2008)	Pedestrian crash type (all severity levels)	65-89	Based on a variety of state applications

Review of Supplemental Studies for WC 407:

The details of the Agent et al. (1996) study are described in the WC 101 section. As shown in Table 59, they estimated the effects of installing sidewalks to result in an estimated reduction in pedestrian crashes of 68 percent. Bahar et al. (2008) used data from several states to estimate a 65 to 89 percent reduction in crashes. By contrast, the TxDOT value of 20 percent represents 20 percent for total crashes.

ROADWAY WORK

This section reviews the published literature related to crash reduction factors for roadway work treatments. The WCs addressed in this section are summarized in Table 56.

Table 56. TxDOT Roadway Work Codes.

Texas Work Code Number	Work Code Name	Report Page Number
501	Modernize Facility to Design Standards	52*
502	Widen Lane(s)	52
503	Widen Paved Shoulder (to 5 ft or less)	55
504	Construct Paved Shoulders (1 to 4 ft)	57
505	Improve Vertical Alignment (Reconstruct the Roadway to Improve Sight Distance)	57
506	Improve Horizontal Alignment	58
507	Increase Superelevation	59
508	Realign Intersection	60*
509	Channelization	60
510	Construct Turn Arounds	62*
514	Grade Separation	62
515	Construct Interchange	63
516	Close Crossover	63
517	Add Through Lanes	64*
518	Install Continuous Turn Lane	64
519	Add Left Turn Lane	66
520	Lengthen Left Turn Lane	68*
521	Add Right Turn Lane	69
522	Lengthen Right Turn Lane	70*
523	Construct Pedestrian Over/Under Pass	70
524	Increase Turning Radius	71
525	Convert to One-Way Frontage Road	72
526	Increase Vertical Clearance (Lower Grade)	73*
527	Increase Vertical Clearance (Remove Structure)	73*
528	Construct Median Crossover	74*
529	Remove Raised Median / Concrete Island	74*
532	Texturize Shoulders (Rolled-in or Milled-in)	74
533	Texturize Shoulders (Profile Pavement Markings)	76
535	Widen Median Opening for Storage	77*
536	Widen Paved Shoulders (to > 5 ft)	77
537	Construct Paved Shoulders (5 ft)	78
538	Convert Two-Lane Facility to Four-Lane Divided	79
539	Install Median on Undivided Facility	80*
540	Install Passing Lanes on Two-Lane Roadways	81
541	Provide Additional Paved Surface Width	82*
542	Centerline Texturing	82

* Additional information could not be located in the published literature.

WC 501: Modernize Facility to Design Standards

Definition: Provide modernization to all features within the right-of-Way to achieve current desirable standards. This includes work such as widening the travelway, widening the shoulders, constructing shoulders, flattening the side slopes, and treating roadside obstacles.

Table 57. Estimated Effects for Modernizing Facility to Design Standards.

Study	Crash	Percent Crash Reduction (%)	Study Details
Texas	Total crashes	15	Service Life (years): 20 Preventable Crash: All
Note: This could be combined with other work codes.			

There do not appear to be any additional studies in the published literature that directly address the safety effects of modernizing a facility to design standards.

WC 502: Widen Lane(s)

Definition: Provide additional width to the lane(s). Refer to WC 517 if adding a through lane.

Review of Supplemental Studies for WC 502:

Zegeer et al. (1980) focused on run-off-road, head-on, and sideswipe crashes. The researchers estimated the safety effects of lane widths on these crash types for rural, two-lane roads. They grouped the study sites by facility type, average daily traffic (ADT), number of access points, lane width, and shoulder width. Horizontal curvature, vertical curvature, and some measure of speed were not included in the study. Ultimately they determined that reductions in crashes up to 39 percent (see Table 58) could be estimated after widening lanes. Table 59 shows the wide variety of crash reductions estimated by Zegeer et al. for this study.

Zegeer et al. (1988) developed a multiplicative crash prediction model. The model considered ADT, lane width, paved and unpaved shoulder width, roadside hazard rating, and terrain. Expected reductions in related crash types were not limited to specific lane or shoulder widths.

Table 58. Estimated Effects for Widening Lane(s).

Study	Crash	Percent Crash Reduction (%)	Study Details
Texas	Total crashes	30	Service Life (years): 20 Preventable Crash: (Roadway Related = 2, 3 or 4) or (Vehicle Movements/Manner of Collison = 13, 21, 23, 30 or 33)
Zegeer et al. (1980)	Crashes related to run-off-road, head-on, and sideswipe crashes	Up to 39	Location: Rural, two-lane roads.
Zegeer et al. (1988)	Crashes related to run-off-road, head-on, and sideswipe crashes	Up to 40	1.22 m of lane widening
Griffin and Mak (1988)	Single vehicle crashes	Up to 50	Lane widening on two-lane, rural roads in Texas Methodology: Weighted least-squares regressions 1.22m of lane widening
Gan et al. (2005)	Single-vehicle run-off roads, multiple-vehicle same direction sideswipe crashes, and multiple-vehicle opposite-direction crashes	Up to 50	Refer to the study details
Harkey et al. (2008)	Related crashes	Up to 33	Refer to the study details

Table 59. The Effect of Lane Widths on Crash Reductions on Rural, Two-Lane Roads

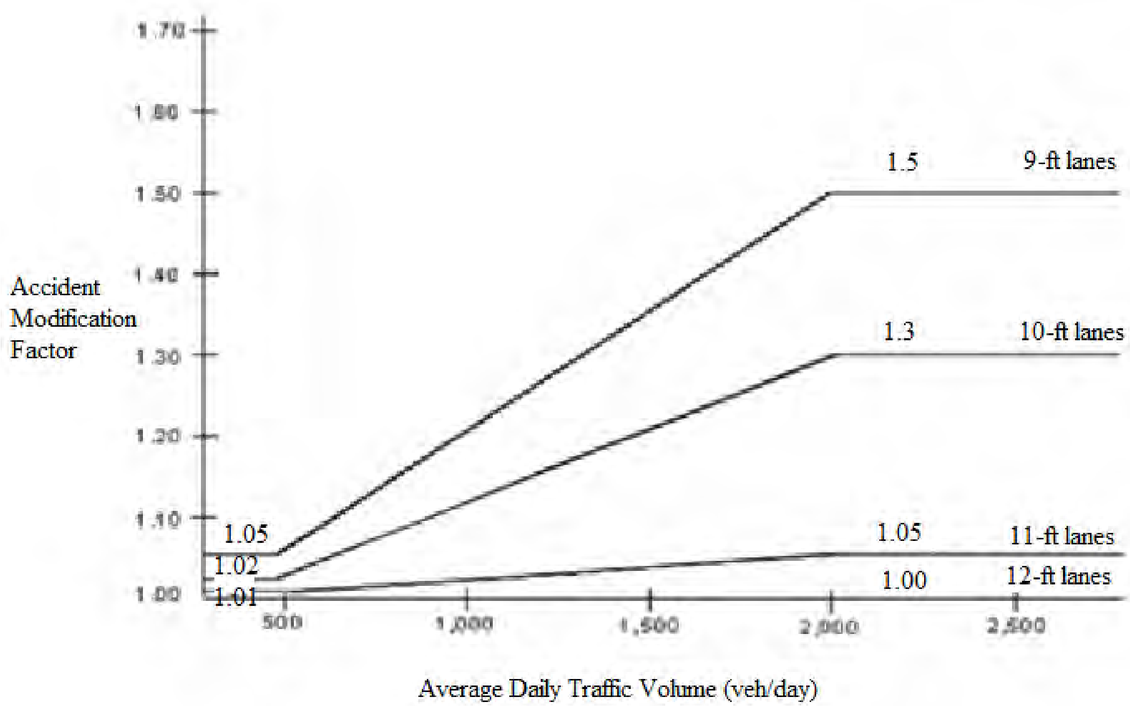
Lane Width (m)		Percentage Crash Reduction
Before	After	
2.1	2.4	10
2.1	2.7	23
2.1	3.0	29
2.1	3.4	39
2.4	2.7	16
2.4	3.0	23
2.4	3.4	36
2.7	3.0	10
2.7	3.4	29
3.0	3.4	23

Source: Adapted from Zegeer et al., 1980

Griffin and Mak (1988) estimated the safety effects of lane widening on two-lane, rural roads in Texas. They subdivided the study sites into four ADT categories (< 401 , 401to 700, 701 to 1000, and 1001 to 1500). The researchers used weighted least-squares regression to analyze single and multi-vehicle crash rates with regard to lane width.

For multivehicle crashes, they did not identify a relationship with lane width. Single vehicle crashes were reported to decrease by up to 50 percent for 1.22m of lane widening (2.44m of surface widening from 5.49m to 7.92m). The study noted that variables other than lane width may contribute to these reductions (e.g., speed and curvature).

Gan et al. (2005) performed a study to help updated the Florida Crash Reduction Factors. In developing CMFs for the lane width, the researchers assumed a CMF value of 1.00 for 12 feet wide lane width. Figure 1 shows the recommended Accident Modification Factors (AMFs) for different lane width (note that an AMF is equivalent to the more common CMF term).



Source: Gan et al., 2005

Figure 1. AMFs for Widening Lanes

Harkey et al. (2008) developed a CMF function for rural two-lane and multilane roads. The equation is shown as below:

$$\mathrm{CMF} = \mathrm{f}(\mathrm{CMF}_{RA} - 1.0)P_{RA} + 1.0$$

CMF_{RA}= crash modification factor for related crashes

P_{RA}= proportion of total crashes constituted by the related crashes

f = factor for roadway type where f is equal to1.00 for rural two-lane roads, 0.75 for undivided multilane, and 0.50 for divided multilane

The percent crash reduction for related crashes based on lane width can be obtained by dividing the difference (subtraction) of the CMF between the before-improvements and after-improvement condition by the CMF for the before condition. Table 60 shows the relevant CMF values.

Table 60. CMF based on Lane Width and Average Daily Traffic.

Lane Width (ft)	Average Daily Traffic (vpd)		
	≤ 400	400 to 2000	≥ 2000
9	1.05	$1.05 + 2.81 * 10^{-4}(\text{ADT} - 400)$	1.50
10	1.02	$1.02 + 1.75 * 10^{-4}(\text{ADT} - 400)$	1.30
11	1.01	$1.01 + 2.5 * 10^{-4}(\text{ADT} - 400)$	1.05
12	1.00	1.00	1.00

Source: Adapted from Harkey et al., 2008

WC 503: Widen Paved Shoulder (to 5 ft. or less)

Definition: Extend the existing paved shoulder to achieve desirable shoulder width. Refer to WC 504 or 537 for constructing a paved shoulder.

Review of Supplemental Studies for WC 503:

The details of the Agent et al. (1996) study are described in the WC 101 section. As shown in Table 61, crash reductions from 15 to 24 percent can be estimated widening the existing paved shoulder.

Zegeer et al., (1988) developed a multiplicative crash prediction model. The model considered ADT, lane width, paved and unpaved shoulder width, roadside hazard rating, and terrain. Expected reductions in related crash types were not limited to specific lane width or shoulder width. The effects of shoulder widening were greater compared to the study in 1980.

Table 61. Estimated Effects for Widening Paved Shoulder (to 5 ft. or less).

Study	Crash	Percent Crash Reduction (%)	Study Details
Texas	Total crashes	25	Service Life (years): 20 Preventable Crash: (Roadway Related = 2, 3 or 4) or (First Harmful Event = 4)
Agent et al. (1996)	Total crashes	24	Countermeasure: Widen paved shoulder of 2-4 ft Data from surveys of 2 states
		15	Countermeasure: Widen paved shoulder of 2-4 ft From a review of one study
Zegeer et al. (1988)	Crashes related to run-off-road, head-on, and sideswipe crashes	49	2.44 m widening
Harkey et al. (2008)	Single-vehicle run-off-road, multiple-vehicle opposing- and same-direction sideswipe crashes	Up to 24	Refer to the study details 24% is calculated with crash data with 4-ft median width and 8-ft median with when ADT is over 2000 veh/day

Details of the 2008 study by Harkey et al. are reviewed in the WC 502 summary. Ultimately they cited two tables (developed by Harwood et al., 2003) for this purpose. Table 62 and Table 63 summarize this information.

Table 62. CMF based on Shoulder Width and Average Daily Traffic.

Shoulder Width (ft)	Average Daily Traffic (vpd)		
	≤ 400	400 to 2000	≥ 2000
0	1.10	$1.1 + 2.5 * 10^{-4}(\text{ADT} - 400)$	1.50
2	1.07	$1.07 + 1.43 * 10^{-4}(\text{ADT} - 400)$	1.30
4	1.02	$1.02 + 8.125 * 10^{-5}(\text{ADT} - 400)$	1.15
6	1.00	1.00	1.00
8	0.98	$0.98 + 6.875 * 10^{-5}(\text{ADT} - 400)$	0.87

Source: Adapted from Harkey et al., 2008

Table 63. CMF based on Shoulder Type, Width and ADT

Shoulder Type	Shoulder Width (ft)							
	0	1	2	3	4	6	8	10
Paved	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Gravel	1.00	1.00	1.01	1.01	1.01	1.02	1.02	1.03
Composite	1.00	1.01	1.02	1.02	1.03	1.04	1.06	1.07
Turf	1.00	1.01	1.03	1.04	1.05	1.08	1.11	1.14

Source: Adapted from Harkey et al., 2008

WC 504: Construct Paved Shoulders (1 – 4 ft.)

Definition: Provide paved shoulders of 1- to 4-foot width where no shoulders existed previously. Refer to WC 503 or 536 for widening paved shoulders.

Table 64. Estimated Effects for Constructing Paved Shoulders (1 – 4 ft.).

Study	Crash	Percent Crash Reduction (%)	Study Details
Texas	Total crashes	25	Service Life (years): 20 Preventable Crash: (Roadway Related = 2, 3 or 4) or (Vehicle Movements/Manner of Collision = 20, 23–24 or 30) or (First Harmful Event = 4)
Agent et al. (1996)	Total crashes	18	Data from survey of 2 states
	Total crashes	20	From a review of 3 studies
	Off road	15	Data from survey of 1 state
Harkey et al. (2008)	Single-vehicle run-off-road, multiple-vehicle opposing- and same-direction sideswipe crashes	Up to 23	Refer to the study details

Review of Supplemental Studies for WC 504:

The details of the Agent et al. (1996) study are described in the WC 101 section. As shown in Table 64, crash reductions of 18 to 20 percent can be expected for the reduction in total crashes; however, the width of the paved shoulder was not detailed in the reference.

Details of the 2008 study by Harkey et al. are reviewed in the WC 502 summary. They estimated crash reductions for related crashes up to 23 percent.

WC 505: Improve Vertical Alignment (Reconstruct the Roadway to Improve Sight Distance)

Definition: Reconstruct the roadway to improve sight distance.

Table 65. Estimated Effects for Improving Vertical Alignment (Reconstruct the Roadway to Improve Sight Distance).

Study	Crash	Percent Crash Reduction (%)	Study Details
Texas	Total crashes	50	Service Life (years): 10 Preventable Crash: (Roadway Related = 2, 3 or 4) or (Vehicle Movements/Manner of Collision = 20–24, 30, 32 or 34)
Hovey and Chowdhury (2005)	Total crashes	20	Countermeasure: flatten crest vertical curve Locations: 3 sites in Ohio Methodology: EB before-after and full Bayes Goodness of fit: SE=0.19 for fatal, serious injury, minor injury crashes, SE=0.191 for all crashes
	Fatal, serious injury and minor injury crashes	51	

<u>Review of Supplemental Studies for WC 505:</u>

Hovey and Chowdhury (2005) studied three sites in Ohio where the vertical curvature was flattened in the roadway profile. The estimated CRF for total crashes following improvements was 0.196 (or a 20 percent reduction in total crashes) with a standard error of estimate of 0.191. The estimated CRF for injury and fatality crashes is 0.512 with a standard error of estimate of 0.190. Based on the data in this study, the estimated CRF values were statistically significant for injury and fatal crashes, but only slightly significant for total crashes.

WC 506: Improve Horizontal Alignment

Definition: Flatten existing curves. Refer to WC 507 for providing superelevation, and WC 508 for intersection realignment.

Table 66. Estimated Effects for Improving Horizontal Alignment.

Study	Crash	Percent Crash Reduction (%)	Study Details
Texas	Total crashes	55	Service Life (years): 10 Preventable Crash: (Roadway Related = 2, 3 or 4) or (Vehicle Movements/Manner of Collision = 20–24 or 30)
Harwood et al. (2000)	Total crashes	Function	Locations: N/A Methodology: Analysis-Driven Expert Panel Applicable to rural two-lane roads only
Pitale et al. (2009)	Total crashes	67	Locations: four curves in rural area in Minnesota Methodology: Simple before/after analysis Goodness of fit: SE=32.1 for all crashes

Review of Supplemental Studies for WC 506:

Harwood et al. (2000) evaluated the effect of horizontal curve geometry on the estimated reduction in crashes. In this study, the total crash CMF for length, radius, and presence or absence of spiral transitions on horizontal curves at rural two-lane roads is as follows:

$$\mathrm{CMF} = \frac{1.55L_C + \frac{80.2}{R} - 0.012S}{1.55L_C}$$

where:

Lc= length of horizontal curve (mi);

R = radius of curvature (ft); and

S = 1 if spiral transition curve is present 0 if spiral transition curve is not present.

The equation was derived from a regression model developed by Zegeer et al. (1992). In a study by Pitale et al. (2009), the researchers found that the annual average number of crashes per curve dropped from 0.25 in the before period to 0.11 in the after period, a reduction of over 50 percent. The annual average crash rate dropped from 1.2 crashes per million vehicle miles in the before period to 0.4 in the after period, a reduction of over 60 percent. These reductions are not statistically significant due to the extremely low number of total crashes based on the available data in this study.

WC 507: Increase Superelevation

Definition: Provide increased superelevation on an existing curve.

Table 67. Estimated Effects for Increasing Superelevation.

Study	Crash	Percent Crash Reduction (%)	Study Details
Texas	Total crashes	65	Service Life (years): 10 Preventable Crash: (Roadway Related = 2, 3 or 4) or (Vehicle Movements/Manner of Collision = 30)
Harwood et al. (2000)	Total	Equation	Locations: Rural two-lane roads Methodology: Analysis-Driven Expert Panel Goodness of fit: Not applicable

Review of Supplemental Studies for WC 507:

The details of the 2000 study by Harwood et al. are included in the WC 506 summary. The researchers used equations developed by Zegeer et al. (1992) to estimate the effect of superelevation deficiencies on total crashes at curved two-lane roadway segments. As part of this study, an expert panel noted there was no safety effect until the superelevation reached 0.01 (see Table 68).

Table 68. CMFs Based on Superelevation Deficiency

Superelevation Deficiency	CMF
< 0.01	1.00
0.01 ≤ Superelevation Deficiency < 0.02	1.00 + 6(SD - 0.01)
≥ 0.02	1.06 + 3(SD - 0.02)

Source: Adapted from Harwood et al., 2000

WC 508: Realign Intersection

Definition: Improve an existing intersection by partial or complete relocation of the roadway(s). Refer to WC 509 for channelization, and WC 506 for improving horizontal alignments.

Table 69. Estimated Effects for Realigning Intersection.

Study	Crash	Percent Crash Reduction (%)	Study Details
Texas	Total crashes	To be defined	Service Life (years): 10 Preventable Crash: Will be determined from supplied diagram

There do not appear to be any additional studies in the published literature that directly address the safety effects of realigning intersections.

WC 509: Channelization

Definition: Install islands and/or pavement markings to control or prohibit vehicular movements. A sketch of the proposed channelization should be provided. Refer to WC 508 for intersection realignment.

Table 70. Estimated Effects for Channelization.

Study	Crash	Percent Crash Reduction (%)	Study Details
Texas	Total crashes	To be defined	Service Life (years): 10 Preventable Crash: Will be determined from supplied diagram
Exnicios (1967)	Total crashes (over two years)	31	Locations: at several suburban intersections located in or near several metropolitan areas.
	Total crashes (over one year)	58	
	Total crashes (over 26 months)	100	
Jonsson et al. (2007)	Total crashes	33	Countermeasure: painted left-turn channelization Locations: 264 four-leg stop-controlled intersections on rural multilane highways in California (the number of intersections installed with channelization is unknown) Methodology: Regression cross-section method Goodness of fit: SE=19 for total crashes and 18 for rear-end and sideswipe crashes
	Rear end and Sideswipe	39	
	Total crashes	13	Countermeasure: raised/curb left-turn channelization Locations: 264 four-leg stop-controlled intersections on rural multilane highways in California (the number of intersections installed with channelization is unknown) Methodology: Regression cross-section method Goodness of fit: SE=28 for total crashes and 27 for rear-end and sideswipe crashes
	Rear end and Sideswipe	25	

Review of Supplemental Studies for WC 509:

Exnicios (1967) evaluated several safety measures, including channelization, that were employed at suburban intersections located in or near several metropolitan areas. They estimated crash reductions ranging from 31 up to 100 percent due to these safety measures.

Jonsson et al. (2007) modelled crashes at intersections on rural four-lane highways. The crashes were divided into four groups: opposite-direction crashes, same-direction crashes, intersecting-direction crashes, and single-vehicle crashes. They estimated that total crashes reduced from 13 to 33 percent.

WC 510: Construct Turn Arounds

Definition: Provide turnarounds at an intersection where none existed previously.

Table 71. Estimated Effects for Constructing Turn Arounds.

Study	Crash	Percent Crash Reduction (%)	Study Details
Texas	Total crashes	40	Service Life (years): 10 Preventable Crash: (Intersection Related = 1 or 2) and (Vehicle Movements/Manner of Collision = 12, 14, 18, 20, 22, 24, 26, 28, 29, or 34)

There do not appear to be any additional studies in the published literature that directly address the safety effects of constructing turnarounds at an intersection where they previously did not exist.

WC 514: Grade Separation

Definition: Construct vertical separation of intersecting roadways.

Table 72. Estimated Effects for Grade Separation.

Study	Crash	Percent Crash Reduction (%)	Study Details
Texas	Total crashes	80	Service Life (years): 30 Preventable Crash: Intersection Related = 1 or 2
Elvik and Erke (2007)	Total crashes	42	Countermeasure: Convert at-grade intersection into grade-separated interchange Location: 4-leg intersection (traffic control not specified) Methodology: Meta-analysis Goodness of fit: SE=10 for total crashes, 5 for injury crashes and 14 for PDO crashes
	Serious and minor injury	57	
	PDO	36	
	Total crashes	27	Countermeasure: Convert at-grade intersection into grade-separated interchange Location: 3-leg and 4-leg signalized intersection Methodology: Meta-analysis Goodness of fit: SE=8 for total crashes and 11 for injury crashes
	Serious and minor injury	28	

Review of Supplemental Studies for WC 514:

Elvik and Erke (2007) updated research that estimated the effect of grade separations on the reduction in crashes. They estimated total crash reductions from 27 percent up to 42 percent.

WC 515: Construct Interchange

Definition: Construct vertical separation of intersecting roadways to include interconnecting ramps.

Table 73. Estimated Effects for Constructing Interchange.

Study	Crash	Percent Crash Reduction (%)	Study Details
Texas	Total crashes	65	Service Life (years): 30 Preventable Crash: Intersection Related = 1 or 2
Agent et al. (1996)	Total crashes	25	Data from survey of 5 states
		42	From a review of 3 studies
	Night	50	Data from survey of 4 states
		56	From a review of 3 studies
Elvik and Erke (2007)	Total crashes	4	Countermeasure: Design diamond, trumpet, or cloverleaf interchange with crossroad above freeway Methodology: Meta-analysis Goodness of fit: SE=10 for total crashes
	Total crashes	38	Countermeasure: Provide diamond interchange Methodology: Meta-analysis Goodness of fit: SE=23 for total crashes, SE=12 for truck related crashes
	Truck related crashes	11	

<u>Review of Supplemental Studies for WC 515:</u>

The details of the Agent et al. (1996) study are described in the WC 101 section. As shown in Table 73, the construction of an interchange can be expected to reduce total crashes from 25 to 42 percent with crashes at night reduced 50 to 56 percent.

The discussion of WC 514 briefly discussed the study by Elvik and Erke (2007) and their efforts to conduct meta-analyses to update estimated crash reductions. Similarly they determined that the construction of an interchange can be expected to reduce crashes from 4 percent (for diamond, trumpets, or cloverleaf interchanges) up to 38 percent (for select diamond interchanges).

WC 516: Close Crossover

Definition: Permanently close an existing crossover.

Table 74. Estimated Effects for Closing a Crossover.

Study	Crash	Percent Crash Reduction (%)	Study Details
Texas	Total crashes	95	Service Life (years): 20 Preventable Crash: (Part of Roadway Involved = 1) and (Vehicle Movements/Manner of Collision = 10, 14, 20–22, 24, 26, 28–30, 34 or 38)
Agent et al. (1996)	Total crashes	49	Data from survey of 9 states
		52	From a review of 6 studies

<u>Review of Supplemental Studies for WC 502:</u>

The details of the Agent et al. (1996) study are described in the WC 101 section. As shown in Table 74, they estimated a 49 to 52 percent reduction in crashes for closing a median opening. The TxDOT value of 95 percent is considerably higher.

WC 517: Add Through Lane

Definition: Provide an additional travel lane.

Table 75. Estimated Effects for Adding Through Lane.

Study	Crash	Percent Crash Reduction (%)	Study Details
Texas	Total crashes	28	Service Life (years): 20 Preventable Crash: Vehicle Movements/Manner of Collision = 20–24, 26–27, 29–30

There do not appear to be any additional studies in the published literature that directly address the safety effects of adding an additional travel lane.

WC 518: Install Continuous Turn Lane

Definition: Provide a continuous two-way left turn lane where none existed previously.

Table 76. Estimated Effects for Installing Continuous Turn Lane.

Study	Crash	Percent Crash Reduction (%)	Study Details
Texas	Total crashes	50	Service Life (years): 10 Preventable Crash: Vehicle Movements/Manner of Collision = 20–22, 24, 26, 28–30, 34 or 38
Hovey and Chowdhury (2005)	Total crashes	8	Location: 3 sites in Ohio Methodology: ED before-after or full Bayes Goodness of fit: SE=15.7 for total crashes, SE=25.4 for F+I crashes
	F+I	20	
Persaud et al. (2008)	Total crashes	36	Location: 78 sites (21.3 mi) in North Carolina, 10 sites (6.0 mi) in Illinois, 31 sites (6.8 mi) in California, and 25 sites (13.2 mi) in Arkansas. Methodology: EB before-after Goodness of fit: SE=4 for total crashes, 8 for injured crashes and 5 for rear-end crashes.
	Serious injury, Minor injury	35	
	Rear-end crashes	47	
Haleem and Abdel-Aty (2011)	Total crashes (major approach of 3-leg stop controlled intersection)	31	Location: 1735 sites in Florida, data from 2003 to 2006 Methodology: Regression cross-section Goodness of fit: SE=9 for total crashes (major approach of 3-leg stop controlled intersection), N/A for total crashes (major approach of 4-leg stop controlled intersection).
	Total crashes (major approach of 4-leg stop controlled intersection)	34	

<u>Review of Supplemental Studies for WC 518:</u>

Details of the 2005 study by Hovey and Chowdhury are reviewed in the WC 505 summary. They estimated an eight percent reduction in total crashes resulting from the installation of a continuous turn lane.

Persaud et al. (2008) studied the safety effects of the installation of TWLTLs on two-lane roads. Using an EB before-after analysis for site and crash data 78 sites (21.3 mi) in North Carolina, 10 sites (6.0 mi) in Illinois, 31 sites (6.8 mi) in California, and 25 sites (13.2 mi) in Arkansas, the estimated the potential crash reductions. Their results revealed a statistically significant reduction in both total crashes (36 percent) and rear-end crashes (47 percent). They also noted that TWLTLs in rural areas appear to be more effective in reducing crashes than those located in urban areas.

Haleem and Abdel-Aty (2011) evaluated data at 2475 unsignalized intersections. Study details are included in the WC 403 summary. They estimated that 31 to 34 percent reductions in total crashes can be expected at locations where a continuous turn lane has been added.

WC 519: Add Left Turn Lane

Definition: Provide an exclusive left turn lane where none existed previously. The affected intersection approaches must be specified

Table 77. Estimated Effects for Adding Left Turn Lane.

<table>
<tr><th>Study</th><th colspan="2">Crash</th><th>Percent Crash Reduction (%)</th><th>Study Details</th></tr>
<tr><td>Texas</td><td colspan="2">Total crashes</td><td>25</td><td>Service Life (years): 10
Preventable Crash: Vehicle Movements/Manner of Collision = 20–22, 24, 26, 28–30, 34 or 38 and Intersection Related 4</td></tr>
<tr><td rowspan="6">Agent et al. (1996)</td><td rowspan="3">Signalized</td><td rowspan="2">Total Crashes</td><td>30</td><td>Data from surveys of 17 states</td></tr>
<tr><td>27</td><td>From a review of 3 studies</td></tr>
<tr><td>Left Turn Rear-End</td><td>75</td><td>Data from surveys of 2 states</td></tr>
<tr><td rowspan="3">Not signalized</td><td rowspan="2">Total Crashes</td><td>28</td><td>Data from surveys of 16 states</td></tr>
<tr><td>30</td><td>From a review of 3 studies</td></tr>
<tr><td>Left Turn Rear-End</td><td>87</td><td>Data from surveys of 2 states</td></tr>
<tr><td>Harwood et al. (2002)</td><td colspan="2">Different categories</td><td>Up to 68</td><td>Refer to the study details</td></tr>
</table>

Review of Supplemental Studies for WC 519:

The details of the Agent et al. (1996) study are described in the WC 101 section. As shown in Table 77, the estimated effect on total crashes for adding a left turn lane is 27 to 30 percent. A reduction of 75 to 87 percent can be estimated for left turn rear-end crash types.

Harwood et al. (2002) performed an observational before-after evaluation related to the safety effects of providing left- and right-turn lanes for at-grade intersections. They gathered data from 280 improved and 300 “not improved” intersections. Following a wide variety of analysis methods (including a yoked comparison or matched-pair approach, the comparison group approach, and EB before-after method), the researchers summarized their findings as shown in

Table 78 (adding one left turn lane for a four-leg intersection), Table 79 (adding one left turn lane for a three-leg intersection), Table 80 (adding left turn lanes in rural locations), and Table 81 (adding left turn lanes in urban regions).

Table 78. Percent Crash Reductions of Adding One Left Turn Lane for 4-Leg Intersections

	Total intersection crashes			**Intersection approach crashes**		
	Total Crashes [a]	**Fatal and Injury Crashes**	**Project-Related Crashes [a]**	**Total Crashes [a]**	**Fatal and Injury Crashes**	**Project-Related Crashes [a]**
Rural intersections						
Unsignalized	28 ± 2.6	35 ± 3.0	37 ± 7.4	55 ± 2.4	61 ± 3.2	--
Newly Signalized [b]	35 ± 7.6	29 ± 6.3	--	44 ± 7.3	42 ± 7.6	--
Urban Intersections						
Unsignalized [b]	27 ± 3.0	29 ± 4.0	25 ± 7.2	20 ± 4.4	55 ± 4.8	51 ± 7.3
Signalized	10 ± 0.8	9 ± 1.3	13 ± 3.2	34 ± 0.8	35 ± 1.3	40 ± 1.8
Newly Signalized [b]	24 ± 2.8	28 ± 5.0	--	28 ± 2.9	43 ± 4.0	--

Note:
Results for unsignalized intersections apply only to left-turn lanes on major-road approaches.
± # means ± standard error.
[a] Includes crashes of all severity levels.
[b] Based on a limited number of sites.

Source: Harwood et al., 2002

Table 79. Percent Crash Reductions of Adding One Left Turn Lane for 3-Leg Intersections

	Total intersection crashes			**Intersection approach crashes**		
	Total Crashes [a]	**Fatal and Injury Crashes**	**Project-Related Crashes [a]**	**Total Crashes [a]**	**Fatal and Injury Crashes**	**Project-Related Crashes [a]**
Rural intersections						
Unsignalized	44 ± 5.5	55 ± 8.3	62 ± 14.5	45 ± 6.5	44 ± 10.9	64 ± 10.5
Newly [b] Signalized	--	--	--	68 ± 9.3	--	--
Urban Intersections						
Unsignalized [b]	33 ± 12.1	--	--	32 ± 13.1	--	--
Signalized	--	--	--	49 ± 13.9	48 ± 23.4	--
Newly [b] Signalized	--	--	--	--	--	--

Note:
Results for unsignalized intersections apply only to left-turn lanes on major-road approaches.
± # means ± standard error.
[a] Includes crashes of all severity levels.
[b] Based on a limited number of sites.

Source: Harwood et al., 2002

Table 80. Expected Percentage Reduction in Total Crashes from Installation of Left-Turn Lanes on the Major-Road Approaches to Rural Intersections

Intersection type	Intersection traffic control	Number of major-road approaches on which left-turn lanes are installed	
		One approach	Both approaches
Three-leg intersection	STOP sign on minor-road approach(es)	44 [a]	--
	Traffic signal	15 [b]	--
Four-leg intersection	STOP sign on minor-road approach(es)	28 [a]	48 [a]
	Traffic signal	18 [b]	33 [b]

[a] Based on EB evaluation.
[b] Based on Reference: Harwood et al., Prediction of the expected safety performance of rural two-lane highways. No. FHWA-RD-99-207, 2000

Source: Harwood et al., 2002

Table 81. Expected Percentage Reduction in Total Crashes from Installation of Left-Turn Lanes on the Major-Road Approaches to Urban Intersections

Intersection type	Intersection traffic control	Number of major-road approaches on which left-turn lanes are installed	
		One approach	Both approaches
Three-leg intersection	STOP sign on minor-road approach(es)	33 [a]	--
	Traffic signal	7 [b]	--
Four-leg intersection	STOP sign on minor-road approach(es)	27 [a]	47 [a]
	Traffic signal	10 [a]	19 [a]

[a] Based on EB evaluation
[b] Based on Reference:
Harwood et al., Prediction of the expected safety performance of rural two-lane highways. No. FHWA-RD-99-207, 2000.

Source: Harwood et al., 2002

WC 520: Lengthen Left Turn Lane

Definition: Provide additional length to an existing exclusive left turn lane. Affected intersection approaches must be specified.

Table 82. Estimated Effects for Lengthening Left Turn Lane.

Study	Crash	Percent Crash Reduction (%)	Study Details
Texas	Total crashes	40	Service Life (years): 10 Preventable Crash: Vehicle Movements/Manner of Collision = 20–22 and Intersection Related ≠4

There do not appear to be any additional studies in the published literature that directly address the safety effects of lengthening an existing exclusive left turn lane.

WC 521: Add Right Turn Lane

Definition: Provide an exclusive right turn lane where none existed previously. Affected intersection approaches must be specified

Table 83. Estimated Effects for Adding Right Turn Lane.

Study	Crash	Percent Crash Reduction (%)	Study Details
Texas	Total crashes	25	Service Life (years): 10 Preventable Crash: Vehicle Movements/Manner of Collision = 20–23, 25–27, 33 or 36 and Intersection Related 4
Agent et al. (1996)	Total crashes	27	Data from surveys of 5 states
Harwood et al. (2002)	Different categories	Up to 40	Refer to the study details

<u>Review of Supplemental Studies for WC 521:</u>

The details of the Agent et al. (1996) study are described in the WC 101 section. As shown in Table 83, adding a right turn lane is estimated to result in a 27 percent reduction in total crashes (very similar to the TxDOT value of 25 percent).

The details of the Harwood et al. (2002) study are described in the WC 519 section. They developed Table 84 to demonstrate the estimated crash reductions due to adding one right turn lane for a four-leg intersection.

Table 84. Percent Crash Reductions of Adding One Right Turn Lane for 4-Leg Intersections

	Total intersection crashes			Intersection approach crashes		
	Total Crashes [a]	**Fatal and Injury Crashes**	**Project-Related Crashes [a]**	**Total Crashes [a]**	**Fatal and Injury Crashes**	**Project-Related Crashes [a]**
Rural intersections						
Unsignalized	14 ± 5.2	23 ± 6.6	--	27 ± 5.3	24 ± 7.9	--
Newly Signalized [b]	--	--	--	--	66 ± 7.6	--
Urban Intersections						
Unsignalized [b]	40± 10.1	--	--	--	--	--
Signalized	4 ± 2.0	9 ± 3.0	--	18 ± 2.0	22 ± 3.1	--

Note:
Results for unsignalized intersections apply only to right-turn lanes on major-road approaches.
± # means ± standard error.
[a] Includes crashes of all severity levels.
[b] Based on a limited number of sites.

Source: Harwood et al., 2002

WC 522: Lengthen Right Turn Lane

Definition: Provide additional length to an existing exclusive right turn lane. Affected intersection approaches must be specified.

Table 85. Estimated Effects for Lengthening Right Turn Lane.

Study	Crash	Percent Crash Reduction (%)	Study Details
Texas	Total crashes	40	Service Life (years): 10 Preventable Crash: Vehicle Movements/Manner of Collision = 20–22 and Intersection Related 4

There do not appear to be any additional studies in the published literature that directly address the safety effects of lengthening an existing right turn lane.

WC 523: Construct Pedestrian Over/Under Pass

Definition: Construct a pedestrian crossover where none existed previously.

Table 86. Estimated Effects for Constructing Pedestrian Over/Under Pass.

Study	Crash	Percent Crash Reduction (%)	Study Details
Texas	Total crashes	95	Service Life (years): 20 Preventable Crash: First Harmful Event = 1
Agent et al. (1996)	Total crashes	90	Sites: 14 Range: 60-95
ITE (2004)	Total crashes	13	Sites: Unsignalized intersections
Gan et al. (2005)	Total crashes	5-100	Note: The values are compiled from practice in different States.
	Fatal and Injuries	90	
	PDO	90	

<u>Review of Supplemental Studies for WC 523:</u>

The details of the Agent et al. (1996) study are described in the WC 101 section. As shown in Table 86, an estimated reduction of total crashes of 90 percent is estimated (similar to the TxDOT value of 95 percent).

ITE (2004) summarized the percent crash reductions in a study based NCHRP 17-18 (3), *Guidance for Implementation of the AASHTO Strategic Highway Safety Plan*. They estimated a 13 percent crash reduction following the installation of pedestrian overpasses or underpasses.

The 2005 study by Gan et al. is reviewed in the WC 502 summary. The researchers found crash reductions ranging from five up to 100 percent as a result of a pedestrian grade separation.

WC 524: Increase Turning Radius

Definition: Provide an increased turning radius at an existing intersection.

Table 87. Estimated Effects for Increasing Turning Radius.

Study	Crash	Percent Crash Reduction (%)	Study Details
Texas	Total crashes	10	Service Life (years): 10 Preventable Crash: [(Vehicle Body Style = 87 or 91) and (First Harmful Event = 7)] or (Vehicle Movements/Manner of Collision = 13, 20–21, 30 or 33)
Agent et al. (1996)	Total crashes	18	Data from survey of 12 states
		21	From a review of 18 studies

Review of Supplemental Studies for WC 524:

The details of the Agent et al. (1996) study are described in the WC 101 section. As shown in Table 88, the estimated reduction in total crashes resulting from increasing the turning radius is 18 to 21 percent (slightly greater than the TxDOT value of 10 percent).

WC 525: Convert to One-Way Frontage Roads

Definition: Convert two-way frontage roads to one-way operation.

Table 88. Estimated Effects for Converting to One-Way Frontage Roads.

Study	Crash	Percent Crash Reduction (%)	Study Details
Texas	Total crashes	25	Service Life (years): 10 Preventable Crash: Part of Roadway Involved = 2
Eisele et al. (2011)	Total non-PDO crashes	57	Location: 19.2 miles segment in 6 cities in Texas Crash data: from 1998 to 2007 Methodology: simple before-after Goodness of fit: confidence interval is available in Table 4-9 of the study report Note: Includes only non-PDO crashes. All values are statistically significant. The CMFs include some impact of the ramp configurations that occur with the conversion as well, which was not possible to separate.
	Non-PDO opposite-direction crashes	96	
	Non-PDO angle and opposite-direction crashes	94	
	Non-PDO angle crashes	83	
	Non-Rear-end crashes	73	
	Non-PDO minor injury crashes	68	
	Non-PDO possible injury crashes	46	
	Non-PDO serious injury or fatality crashes	68	
	Non-PDO opposite-direction crashes (interchange intersection)	80	
	Non-PDO opposite-direction crashes including a left turn (interchange intersection)	85	
	Non-PDO angle and opposite-direction crashes including a left turn (interchange intersection)	77	
	Non-PDO minor injury crashes (interchange intersection)	86	

Review of Supplemental Studies for WC 525:

Eisele et al. (2011) evaluated the safety impacts of converting frontage roads from two-way to one-way. They used five Texas locations frontage roads were converted from two-way operation to one-way operation as a treatment group and one Texas site that remained two-way operations as a comparison group. The researchers developed CMFs for converting frontage road and focused on non-PDO crashes only. The TxDOT total crash reduction value of 25 percent was less than all of their non-PDO crash reduction estimates.

WC 526: Increase Vertical Clearance (Lower Grade)

Definition: Increase vertical clearance of a roadway underneath an overhead obstacle by lowering the roadway grade.

Table 89. Estimated Effects for Increasing Vertical Clearance (Lower Grade).

Study	Crash	Percent Crash Reduction (%)	Study Details
Texas	Total crashes	50	Service Life (years): 10 Preventable Crash: Object Struck = 43

There do not appear to be any additional studies in the published literature that directly address the safety effects of increasing the vertical clearance by lowering the roadway grade underneath.

WC 527: Increase Vertical Clearance (Remove Structure)

Definition: Remove an overhead structure in order to increase vertical clearance.

Table 90. Estimated Effects for Increasing Vertical Clearance (Remove Structure).

Study	Crash	Percent Crash Reduction (%)	Study Details
Texas	Total crashes	95	Service Life (years): 10 Preventable Crash: Object Struck = 43

There do not appear to be any additional studies in the published literature that directly address the safety effects of removing an overhead structure in order to increase vertical clearance.

WC 528: Construct Median Crossover

Definition: Provide crossovers in the median where none previously existed.

Table 91. Estimated Effects for Constructing Median Crossover.

Study	Crash	Percent Crash Reduction (%)	Study Details
Texas	Total crashes	20	Service Life (years): 10 Preventable Crash: (Part of Roadway Involved = 1) and (Vehicle Movements/Manner of Collision = 10, 14, 20–22, 24, 26, 28, 29, 34 or 38)

There do not appear to be any additional studies in the published literature that directly address the safety effects of providing a crossover in the median where one previously did not exist.

WC 529: Remove Raised Median/Concrete Island

Definition: Permanently remove raised median/concrete island.

Table 92. Estimated Effects for Removing Raised Median/Concrete Island.

Study	Crash	Percent Crash Reduction (%)	Study Details
Texas	Total crashes	35	Service Life (years): 10 Preventable Crash: Object Struck = 21 or 36

There do not appear to be any additional studies in the published literature that directly address the safety effects of permanently removing a raised median or concrete island.

WC 532: Texturize Shoulders (Rolled-in or Milled-in)

Definition: Install milled-in or rolled-in rumble strips along the shoulder.

Table 93. Estimated Effects for Texturizing Shoulders (Rolled-in or Milled-in).

Study	Crash	Percent Crash Reduction (%)	Study Details
Texas	Total crashes	50	Service Life (years): 10 Preventable Crash: (Roadway Related = 2, 3 or 4) or (Vehicle Movements/Manner of Collison = 30)
Griffith (1999)	All Single-Vehicle Run-Off-Road Crashes (all freeways)	18	Location: 55 treatment sites and 55 matched comparison sites from rural and urban freeways in Illinois. Treatment sites covered 196 miles of rural freeway and 67 miles of urban freeway. Methodology: Before-after with comparison site Goodness of fit: SE=7, 12, 10 and 16 for the crash reduction percentages listed on the left. Note: Results for all freeways based on yoked comparison analysis; results for rural freeways based on comparison group method using 29 of the treatment sites. Results could not be developed for urban sites separately. An analysis of multi-vehicle crashes showed rumble strips to have no effect on this type of crash
	Injury Single-Vehicle Run-Off-Road Crashes (all freeways)	13	
	All Single-Vehicle Run-Off-Road Crashes (Rural freeways)	21	
	Injury Single-Vehicle Run-Off-Road Crashes (Rural freeways)	7	
Carrasco et al. (2004)	Run-off-road, single vehicle (crashes)	10	Countermeasure: install milled-in rumble strips Location: rural multilane divided highway in MN Methodology: Simple before-after study Goodness of fit: SE=25, 33, 13, 19 for reduction percentages listed on the left
	Run-off-road, single vehicle (injury)	22	
	Total crashes	16	
	Injury crashes	17	
	Run-off-road, single vehicle (crashes)	22	Methodology: Before-after study with the yoked comparison
	Run-off-road, single vehicle (injury)	51	
	Total crashes	21	
	Injury crashes	26	
Smith and Ivan (2005)	Single-vehicle, fixed-object crashes	33	Location: Sections of 20 freeways throughout Connecticut Crash Data: 1993 to 1996 and 1997 to 2000 Methodology: Before-after study
	Run-off-the-road crashes (in the interchange)	48	
	Run-off-the-road crashes (in the roadway with 65 mph speed limit or smaller)	13	

Review of Supplemental Studies for WC 532:

Griffith (1999) estimated the safety effects of continuous shoulder rumble strips (CSRS) on freeways. The before-after study included HSIS sites in California and Illinois. The results showed that a potential adverse effect of a driver being startled or experiencing panic (leading to a crash) were statistically insignificant.

Carrasco et al. (2004) examined the safety effects of shoulder rumble strips (SRS) on rural multi-lane divided highways. The researchers used HSIS data for Minnesota including 23 SRS sites and eight comparison sites. Two before-and-after safety study approaches were employed in this study: 1) simple before-after study with predicted volume during after period, and 2) before-after study with yoked comparisons involving one-to-one matching between study sites and reference sites.

Smith and Ivan (2005) also evaluated the safety effects for SRS locations along Connecticut freeways. They specifically targeted single-vehicle, fixed-object crashes. They used a before-after analysis with crash data during 1993 to 1996 (before period) and 1997 to 2000 (after period).

The TxDOT estimated reduction of 50 percent for total crashes is generally higher than those estimated in the published literature.

WC 533: Texturize Shoulders (Profile Pavement Markers)

Definition: Install high-profile pavement markers along the shoulder.

Review of Supplemental Studies for WC 533:

Bahar et al. (2004) employed an EB before-after methodology to evaluate the safety effects of permanent raised pavement markers (PRPMs). Six out of the 29 surveyed states indicated they had a complete data source for volume, crash, roadway attribute, and PRPM installation. The data were gathered to analyze snowplowable PRPMs on nonintersection crashes on two-lane roadways, four-lane expressways, and four-lane freeways based on the data samples from Illinois, Missouri, Pennsylvania, New York, Wisconsin, and New Jersey. The researchers determined that their safety effects of PRPMs were not viable for four-lane expressways.

Table 94. Estimated Effects for Texturizing Shoulders (Profile Pavement Markers).

Study	Crash	Percent Crash Reduction (%)	Study Details
Texas	Total crashes	60	Service Life (years): 5 Preventable Crash: (Roadway Related = 2, 3 or 4) or (Vehicle Movements/Manner of Collison = 30) or (Surface Condition = 2 or 4)
Bahar et al. (2004)	Nighttime crashes (AADT < 20,000)	-13	Location: 983 miles for all two-lane roadways; 2713 miles for all four-lane freeways; 251 miles for all four-lane expressways were selected in the states of Illinois, Missouri, New Jersey, New York, Pennsylvania, and Wisconsin. Methodology: EB before-after Goodness of fit: SE=16, 25, and 25 for reduction percentages listed on the left.
	Nighttime crashes (20,000 < AADT < 60,000)	6	
	Nighttime crashes (AADT > 60,000)	33	

WC 535: Widen Median Opening for Storage

Definition: Widen an existing opening in the median to accommodate vehicles for storage.

Table 95. Estimated Effects for Widening Median Opening for Storage.

Study	Crash	Percent Crash Reduction (%)	Study Details
Texas	Total crashes	20	Service Life (years): 10 Preventable Crash: Vehicle Movements/Manner of Collision = 10, 14, 20 or 21

There do not appear to be any additional studies in the published literature that directly address the safety effects of widening an existing opening in a median so as to accommodate storage of turning vehicles.

WC 536: Widen Paved Shoulders (to > 5 ft)

Definition: Extend the existing paved shoulder to greater than 5 ft. Refer to WC 504 or 537 for constructing a paved shoulder.

Table 96. Estimated Effects for Widening Paved Shoulders (to > 5 ft).

Study	Crash	Percent Crash Reduction (%)	Study Details
Texas	Total crashes	40	Service Life (years): 20 Preventable Crash: (Roadway Related = 2,3 or 4) or (First Harmful Event = 4)
Harkey et al. (2008)	Single-vehicle run-off-road, multiple-vehicle opposing- and same-direction sideswipe crashes	Up to 33	-Refer to the study details 33% is calculated with crash data with 2-ft median width and 8-ft median with when ADT is over 2000 veh/day
Stamatiadis et al. (2009)	Total crashes	13	Countermeasure: Widen paved shoulder from 3 ft to 5 ft Location: 2308 mile-years in California, Kentucky, and Minnesota Methodology: Regression cross-section
	Single vehicle crashes	10	
	Total crashes	18	Countermeasure: Widen paved shoulder from 3 ft to 6 ft Location: 2308 mile-years for states shown above Methodology: Regression cross-section
	Single vehicle crashes	15	
	Total crashes	24	Countermeasure: Widen paved shoulder from 3 ft to 7 ft Location: 2308 mile-years for states shown above Methodology: Regression cross-section
	Single vehicle crashes	19	
	Total crashes	29	Countermeasure: Widen paved shoulder from 3 ft to 8 ft Location: 2308 mile-years for states shown above Methodology: Regression cross-section
	Single vehicle crashes	23	

Review of Supplemental Studies for WC 536:

Details of the 2008 study by Harkey et al. are reviewed in the WC 502 summary. They estimated up to a 33 percent reduction in related crash types as a result of widening shoulders.

Stamatiadis et al. (2009) attempted to quantify both the safety and operational impacts of shoulder and median width. They developed their analysis based on a compilation of recent practical field experience and a literature review.

WC 537: Construct Paved Shoulders (5 ft)

Definition: Provide paved shoulders 5 feet or greater where no shoulders existed previously. Refer to WC 503 or 536 for widening paved shoulders.

Table 97. Estimated Effects for Constructing Paved Shoulders (5 ft).

Study	Crash	Percent Crash Reduction (%)	Study Details
Texas	Total crashes	50	Service Life (years): 10 Preventable Crash: (Roadway Related = 2, 3 or 4) or (Vehicle Movements/Manner of Collison = 30)
Zegeer et al. (1980)	Crashes related to run-off-road, head-on, and sideswipe crashes	15 (see Table 98 for additional widths)	Location: in rural, two-lane roads. Shoulder width of 3.9-5.9 ft compared to no shoulder
Harkey et al. (2008)	Single-vehicle run-off-road, multiple-vehicle opposing- and same-direction sideswipe crashes	Up to 23 (4-ft shoulder)	Refer to the study details 23% is calculated with crash data with 0-ft median width and 4-ft median with when ADT is over 2000 veh/day

Review of Supplemental Studies for WC 537:

The 1980 study by Zegeer et al. is reviewed in the WC 502 summary. This study focused on run-off-road, head-on, and sideswipe crashes on rural, two-lane roads. Table 98 summaries their findings.

Table 98. Effect of Shoulder Widths on Crash Reductions on Rural, Two-Lane Roads.

Shoulder Width (m)		Percentage Reduction in Crashes
Before	After	
None	0.3-0.9	6
None	1.2-1.8	15
None	2.1-2.7	21
0.3-0.9	1.2-1.8	10
0.3-0.9	2.1-2.7	16
1.2-1.8	2.1-2.7	8

Source: Adapted from Zegeer et al., 1980

Details of the 2008 study by Harkey et al. are reviewed in the WC 502 summary. They estimated up to a 23 percent reduction in related crashes due to construction of a paved shoulder.

WC 538: Convert Two-Lane Facility to Four-Lane Divided

Definition: Convert an existing two-lane facility to a four-lane divided facility.

Table 99. Estimated Effects for Converting 2-Lane Facility to 4-Lane Divided.

Study	Crash	Percent Crash Reduction (%)	Study Details
Texas	Total crashes	45	Service Life (years): 20 Preventable Crash: (Roadway Related = 2, 3 or 4) or (Vehicle Movements/Manner of Collison = 10, 13, 14, 20, 21, 22, 24 or 30)
Council and Stewart (1999)	Total crashes (divided sections)	40-60	Location: Typical sections of two- and four-lane roadways in California, Michigan, North Carolina, and Washington Methodology: Cross-sectional analysis Goodness of fit: Not as strong as would be the results of before-after analyses of a large sample of locations

Review of Supplemental Studies for WC 538:

Council and Stewart (1999) estimated the safety benefits of conversions of rural two-lane roadways to four-lane roadways using cross-sectional models. The models produced crash rates for typical sections of two-lane and four-lane roadways in four different states. Two typical sections of the rural two-way roads were defined in this study: a 24-ft paved travelway with 6-ft or 8-ft shoulders and a 22-ft paved travelway with 6-ft shoulders. The typical section for four-lane undivided rural roads was defined as a 48-ft paved travelway with 8-ft shoulders. Six typical sections for four-lane divided rural roads were defined as 24-ft paved travelway in each direction with 10-ft or 12-ft shoulders and a 16- to 60-ft median. They observed a 40 to 60 percent estimated reduction in crashes. This is consistent with the value used by TxDOT.

WC 539: Install Median on Undivided Facility

Definition: Install a grass or flush median on an undivided facility.

Table 100. Estimated Effects for Installing Median on Undivided Facility.

Study	Crash	Percent Crash Reduction (%)	Study Details
Texas	Total crashes	40	Service Life (years): 20 Preventable Crash: Vehicle Movements/Manner of Collision = 20–24 or 30

There do not appear to be any additional studies in the published literature that directly address the safety effects of installing a grass or flush median on an undivided facility.

WC 540: Install Passing Lanes on 2-lane roadway

Definition: Install passing lanes on a 2-lane roadway where none currently exist.

Table 101. Estimated Effects for Installing Passing Lanes on 2-lane roadway.

Study	Crash		Percent Crash Reduction (%)	Study Details
Texas	Total crashes		25	Service Life (years): 15 Preventable Crash: (Roadway Related = 2 or 3) or (Vehicle Movements/Manner of Collison = 20–24 or 30)
Harwood et al. (2000)	Total crashes	One-way passing lane	25	Methodology: Analysis-Driven Expert Panel Estimates are based on work by Harwood and St. John – (1984) and Nettelbad (1979)
		Two-way passing lane	35	
Park et al. (2012)	F+I crashes (non-intersection)		35	Study locations: study sites in seven Districts (Paris, Childress, Corpus Christi, Austin, Wichita Falls, Yoakum, and Bryan) in Texas. Methodology: EB before-after method Goodness of fit: SE=11 for F+I crashes (non-intersection) and 9 for F+I crashes (segment + intersection)
	F+I crashes (segment + intersection)		42	

<u>Review of Supplemental Studies for WC 540:</u>

The 2000 study by Harwood et al., 2000 is reviewed in the summary for WC 506. Based on this study, a CMF of 0.75 (i.e. a 25 percent reduction in crashes) can be estimated for a one-way passing lane (single direction of travel) and a CMF of 0.65 (or 35 percent reduction) is estimated for a two-way passing lane (short four-lane sections). The passing lanes are assumed to be operationally warranted with appropriate length. The associated crashes only included those that occurred within the passing lane section.

Park et al. (2012) evaluated the effectiveness of Super 2 highways in Texas. These highways have a periodic passing lane that has been added to a two-lane rural highway so as to allow passing and dispersion of developed traffic platoons. The researchers used an EB before-after study to analyze the reduction in crashes. They used four reference groups from Texas corridors and five study corridors for a total of approximately 53 centerline miles. Their analysis examined crash data for twelve years (1997-2001 and 2003-2009).

WC 541: Provide Additional Paved Surface Width

Definition: Provide additional paved surface width with appropriate subsurface to each side of two lane, two-way roadways with existing paved surface width less than 24' to a maximum width of 28'.

Table 102. Estimated Effects for Providing Additional Paved Surface Width.

Study	Crash	Percent Crash Reduction (%)	Study Details
Texas	Total crashes	30	Service Life (years): 20 Preventable Crash: (Roadway Related = 2, 3 or 4) or (Vehicle Movements/ Manner of Collision = 21 or 30) or (First Harmful Event = 10)

There do not appear to be any additional studies in the published literature that directly address the safety effects of providing additional paved surface width to each side of two-lane, two-way roadways with widths less than 24 feet up to a maximum of 28 feet.

WC 542: Centerline Texturing

Definition: Install milled-in rumble strips along the centerline.

Table 103. Estimated Effects for Centerline Texturing.

Study	Crash	Percent Crash Reduction (%)	Study Details
Texas	Total crashes	35	Service Life (years): 10 Preventable Crash: (Vehicle Movements/Manner of Collision = 21 or 30) or (Roadway Related = 2 or 3)
Persaud et al. (2003)	Total crashes	14	Location: 98 treatment sites, consisting of 210 miles on rural two-lane roads in the states of California, Colorado, Delaware, Maryland, Minnesota, Oregon, and Washington. Methodology: EB before-after method Goodness of fit: SE=5, 12 8 and 15 for the reduction percentages listed on the left.
	Frontal/Opposing-Direction Sideswipe Crashes	21	
	All injury crashes	15	
	All injury crashes (Frontal/Opposing-Direction Sideswipe Crashes)	25	

Review of Supplemental Studies for WC 502:

The 2003 study by Persaud et al. is reviewed in the WC 404 summary. Table 104 summarizes their findings. Crash reductions ranging from 14 to 25 percent can be estimated due to installing centerline rumble strips on rural two-lane highways. These values are somewhat lower than those used by TxDOT.

Table 104. CMF of Installing Centerline Rumble Strips on Rural Two-Lane Roads.

Crash Type	Number of Improved Sites	CMF (SE)
All Severities		
Total Crashes	98	0.86 (0.05)
Frontal/Opposing-Direction Sideswipe Crashes		0.79 (0.12)
Injury Crashes		
Total Crashes	98	0.85 (0.08)
Frontal/Opposing-Direction Sideswipe Crashes		0.75 (0.15)

Source: Adapted from Persaud et al., 2003

CHAPTER 3. MERGING WORK CODES

CURRENT TXDOT PROCEDURES TO COMBINE WORK CODES

Recently, TxDOT developed a procedure for combining CMFs. There is a hierarchy in the way CMFs related to work codes are applied, whenever a combination is under consideration. In this procedure, the CMFs are adjusted incrementally based on certain criteria. There is an implied understanding in this procedure that when two CMFs do not have independent effects, compounding CMF in a multiplicative way leads to an incorrect estimate of the combined effect of the CMFs (typically an overly optimistic estimate). There are three levels for adjusting the CMF. Each level represents a two-fold cut in the expected effectiveness of the CMF adjusted at the previous level, as shown in Eq. 1.

Eq. 1. Incremental adjustment of CMF

$$CMF^{*} = 1 - \frac{1 - CMF}{2^{L}}$$

Where:

CMF^{*} =	Modified Crash Modification Factor, given a level of adjustment "L";
CMF =	Crash Modification Factor as given in the literature; and
L =	Level of adjustment for $L \in \{0,1,2\}$. (ancillary variable created for this analysis only)

It is important to note that CRF (Crash Reduction Factor) equals 1 – CMF and is often referred to as a percentage value instead of the proportion calculated by this equation.

By definition, CMF^{*}=1.0 for level L=3, otherwise, a CMF^{*}=1.0 would normally correspond to an infinite value of L. Table 105 shows a scoring system on how the the level of adjustment is selected. The current weighting procedure incorporates a systematic evaluation of the CMF, balancing the following areas:

1. Expected Effectiveness (per preventable crash type and conditional criteria);
2. Project Complexity/ monetary commitment (per amount of work criterion); and
3. Strength of Supporting Evidence (per proven criterion).

Each of these evaluations is examined in more detail in the following sections of this chapter.

Table 105. Selection Criteria for Level of Adjustment of CMF.

L	Type of CMF	Preventable Crash Types	Amount of Work	Conditional	Proven	Total
0	Full CMF - 3	Completely different preventable crash types as work code with the most preventable crash types	Majority of work on project attributed to work code (51-99%)	Work code is equally effective in all types of conditions	Work code has been evaluated and tested as a proven countermeasure in Texas	11-12 Points (10-12 main item)
1	Reduced CMF - 2	Some of the same preventable crash types as the work code with the most preventable crash types	Average amount of work on project attributed to work code (33-50%)	Work code is effective in most conditions but is more beneficial in a particular condition	Work code has been endorsed as a proven countermeasure by the FHWA and other safety organizations	8-10 Points (8-9 main item)
2	Minimal CMF - 1	Mostly same preventable crash types as work code with the most preventable crash types	Minimal amount of work on project attributed to work code (15-32%)	Work code typically used for a particular condition (weather, time of day, traffic conditions, types of vehicles)	New work code lacking in data confirming effectiveness but positive results expected	4-7 Points
3	No CMF - 0	Exact same preventable crash types as work code with the most preventable crash types	Incidental amount of work on project attributed to work code (0-14%)	Work code is not effective in a particular condition (i.e. safety lighting is not effective in the daytime)	New work code lacking in data confirming effectiveness and results questionable	0-3 Points

Source: TxDOT

FIRST PART: EVALUATION OF EXPECTED EFFECTIVENESS OF COMBINED CMFS

The first part of this evaluation focuses on qualifying how the criteria in the current procedure consider the expected effectiveness (i.e. preventable crash types and conditional). It is current consensus among transportation researchers that the multiplicative combination of CMFs under the independent assumption may lead to severe biased estimation.

Theoretical Implications of Combining CMFs as Factors

The research team considers it useful to review the probability theory as this serves as a foundation for combining CMFs in a multiplicative fashion. This review can also help shed light on the implications underlying current TxDOT procedures. To help visualize these cases, the researchers have explored various hypothetical scenarios, keeping in mind their relation to the levels of adjustment in the current procedures.

Case 1: Combining Statistically Independent CMFs

Let the union symbol, "U", denote all the crashes of one type that would occur at a certain facility. Let *A* and *B* denote two countermeasures designed to reduce U (i.e. the countermeasures represent the TxDOT WCs). In Figure 2, sets *A* and *B* (shown as Venn diagrams) represent the number of crashes that are prevented when implementing work codes *A* and *B* respectively.

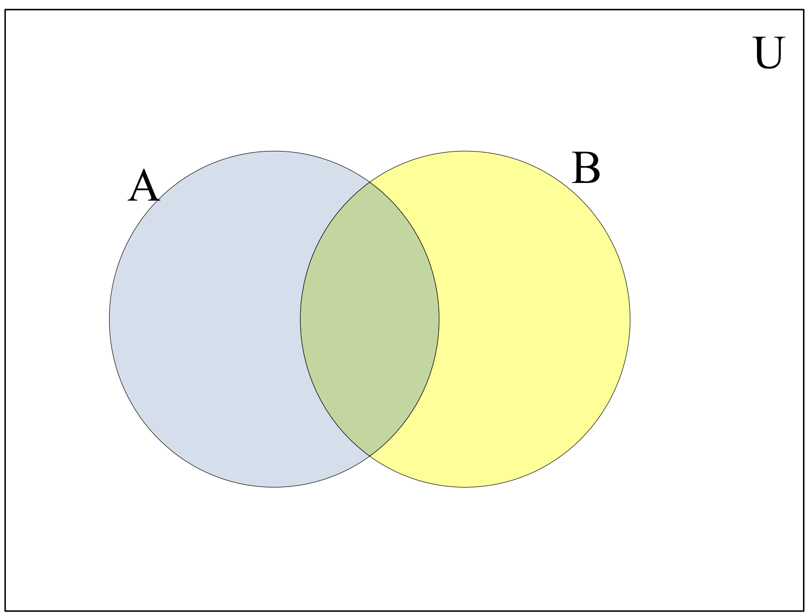


Figure 2. Venn Diagram of Hypothetical Preventable Crashes for Work Codes A and B

It is important to note that, in general, there is an implied overlap between the crashes that are preventable by implementing *A* and those that are preventable by implementing *B* when both countermeasures are independent of each other. To illustrate this fact numerically, the following values are assumed: U=100; *A*=20; and *B*=5.

In other words, under the assumption that there are a total of 100 crashes observed for the facility when no countermeasures are implemented, countermeasure *A* prevents 20 of those crashes when implemented by itself. Similarly, countermeasure *B* prevents 5 crashes when implemented by itself.

The associated CMFs are then:

$$CMF_A = 1 - \frac{20}{100} = 0.80$$

$$CMF_B = 1 - \frac{5}{100} = 0.95$$

It is of interest to determine how many crashes would be prevented if both countermeasures are implemented. If both countermeasures are statistically independent, then the crash reductions expressed as a combined CMF should be simply:

$$CMF_{A \wedge B} = CMF_A \times CMF_B = 0.80 \times 0.95 = 0.76.$$

The implication of this result is that when applying truly independent CMFs, the overlap region in Figure 2 must not be empty. For the example given, there should be one crash in that region, as shown in Figure 3. This crash can be prevented when either or both countermeasures are in place.

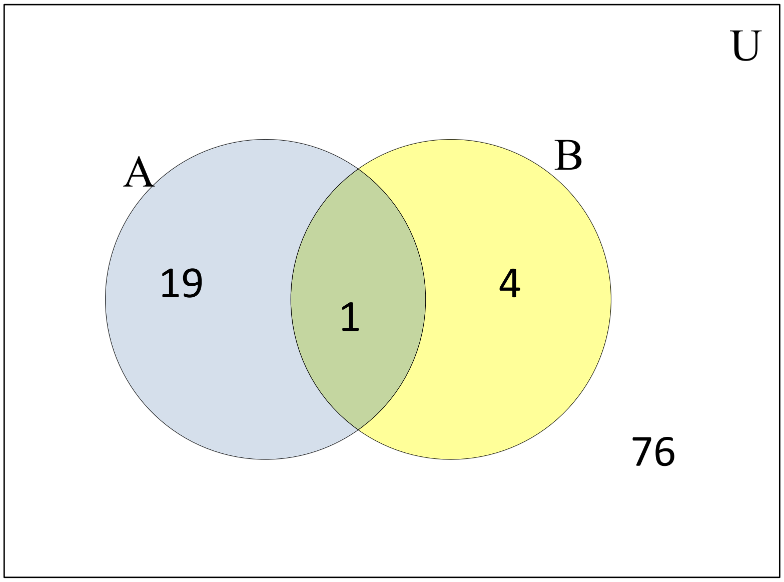


Figure 3. Venn Diagram for Independent CMFs A and B

Based on this assumption, the combined effectiveness can be computed based on the information shown in Figure 3 and numerically expressed as follows:

$$CMF_{A\wedge B} = 1 - \left(\frac{19 + 1 + 4}{100}\right) = 0.76$$

It can be shown that if any two CMFs are independent, then the percentage of crashes that can be prevented by implementing either or both of the CMFs must be equal to $(\boldsymbol{CRF_A}) \times (\boldsymbol{CRF_B})$. This condition can be verified for this simplified example, but it holds true for any pair of subsets of "preventable" crashes from a type U of crashes.

Relationship with the Levels of Adjustment in Current Procedures

As described in Table 105, the level of adjustment that warrants applying the full CMF is L=0. Under the criterion Preventable Crash Types it says "Completely different preventable crash types." Because the previous review of the theory has established that a certain overlap in the number of preventable crashes should be present for two statistically independent CMFs, the description that best corresponds to this independence condition is L=1, where the description says "Some of the same preventable crash types…" The next example cases examine CMFs that are statistically co-dependent and address how those considerations could potentially be included in the current TxDOT procedures.

Case 2: Combining Statistically Co-dependent CMFs that affect the Same Types of Crashes

Consider a case similar to Case 1, but with a slight but significant difference: A larger number of crashes that could be prevented with either countermeasure *A* or *B* (see Figure 3).

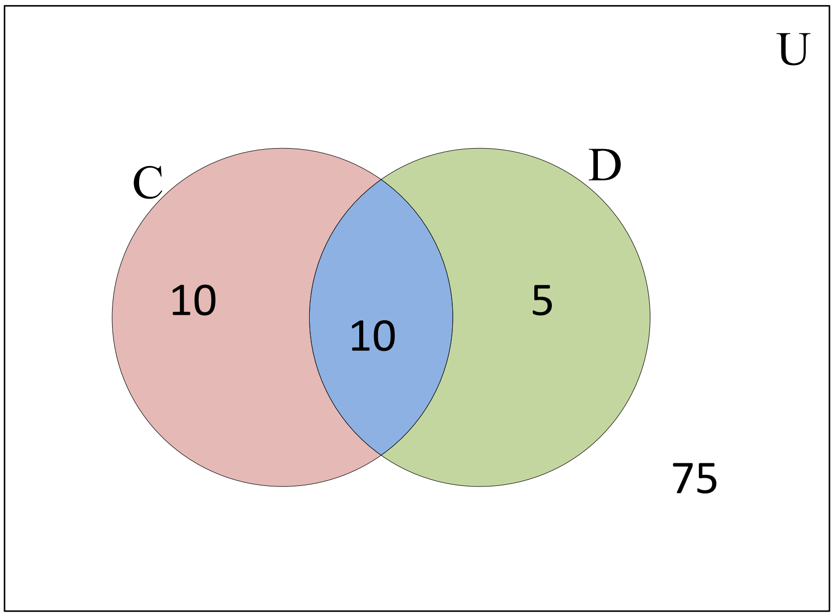


Figure 4. Venn Diagram Co-dependent CMFs C and D

The associated CMFs for countermeasures *C* and *D* are:

$$CMF_C = 1 - \frac{20}{100} = 0.80$$

$$CMF_D = 1 - \frac{15}{100} = 0.75$$

In this case, however, the combined effectiveness of countermeasures *C* and *D* cannot be calculated by multiplying these CMFs since the overlap clearly exceeds the number of crashes required for true independence between CMFs (the three crashes reviewed in the Case 1 summary and computed as 0.20 x 0.15 = 0.03 x100%). The product of these CMFs would incorrectly yield the following:

$$CMF_C \times CMF_D = 0.80 \times 0.85 = 0.68.$$

In reality, Figure 4 shows that the combined effectiveness is not as good as the product would indicate:

$$CMF_{C \wedge D} = 1 - \frac{10+10+5}{100} = 0.75.$$

Relationship with the Levels of Adjustment in Current Procedures

The situation illustrated in Case 2 is representative of the conditions that levels 1 and 2 (shown in Table 105) intend to capture via criteria in columns Preventable Crash Type and Conditional.

Case 3: Combining CMFs of Nested Countermeasures

Nested countermeasures represent situations where all crashes preventable by one countermeasure are a subset of those preventable by another, more comprehensive countermeasure, as shown in Figure 5. This condition represents the extreme condition where the overlap is as large as possible.

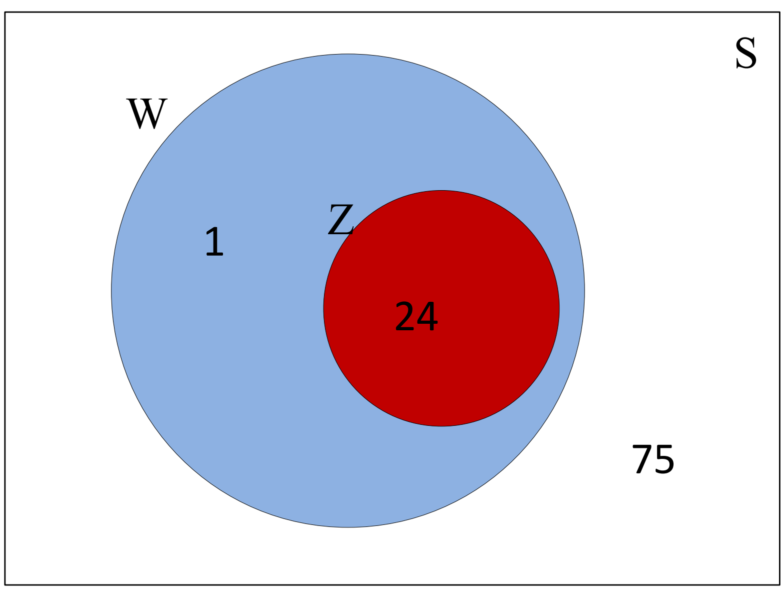


Figure 5. Venn Diagram for Nested CMFs *W* and *Z*

In this case,

$$CMF_W = 1 - \frac{25}{100} = 0.75$$

$$CMF_Z = 1 - \frac{24}{100} = 0.76$$

The product of CMFs incorrectly yields:

$$CMF_W \times CMF_Z = 0.75 \times 0.76 = 0.57$$

In reality, Figure 5 shows that the combined effectiveness is overestimated by the product:

$$CMF_{E \wedge F} = 1 - \frac{1 + 24}{100} = 0.75$$

The amount of overestimation resulting from multiplying CMFs can be computed by subtraction 0.75-0.57= 0.18.

As previously indicated, multiplying the CMFs for countermeasures with nested effectiveness can be expected to overestimate the actual combined effectiveness by the largest possible amount. It can be shown that for two given CMFs, the amount of this overestimation is always:

$$Overestimation \leq CMF_W \times (1 - CMF_Z)$$

Where the equality occurs at $Z \subseteq W$.

For this example, this overestimation can be calculated as: 0.75 x (1- 0.76) = 0.18.

Case 4: Combining CMFs for Completely Unrelated Countermeasures

At the opposite extreme, situations where the all crashes preventable by one countermeasure are completely unrelated to those preventable by another are cases of potential underestimation of the combined effect. Figure 6 illustrates this situation. For this condition, the overlap is equal to zero.

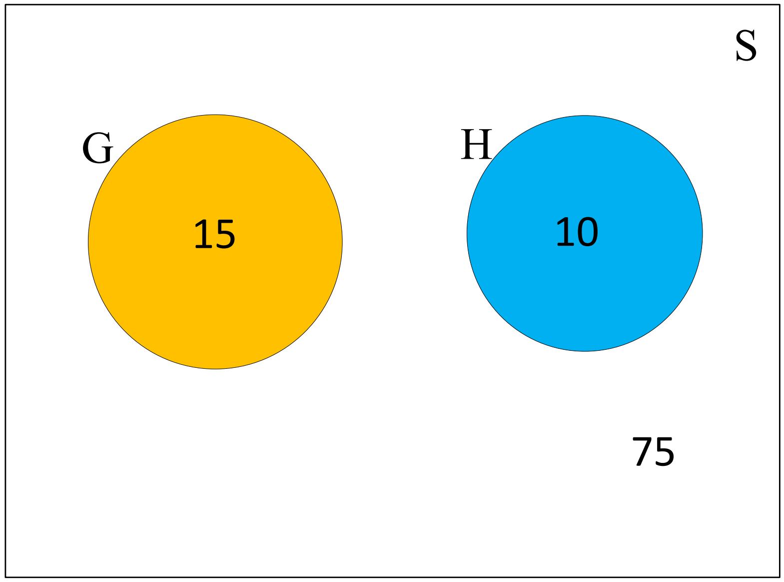


Figure 6. Venn Diagram for Mutually Exclusive CMFs G and H

In this case, each CMF can be calculated as:

$$CMF_G = 1 - \frac{15}{100} = 0.85$$

$$CMF_H = 1 - \frac{10}{100} = 0.90$$

The product of CMFs incorrectly yields:

$$CMF_G \times CMF_H = 0.85 \times 0.90 = 0.765$$

In reality, Figure 6 shows that the combined effectiveness is overestimated by the product:

$$CMF_{G \wedge H} = 1 - \frac{15 + 10}{100} = 0.75$$

The effectiveness of the combination is then under-estimated in this case by 0.765-0.75= 0.015. It can be shown that for the two given CMFs, the amount of this under-estimation is always:

$$Underestimation = (1 - CMF_G) \times (1 - CMF_H)$$

For the example given, this underestimation can be calculated as: (1 - 0.85) x (1 - 0.90) = 0.015.

Case 5: Combining Unrelated CMFs Defined for Different Types of Crashes

Any of the above cases could involve CMFs defined for different types of crashes. For example, CMF_I could be given for angle crashes, and CMF_J for rear-end crashes. Before the combined effectiveness of these types of crashes can be determined, one needs to find the equivalent CMFs defined for a common baseline of crashes. For the given example consider the following diagram shown in Figure 7.

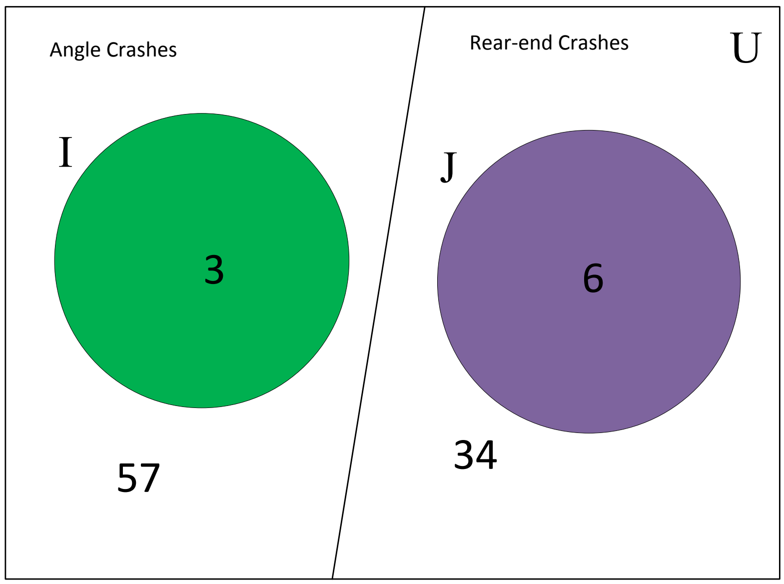


Figure 7. Venn Diagram for Mutually-Exclusive CMFs for Different Types of Crashes

In this case, the CMFs and their relationship to crash types are:

$$CMF_I = 1 - \left(\frac{3}{57+3}\right) = 0.95$$

$$CMF_J = 1 - \left(\frac{6}{34+6}\right) = 0.85$$

For the given CMFs, combining the estimated values in their current format is not appropriate because they represent different crash types. The first step is, therefore, to convert them to a common denominator, in this case U=All Angle and Rear-end crashes. This transformation can be performed as follows:

$$CMF_I' = 1 - \frac{3}{100} = 0.97$$

$$CMF_J' = 1 - \frac{6}{100} = 0.94$$

Now that the CMFs are given for a common reference, it is clear that the problem at hand has transformed into Case 4, therefore:

$$CMF_{I \wedge J} = 1 - \frac{3+6}{100} = 0.91$$

It can be shown that to transform CMFs given for subsets of crashes that are mutually exclusive, the combined CMF is simply a weighted average of the original CMFs using the proportions corresponding to the respective types of crashes as weights:

$$CMF_{I \wedge J} = CMF_I \times P(Crash_{type\ 1}) + CMF_J \times P(Crash_{type\ 2})$$

Summary

This evaluation of the theoretical implications of combining work codes demonstrated that the two effectiveness criteria in the current methodology are closely related: the Preventable Crash Types parameter determines the individual "universe" of crashes to which each work code applies, while the Conditional parameter further qualifies other limits of application of individual work codes. Jointly, these two parameters define a "pooled universe" of application to the combined work codes, as well as the potential amount of overlap between the safety effects of the work codes being combined.

The next subsection explores how these theoretical implications yield a range of estimates for a combination of work codes and how these combinations compare with combinations obtained using the current procedure.

Practical Application of Combining Various Types of CMFs

The following section demonstrates how to combine the CMFs of various work codes while explicitly considering the CMF relationships explored in the previous section of this chapter.

Scenario 1

It is of interest to install a median barrier (WC 201) at the same location where the road will be resurfaced (WC 303). WC 201is defined as "Construct a metal, concrete, or cable safety system median barrier where none existed previously." WC 303 is defined as "provide a new roadway surface to increase pavement skid numbers on all the lanes."

The required data checklist for this assessment includes:

1. Scope of assessment,
2. Associated CMFs (or CRFs) and types of crashes affected by work code, and
3. Relative proportions of those types of crashes.

Scope of Assessment

Is the analysis intended to assess the combined effect of work codes on the total number of crashes? The answer is *Yes* for this case; however, the methodology restricts the assessment to just a subset of those crashes (see scenario 2).

Associated CMFs and Types of Affected Crashes

The TxDOT *2014 Work Codes.xlsx* spreadsheet tool worksheet named "Microstrategy" defines WC 201 and 303 as follows:

Work Code	CRF	Crash Types
201	0.55	Manner of Coll= 30
303	0.30	Surf_Cond = 2 or 4

Relative Proportions of those Types of Crashes

To have the best estimate of these proportions, the analyst should query the TxDOT Crash Records Information System (CRIS) database to cross-compare the frequencies of the two types of crashes. For the example of WC 201 and WC 303, this query includes years 2011-2014 (see Table 106). As shown in the table, there is an overlap between the types of crashes that these work codes would affect. Therefore, cases 1, 2 and 3 from the theoretical considerations section are all possible and thus they should be considered.

Table 106. Cross Table of Types of Crashes for Work Codes 201 and 303

		Surf_Cond_ID (%)									
		0	1	2	3	5	6	8	9	10	Row Totals
FHE_Collsn_ID	1	0.1434	19.2887	3.7374	0.2509	0.0530	0.7017	0.0799	0.0650	0.2446	*24.56*
	2	0.0063	1.0238	0.1451	0.0040	0.0009	0.0104	0.0050	0.0024	0.0096	*1.21*
	3	0.0073	1.1840	0.1979	0.0065		0.0077	0.0052	0.0022	0.0090	*1.42*
	4	0.0507	2.6749	0.1739	0.0030	0.0006	0.0033	0.0123	0.0010	0.0239	*2.94*
	5	0.1236	1.1304	0.0830	0.0014	0.0003	0.0037	0.0084	0.0009	0.0065	*1.36*
	10	0.0237	10.8035	1.2264	0.0162	0.0038	0.0194	0.0105	0.0087	0.0108	*12.12*
	11	0.0041	0.6365	0.0472	0.0009		0.0005	0.0016	0.0004	0.0023	*0.69*
	12	0.0008	0.0938	0.0191	0.0010		0.0036			0.0004	*0.12*
	13	0.0067	1.4426	0.1792	0.0026	0.0007	0.0037	0.0026	0.0020	0.0018	*1.64*
	14	0.0068	3.3743	0.4013	0.0039	0.0009	0.0041	0.0028	0.0016	0.0038	*3.80*
	15		0.0076								*0.01*
	16	0.0002	0.0658	0.0079			0.0003				*0.07*
	17	0.0014	0.2200	0.0511	0.0009	0.0002	0.0038	0.0009	0.0020	0.0007	*0.28*
	18		0.0779	0.0046							*0.08*
	19	0.0005	0.2395	0.0374	0.0007		0.0003	0.0005		0.0008	*0.28*
	20	0.0441	10.0985	1.3932	0.0300	0.0048	0.0711	0.0200	0.0113	0.0054	*11.68*
	21	0.0503	7.0627	0.8194	0.0358	0.0081	0.0870	0.0136	0.0105	0.0037	*8.09*
	22	0.0605	13.0625	1.8679	0.0288	0.0049	0.0415	0.0267	0.0108	0.0043	*15.11*
	23	0.0060	1.2508	0.1150	0.0023		0.0018	0.0027	0.0008	0.0011	*1.38*
	24	0.0090	1.9424	0.1759	0.0025	0.0004	0.0014	0.0026	0.0007	0.0021	*2.14*
	25	0.0011	0.2355	0.0208			0.0002	0.0003		0.0003	*0.26*
	26		0.0077	0.0002							*0.01*
	27		0.0681	0.0050							*0.07*
	28	0.0026	0.3744	0.0366	0.0003	0.0002	0.0006	0.0012			*0.42*
	29		0.0211	0.0017	0.0002						*0.02*
	30	0.0023	1.1019	**0.2494**	0.0090	0.0044	0.0314	0.0040	0.0046	0.0138	***1.42***
	31	0.0046	0.4017	0.0348	0.0007	0.0002	0.0007	0.0018		0.0021	*0.45*
	32		0.0872	0.0149	0.0002		0.0018		0.0005	0.0008	*0.11*
	33		0.0136	0.0019							*0.02*
	34	0.0085	5.7456	0.6176	0.0072	0.0019	0.0053	0.0032	0.0018	0.0005	*6.39*
	35	0.0035	0.4181	0.0381	0.0006	0.0002		0.0010	0.0004	0.0008	*0.46*
	36	0.0015	0.1607	0.0159			0.0002	0.0003			*0.18*
	37		0.0009								*0.00*
	38		0.0848	0.0069							*0.09*
	39		0.0149	0.0027					0.0002		*0.02*
	40	0.0046	0.6326	0.0369	0.0005		0.0007	0.0027		0.0008	*0.68*
	41		0.0022								*0.00*
	42		0.0036	0.0002							*0.00*
	43	0.0005	0.0697	0.0054							*0.08*
	44	0.0002	0.0302	0.0014							*0.03*
	45	0.0018	0.1852	0.0092	0.0003			0.0006			*0.20*
	46	0.0014	0.0979	0.0096	0.0003		0.0005	0.0002		0.0003	*0.11*
	Column Totals	*0.58*	*85.44*	***11.79***	*0.41*	*0.09*	*1.01*	*0.21*	*0.13*	*0.35*	*100.00*

The absolute CRFs are (relative to total crashes):

$$CRF'_{201} = CRF_{201} \times P(Collsn_{ID} = 30) = 0.55 \times 0.0142 = 0.00781$$

$$CRF'_{303} = CRF_{303} \times P(\{Surf\_Cond\_ID = 2\} \vee \{Surf\_Cond\_ID = 4\}) = 0.30 \times 0.1179 = 0.0354$$

Case 1: Assuming effects are independent:

$$CMF_{201 \wedge 303} = 1 - 0.0354 - 0.00781 + 0.0354 \times 0.00781 = 0.9571$$

Case 2: Assuming effects are co-dependent (extreme case):

$$CMF_{201 \wedge 303} = 1 - 0.0354 - 0.00781 = 0.9568$$

Case 3: Assuming effects are unrelated (extreme case):

$$CMF_{201 \wedge 303} = 1 - 0.0354 - 0.00781 = 0.9490$$

<u>Conclusion:</u>

The results are very comparable, regardless of the independence assumption. The combined CMF is expected to range from 0.949 up to 0.957.

Scenario 2

Consider a slight modification to the Scenario 1 application. Assume that it is still of interest to apply both work codes 201 and 303 at a particular location; however, in this case the analyst needs to assess the effectiveness only in terms of the types of crashes that the work codes pertain to (as opposed to an assessment considering all crashes at the location).

The checklist is again:

1. Scope of assessment,
2. Associated CMFs (or CRFs) and types of crashes affected by work code, and
3. Relative proportions of those types of crashes.

Scope of assessment

The scope of the analysis in this case is to evaluate the subset of crashes that are directly affected by the countermeasure (and not just the total number of crashes as previously evaluated).

Associated CMFs and Types of Affected Crashes

Per the 2014 TxDOT Work Code spreadsheet and the table of definitions for work codes, the definition and values are similar to those described in Scenario 1.

Work Code	CRF	Crash Types
201	0.55	Manner of Coll= 30
303	0.30	Surf_Cond = 2 or 4

Relative Proportions for Affected Crash Types

The proportions for Scenario 2 can again be calculated from Table 106. It is necessary for this scenario, however, to adjust the proportions for their specific subset of crashes: Manner of Coll=30 or Surf_Cond=2 or Surf_Cond=2.

The relative CRFs are:

$$CRF'_{201} = \frac{CRF_{201} \times P(Collsn_{ID} = 30)}{P(Collsn_{ID} = 30 \vee Surf\_Cond\_ID = 2 \vee Surf\_Cond\_ID = 4)} = \frac{0.55 \times 0.0142}{0.1149 + 0.0142} = 0.060$$

$$CRF'_{303} = \frac{CRF_{303} \times P(\{Surf\_Cond\_ID = 2\} \vee \{Surf\_Cond\_ID = 4\})}{P(Collsn_{ID} = 30 \vee Surf\_Cond\_ID = 2 \vee Surf\_Cond\_ID = 4)} = \frac{0.30 \times 0.1179}{0.1149 + 0.0142} = 0.274$$

Assuming the effects are perfectly co-dependent (an unlikely scenario), we calculate the combined CMF as:

$$CMF_{201 \wedge 303} = 1 - 0.274 = 0.7260$$

Assuming the effects are completely independent, the combined CMF would then be:

$$CMF_{201 \wedge 303} = 1 - 0.274 - 0.060 + 0.274 \times 0.060 = 0.6821$$

Assuming effects are completely unrelated (an extreme and very optimistic case), the combined CMF is :

$$CMF_{201\wedge 303} = 1 - 0.060 - 0.274 = 0.6655.$$

Conclusion:

The results for Scenario 2 are still comparable to those observed in Scenario 1, but they extend over a relatively larger range, regardless of the independence assumption. As a result, the combined CMF is expected to range from 0.6655 up to 0.7260. In the spreadsheet provided by TxDOT, this combination is estimated at 0.32. The discrepancy is due to the different baseline between the CMFs (i.e. types of crashes affected by work codes).

Scenario 3

Assume there is a need to consider increasing the superelevation (WC 507) at the same location where shoulder rumble strips will be rolled or milled into place (WC 532). This evaluation should be assessed only on the types of crashes that the work codes pertain to, similar to Scenario 2.

The checklist is again:

1. Scope of assessment,
2. Associated CMFs (or CRFs) and types of crashes affected by work code, and
3. Relative proportions of those types of crashes.

Scope of assessment

The scope of the analysis in this case is a subset of all crashes: only those affected by either work code. Looking at the definitions of these work codes (507= Improve superelevation; 532=Texturize Shoulders), it is evident that they affect exactly the same types of crashes (Roadway Related = 2, 3, or 4; Veh Movements/Manner of Collision=30).

Associated CMFs and Types of Affected Crashes

Based on the 2014 TxDOT WC summary, the associated values for these codes are:

Work Code	CRF	Crash Types
507	0.55	Manner of Coll= 30 or (Roadway Related = 2, 3, or 4)
532	0.65	Manner of Coll= 30 or (Roadway Related = 2, 3, or 4)

Relative Proportions for Affect Crash Types

In contrast to Scenario 2, it is not necessary to adjust the subset of crashes affected, since both CMFs already affect the same (common set) of crash types. This more direct calculation would then be as follows:

Assuming effects are perfectly co-dependent:

$$CMF_{507\&532} = 1 - 0.65 = 0.350$$

Assuming effects are independent:

$$CMF_{507\&532} = 1 - 0.65 - 0.55 + 0.65 \times 0.55 = 0.1575$$

The calculation to assuming that the effects are unrelated does not yield a physically possible answer because the CRFs add up to more than 100%. Therefore, in the most optimistic scenario, the effects of the treatments would eliminate all crashes of the affected type (a highly unlikely scenario).

Conclusion:

The results are very sensible to the assumption of independence between treatments. The effect of the combined CMF should range from 0.0 up to 0.350. In the TxDOT spreadsheet tool, this combination is estimated at 0.26, slightly more conservative than assuming the effects are independent (combined CMF of 0.1575).

Scenario 4

It is of interest to again apply work codes 507 and 532 at a particular location, in this case safety will be assessed in terms of total crashes at this location. A table with proportions is required, similar to that created in Scenario 2 (see Table 107).

These proportions are in relation to the following subset of crashes: Manner of Coll= 30 Or Roadway Related=2 Or Roadway Related=3 Or Roadway Related= 4.

Table 107. Cross Table of Types of Crashes for Work Codes 507 and 532

		Road_Relat_ID (%)						
		1	2	3	4	5	6	Row Totals
FHE_Collsn_ID	Manner of Collision=30	1.4118	**0.0033**	**0.0009**	**0.0018**	0.0702	0.0000	**1.49**
	Other Manners	72.6484	16.6848	0.1917	2.1098	6.8766	0.0007	98.51
	Columns Total	74.06	**16.69**	**0.19**	**2.11**	6.95	0.00	100.00

The relative CRFs are then:

$$CRF'_{507} = CRF_{507} \times P\left(Collsn_{ID} = 30 \vee Road_{Relat_{ID}} = 2 \vee Road_{Relat_{ID}} = 3 \vee Road_{Relat_{ID}} = 4\right)$$
$$= 0.55 \times (0.0149 + 0.1668 + 0.0019 + 0.021) = 0.55 \times 0.2048 = 0.1126$$

$$CRF'_{532} = CRF_{532} \times P\left(Collsn_{ID} = 30 \vee Road_{Relat_{ID}} = 2 \vee Road_{Relat_{ID}} = 3 \vee Road_{Relat_{ID}} = 4\right)$$
$$= 0.65 \times (0.0149 + 0.1668 + 0.0019 + 0.021) = 0.65 \times 0.2048 = 0.1331$$

Assuming effects are perfectly overlapped (extreme case, most pessimistic):

$$CMF_{507 \wedge 532} = 1 - 0.1331 = 0.8669$$

Assuming effects are independent:

$$CMF_{507 \wedge 532} = 1 - 0.1331 - 0.1125 + 0.1331 \times 0.1125 = 0.7693$$

Assuming that effects are unrelated, as was established in Scenario 3, results in an overly optimistic result as this assumption means that all crashes that can be affected by the combined CMFs will be eliminated. For this example, the calculation would be:

$$CMF_{507 \wedge 532} = 1 - 0.1331 - 0.1125 = 0.7543$$

Conclusion:

The results for the independent assumption are very comparable to results when assuming that CMFs are completely unrelated. However, assuming independence may result in overestimating the benefit of the combination of work codes 507 and 532 by: 0.8670-0.7693= 0.0977, if the effects are, in fact, maximally overlapped. The combined CMF for this scenario is expected to range from 0.7543 up to 0.8670. In the spreadsheet provided by TxDOT, however, this combination is estimated at 0.26, as observed in Scenario 3. The discrepancy is due to the different baseline CMFs (i.e. types of crashes affected by work codes). This was demonstrated in Scenario 3, where the calculations in this methodology agreed with current TxDOT methods.

Summary

The research team explored scenarios for combining some specific work code options. This evaluation determined that when the current methodology is applied to a well-defined universe of crashes, the results fall within the range of what would be theoretically possible. However, severe bias may occur if a misalignment occurs between work codes being combined without explicit computation consideration for their applicable crashes.

This exploration of scenarios suggests that a revised methodology should include a step to determine the "universe of applicable crashes" that is common to both work codes before they can be combined. It is critical to adjust the corresponding CMFs to that common set of applicable crashes before attempting to combine them.

The next section documents the development of a systematic procedure to determine the common applicable crashes, adjust the given CMFs to that common base, and find the expected range of the combination of work codes.

SECOND PART: FRAMEWORK FOR AN IMPROVED METHODOLOGY TO COMBINE WORK CODES

This section of the chapter documents a revised methodology to combining work codes considering the insights outlined in the previous section.

Assessment of Current Criteria

The first step in developing an updated methodology to combine work codes is assessing if the current criteria should remain unchanged. Upon closer inspection, current criteria can be described in terms of three main types: 1) Pertaining to crash distributions and overlap of effects (Preventable Crash Types and Conditional, the two criteria thoroughly assessed at this point); 2) Pertaining to economic considerations (i.e. Amount of Work); and 3) Pertaining to reliability of the individual work code CMFs. Type 1 and 3 are very closely related with each other, and can be handled in terms of statistical properties of the CMFs. Type 2 is an important criterion, but it is of a different nature than the other two.

The research team considers that the criteria in the current methodology should be separated at different steps in the revised methodology, in order to avoid giving additive weights in the same scale (i.e. 1 to 3 points in the current methodology) to criteria that has a very different nature. In the current procedure, the four current criteria may equally sway the estimated combination of work codes equally (i.e. a point given weights the same, regardless of the criterion from which it comes). For the revised methodology, the research team recommends a two-step approach:

1. Initial determination of the possible range for the combination of work codes based on statistical properties of their CMFs and of the types of crashes to which the work codes pertain.
2. Select the combination of CMFs within the range obtained in step 1 giving weight to the best information available about the reliability of the CMFs in the combination, or applying conservative weights in case of limited documentation regarding reliability.

The research team further recommends that economic considerations (i.e. Amount of Work criterion) should not have a weight on the previous two steps, which intend to estimate the expected safety of the joint CMF from the combined work codes. Economic considerations should be addressed in a more formal economic analysis at a later stage. In that later analysis, the cost of implementing the work codes should be compared to the expected safety benefits (estimated in the two proposed steps).

The following sections document the development of the proposed two-step methodology to combine work codes.

Step 1 of Updating the Methodology: Determining Feasible Range of Combined CRF

The previous section of this document has shown that it is necessary to have knowledge about the relationship between the applicable types of crashes in order to successfully combine work codes. The initial approach the research team took was to closely examine if there are groups among the current work codes that share the same applicable types of crashes. Per the analysis in the previous section, if such "families" of work codes exist, there is a potential to facilitate the combination of the work codes that comprise them.

Identifying Groups of Existing Work Codes with Common Sets of Applicable Crashes

To gain a better understanding of currently available work codes, the research team analysed the similarities between work codes whose first digit is "1". Work codes were grouped in Phyla based on their types of crashes. Each phylum (or family) is such that its work codes are applicable to the same types of crashes. Table 108 is a cross-tabulation table that shows an "X" for work codes with corresponding applicable types of crashes.

In this matrix, a given Work Code row represents the set of crashes applicable to that work code. A matching column (for a given row) indicates that the set of crashes in the row is a superset of the crashes corresponding to the column.

Similarly, for a given work code column, a matching row indicates that the set of crashes for the column is a subset of the set of crashes from the row. Therefore, given the matches in this matrix, an exact match between applicable crashes occurs when the column and the row corresponding to two work codes are symmetric. That is, when the applicable set of crashes from one work code is both subset and superset for the set of applicable crashes of the other given work code.

Table 108. Matrix of Work Codes with Matching Types of Applicable Crashes

Work Code	101	102	104	105	106	107	108	110	111	112	114	118	119	121	122	123	124	125	126	127	128	129	130	131	133	136	137	138
101	X															X		X				X	X			X	X	
102		X		X	X									X	X		X		X	X	X							
104			X																									
105		X		X	X									X	X		X		X	X	X							
106		X		X	X									X	X		X		X	X	X							
107						X	X					X																
108						X	X					X																
110						X	X	X				X												X				
111									X		X														X			
112										X																		
114									X		X														X			
118						X	X					X																
119													X															
121		X		X	X									X	X		X		X	X	X							
122		X		X	X									X	X		X		X	X	X							
123																X		X				X	X			X	X	
124		X		X	X									X	X		X		X	X	X							
125																X		X				X	X			X	X	
126		X		X	X									X	X		X		X	X	X							
127		X		X	X									X	X		X		X	X	X							
128		X		X	X									X	X		X		X	X	X							
129																X		X				X	X			X	X	
130																X		X				X	X			X	X	
131						X	X	X				X												X				
133									X		X														X			
136																X		X				X	X			X	X	
137																X		X				X	X			X	X	
138						X	X					X																X

Using the matches in Table 108, the research team classified 11 phyla of work codes that are applicable to a common set of crashes. These phyla are shown in Table 109.

Table 109. Identified Phyla from the Relations Observed in Table 108

Phylum Number	Work Codes	Facility Type	Facility Character	Comments
1	101	Seg	U + R	Subset of Ph10
2	102, 105, 106, 121, 122, 124, 126, 127, 128	Int	U + R	Superset of Ph11
3	104	Seg	U + R	No subset is defined, depend on each situation
4	107, 108, 118	Seg + Int	U+R	Superset of Ph5 and Ph11
5	110, 131	Seg + Int	U+ R	Subset of Ph4
6	114, 133	Seg + Int	U+R	Superset of all other Phyla
7	111*	Seg + Int	U	This phylum matches phylum 6 but it is only applicable to urban roads
8	112	Seg + Int	U+ R	
9	119	Seg + Int	U+ R	
10	123, 125, 129, 130, 136, 137	Curves	U+ R	Superset of Ph1
11	138	Int	U + R	Subset of Ph4 and Ph2

When combining two codes within one Phylum, a proportional adjustment is not required unless the scope of the assessment is to be changed (for example, the desired combined CMF is required in terms of total crashes). In that case, the same proportional factor is to be applied to both work codes, either before or after the combination of work codes as they are given.

When combining two work codes whose phyla do not overlap, their values should first be adjusted to represent a proportion of the joint set of crashes. Since the types of crashes do not overlap, the combined reduction factor is simply the addition of the reduction factors.

Finally, before combining two work codes from overlapping phyla, the CRFs (or CMFs) should be adjusted to be representative of the joint set of crashes. The amount of overlap between types of crashes may play a limiting role in the maximum possible overlap between the effectiveness of two CMFs to be combined. The minimum possible effectiveness is:

P(A)+P(B)-min[P(B), Proportion of intercept between applicable crashes)]

and the maximum possible value is the sum of the two CRFs. The research team developed a matrix of overlaps between the identified phyla using year 2014 in the CRIS database as shown in Table 110.

Table 110. Number of 2014 Crashes per Phylum and Phyla Intersections

	1	2	4	5	6	7	8	9	10	11
1	**302,657**									
2	95,627	**223,469**								
4	75,787	198,932	**204,481**							
5	232	2,284	6,585	**6,585**						
6	302,657	223,469	204,481	6,585	**552,864**					
7	1,185	1,141	786	141	2,663	**419,170**				
8	10	0	0	0	209	9	**209**			
9	194,286	89,681	89,681	0	218,175	485	0	**218,175**		
10	302,657	106,752	86,912	232	322,003	1,287	10	213,632	**322,003**	
11	6	26,365	26,365	0	26,365	50	10	0	6	**26,365**

Total Crashes for a given phylum
One phylum is a subset of the other (maximum overlap)
Limited overlap in the number of crashes

Table 110 shows a large amount of heterogeneity among phyla. The number of applicable crashes per phylum ranges from only 209 for phylum 8 up to 552,864 crashes for phylum 6 (using 2014 crash data only). The amount of overlap between these subsets of crashes also ranges very widely.

Discussion

A critical limitation of using the numbers in Table 110 for the revised methodology is that this table shows crashes that may have occurred at very different facility types or road characters (for instance, there is no distinction between freeways and local roads, between segments and intersections, between rural and urban environments). In order to maximize the accuracy of the revised methodology, the research team decided to incorporate explicit location filters to be applied before determining the set of common applicable crashes when combining work codes. These filters include:

1. A filter for road character (rural vs. urban);
2. A filter for facility type (ranging from local roads to freeways);
3. A filter for Curve locations; and
4. A filter for intersection locations.

Unfortunately, another limitation that Table 110 highlights is that constructing phyla representing all work codes may not be a viable strategy for an all-encompassing revision of the current methodology and ultimately to develop a new recommended one, since there are eleven phyla just to combine work codes starting with 1. These phyla are not only plentiful but also very heterogeneous, so the effort of defining and documenting them is not likely to reduce the amount of computations that would be saved later in the process of combining work codes.

Methodology Development over a Subset of Work Codes

The research team sought and incorporated feedback from TxDOT regarding the development of the updated methodology. TxDOT provided a subset of work codes to be used in these efforts. The criterion to select this subset was the frequency with which these codes have been required to be combined in recent years. All "100" work codes were pooled with this subset, since files and coding for these work codes have already been prepared from the analysis in the previous section. The select pool of work codes to develop the methodology is shown in Table 111.

Table 111. Select Work Codes for Methodology Development

Family of Work Codes	Select Work Codes
100	101, 102, 105, 106, 107, 108, 110, 111, 112, 114, 118, 119, 121, 122, 123, 124, 125, 128, 130, 131, 133, 136, 137, 138
200	201, 203, 204, 207, 209, 218
300	303, 304, 305, 306, 307
400	401, 402, 403, 404, 407
500	502, 503, 504, 505, 506, 507, 514, 518, 519, 521, 523, 532, 533, 534, 536, 537, 540, 541, 542, 543, 544, 545, 546, 547

Based on the findings of the previous sections, the research team made no further attempt to develop phyla encompassing the codes in Table 111. Instead, the research team decided to develop an automated tool to incorporate the considerations of overlap between crash types. This tool will be described in the following sections.

Development of a Database and Queries to Combine Work Codes

The research team determined that a database tool will be a useful resource for expediting the identification of applicable crashes for each work code. The tool also should be user friendly yet powerful enough to process the large underlying database. The following section reviews development of this resource for the purposes of refining how TxDOT work codes can be combined in the future.

File with Filters on CRIS Variables for Each Work Code

The research team performed an analysis of the work codes in Table 111 to determine the minimum set of criteria necessary to identify the crash types applicable for any particular work code. This minimum set of criteria is expressed as variables from the CRIS database in the most current documentation of the work codes. The set of variables required to identify the applicable crashes for any of the work codes included in Table 111 are shown in Table 112.

Table 112. Minimum Set of CRIS Variables Required to determine Applicable Crashes for Work Codes Selected for Methodology Development

CRIS Variable
COLLSN_ID
ROAD_RELAT_ID
INTRSCT_RELAT_ID
HARM_EVNT_ID
OBJ_STRUCK_ID
ROAD_PART_ADJ
BRIDGE_DETAIL
SURF_COND
LIGHT_COND

Using these variables, the researchers created a file with the appropriate combinations required to produce the set of applicable crashes for each Table 111 work code. As an example, the set of conditions to filter applicable crashes for work codes 137 and 516 are shown in Table 113.

Table 113. Sample Set of Conditions Required to Obtain Applicable Crashes to Work Codes 137 and 516

Work Code	COLLSN_ID	ROAD_RELAT_ID	INTRSCT_RELAT_ID	HARM_EVNT_ID	OBJ_STRUCK_ID	ROAD_PART_ADJ	BRIDGE_DETAIL	SURF_COND	LIGHT_COND
137	20	0	0	0	0	0	0	0	0
137	21	0	0	0	0	0	0	0	0
137	22	0	0	0	0	0	0	0	0
137	23	0	0	0	0	0	0	0	0
137	24	0	0	0	0	0	0	0	0
137	30	0	0	0	0	0	0	0	0
137	0	2	0	0	0	0	0	0	0
137	0	3	0	0	0	0	0	0	0
137	0	4	0	0	0	0	0	0	0
516	10	0	0	0	0	1	0	0	0
516	14	0	0	0	0	1	0	0	0
516	20	0	0	0	0	1	0	0	0
516	21	0	0	0	0	1	0	0	0
516	22	0	0	0	0	1	0	0	0
516	24	0	0	0	0	1	0	0	0
516	26	0	0	0	0	1	0	0	0
516	28	0	0	0	0	1	0	0	0
516	29	0	0	0	0	1	0	0	0
516	30	0	0	0	0	1	0	0	0
516	34	0	0	0	0	1	0	0	0
516	38	0	0	0	0	1	0	0	0

The coding for this table is straight forward. Any condition or set of conditions to be applied as alternatives (i.e. an OR statement) is coded as a separate set of lines. An example of this type of coding is given in the first six rows in Table 113. Jointly, these rows indicate that work 137 is applicable to crashes with any value in the set {20, 21, 22, 23, 24, 30} for variable COLLSN_ID in the CRIS database.

When a row has values different than zero for more than one variable, the result is the application of simultaneous filters to the corresponding variables (i.e. AND statement). That is the case of the last 12 rows in Table 113. These rows jointly indicate that the crashes applicable to work code 516 are those with a value of 1 for the variable ROAD_PART_ADJ and any of the following values for the variable COLLSN_ID: {10, 14, 20, 21, 22, 24, 26, 28, 29, 30, 34, 38}.

The total set of combinations coded in the fashion shown in Table 113 amounted to 669 rows and was saved in a text file named "Codes and Conditons.csv." This file was linked from an MS Access file where other required files and corresponding queries were integrated as will be described in the following sections.

File with CMFs and other Details for Each Work Code

The research team created a separate file containing the CRF corresponding to each work code in the subset of interest. This file contains only three columns: CODE, corresponding to the work code; CRF; and Service, which indicates the service life of each treatment. Currently, only the first two columns are used in the database. However, this file should be supplemented with relevant information about the work code or the corresponding CMF in future work. The service life, for example, will ultimately be used for the economic evaluation.

File with Summaries of All Texas Crashes in 2012-2014

The research team queried the CRIS database for years 2012-2014 and found 1,567,904 unfiltered records. The research team summarized these records by the individual combinations of filters regarding the nine CRIS database variables identified earlier. A table with 144,646 summary records resulted from this effort. This synthesized file allows querying the total unfiltered records without losing resolution regarding the nine CRIS variables. This synthesized file was exported into the MS Access file.

Tables with Global Filters to be Applied When Estimating the Combination of Work Codes

Based on the analysis in the first section of this chapter, the research team decided to incorporate a set of tables allowing the user of the database tool to apply global filters prior to estimating the combination of work codes. In the database tool, these global filters are applied before any filters specific to the work codes are to be combined. This way, more accuracy is introduced in the following computations:

- Set of applicable crashes, which results from the union of the applicable crashes for each individual work code;
- Proportions of the set applicable crashes relative to total crashes; and
- Amount of overlap between individual sets of applicable crashes.

The global filters were grouped into three tables that were created in the database. These tables contain flags that the user can turn on or off before running any analyses. The global filters are as follows:

- Filters by Location: Intersections, Curves, Segments;
- Filters by Year: 2012, 2013, 2014; and
- Filters by road type, shown in Table 114.

Table 114. Filters by Road Type

ID	FUNC_SYS_ID	FUNC_SYS_DESC
1	1	RURAL INTERSTATE
7	11	URBAN PRIN ARTERIAL (IH)
8	12	URBAN PRIN ARTERIAL (OTHER FREEWAY)
9	14	URBAN PRIN ARTERIAL (OTHER)
10	16	URBAN MINOR ARTERIAL
11	17	URBAN COLLECTOR
12	19	URBAN LOCAL
2	2	RURAL PRIN ARTERIAL
3	6	RURAL MINOR ARTERIAL
4	7	RURAL MAJOR COLL
5	8	RURAL MINOR COLL
6	9	RURAL LOCAL

The research team automated a set of sequential queries using the data and filters described in this section in order to estimate the combination of CRFs corresponding to a pair of work codes. The result of those sequential queries is the estimation of the feasible range of values for the combination of CRFs when accounting for the proportions of individual applicable crashes of each work code relative to the minimum superset containing applicable crashes for both work codes (this is referred to simply as the set of applicable crashes).

Additionally, the calculations take into account the maximum feasible overlap between the combined effects of the work codes. This maximum overlap equals the maximum value as identified in the first section of this chapter unless the amount of overlap between individual sets of applicable crashes is smaller than that theoretical maximum. If that is the case, the maximum feasible overlap equals the overlap between individual sets of applicable crashes.

The feasible range of values for the combined CRF is calculated in relation to two sets of crashes:

1. The set of applicable crashes (i.e. the superset of the two individual sets of applicable crashes); and
2. The set of total crashes, defined by the global filters applied before the combination analysis.

The next section describes step 2 of the proposed updated methodology.

Step 2 of Updated Methodology: Selecting one value from the range of Combined CRFs obtained in step 1.

Ideally, the research team recommends incorporating considerations of reliability of the individual CRFs in order to arrive to a point estimate of the combined CRF in step 2. The main consideration in this step should be the standard error of each CRF, along with other characteristics of the studies that developed such CRFs. Though desirable, this information is not currently available for the set of CRFs in the current work codes. Obtaining such information and incorporating it into the documentation of current work codes should be the objective of further research, as well as developing a protocol for step 2 of this methodology that incorporates such details.

The research team decided to develop a standardized weighting average procedure to combine the three estimates obtained in step 1. Upon closer examination, the research team noted some geometric properties of the combination of CMFs. Given that one of the two CMFs is fixed, the geometric space of the range of feasible values for a combination of CMFs is a parallelogram, that always falls within the square defined by the points (0,0), (0,1), (1,1), and (1,0), as shown in Figure 8.

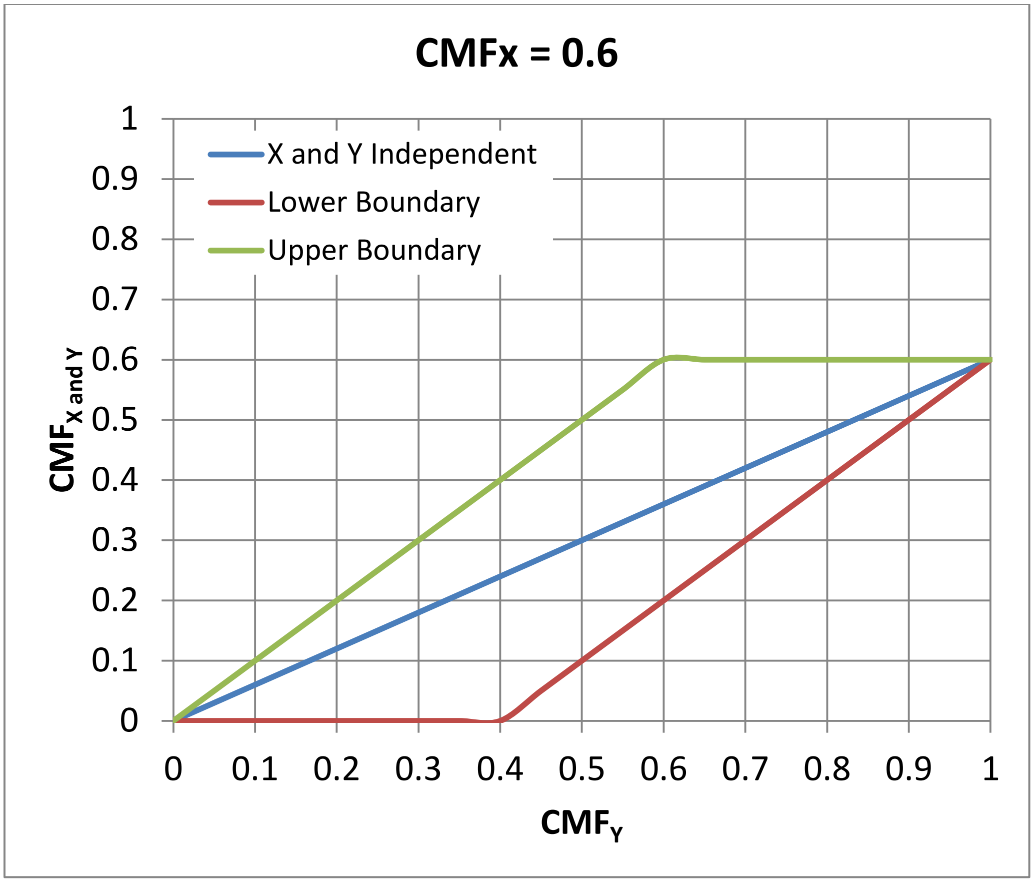


Figure 8. Feasible Space of Combining CMF=0.6 with any other CMF.

It is clear that the assumption of independence becomes more likely in the extremes of the parallelogram, closer to the upper limit on lower values of the second CMF (which is more conservative), and closer to the lower limit for the larger values of the second CMF (which is more optimistic). However, in the region of lower values for the second CMF (Y), the grand estimate is a greater overall improvement (i.e. low values for the combined CMF). Conversely, in the region with larger values for CMF_Y, the range of values for the combined CMF appears to be less effectiveness. Knowing the boundaries of the feasible space and that the value for independent effects "self-weights" (i.e. countering the trend for the range of values for the combined CMF), the research team determined applying a set of fixed weights can potentially yield a combined estimate that is conservative in most cases.

In the case of CRFs, the relationships are inverted. Therefore, the assessment procedure should place more weight on the minimum feasible value for the combined CRF and less on the maximum feasible value. After some considerations of complexity, the research team arrived at the following weighting scheme using as reference the value under the assumption of independence of effects:

- The minimum feasible value is weighted twice as much as the value assuming independence of effects;
- The maximum feasible value is weighted one half of the weight given to the value assuming independence effects.

The research team reviewed how the weighted average perform under the above scheme for a range of values of the two CRFs to be combined. Results indicate that the resulting estimates tend to be more conservative than the assumption of independent effects.

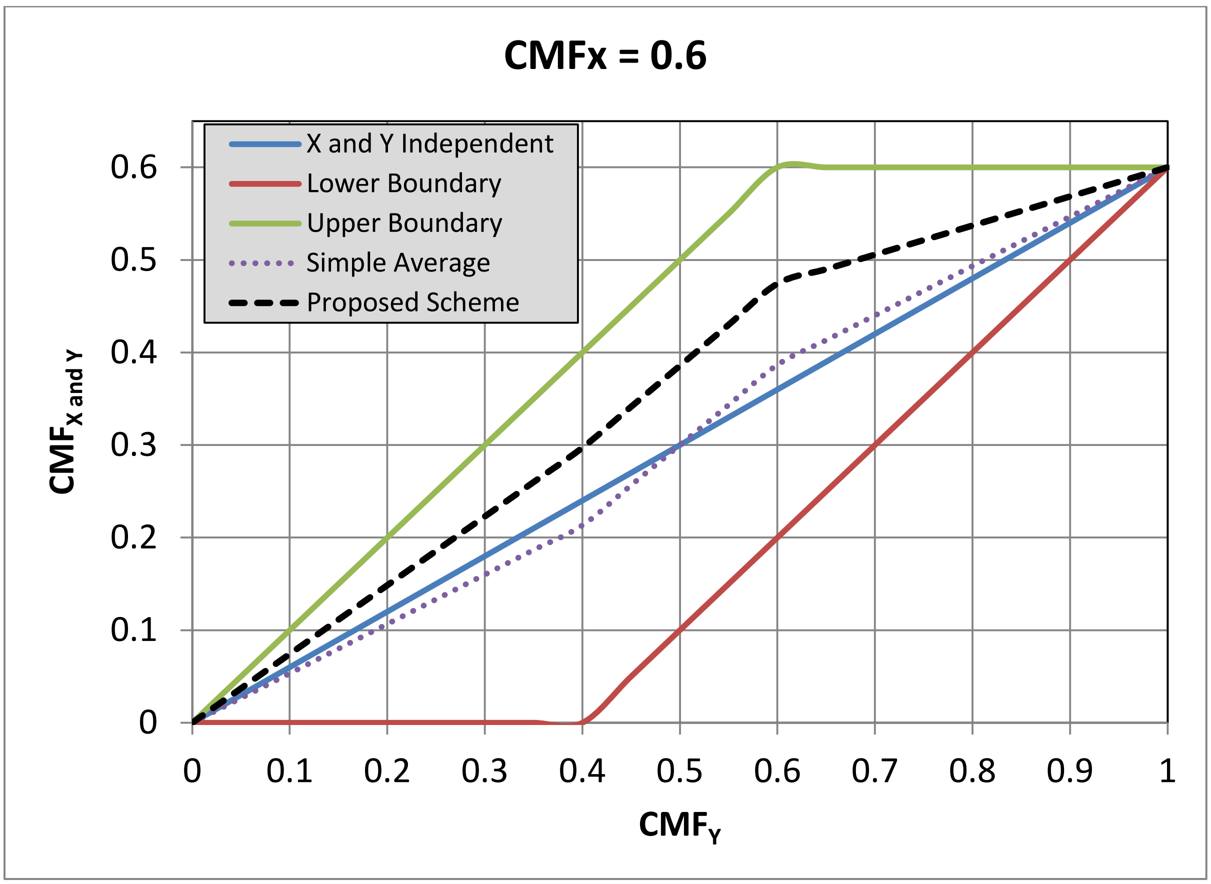


Figure 9. Sample Performance of Proposed Scheme.

The research team incorporated the weighting scheme described for step 2 in combination with the data and tables in step 1 to arrive at a conservative point estimate of the combined CRF. The next and final part of this chapter describes the use of the access database tool that automates the procedures described in this document.

THIRD PART: DATABASE TOOL FOR COMBINATION OF WORK CODES

As described in the previous section of this chapter, the research team developed a database to facilitate the procedures of the updated methodology to combine work codes. The name of the file main file is “DB Combine Work Codes.accdb.” When this file is opened, the initial screen that is displayed will look like that shown in Figure 10.

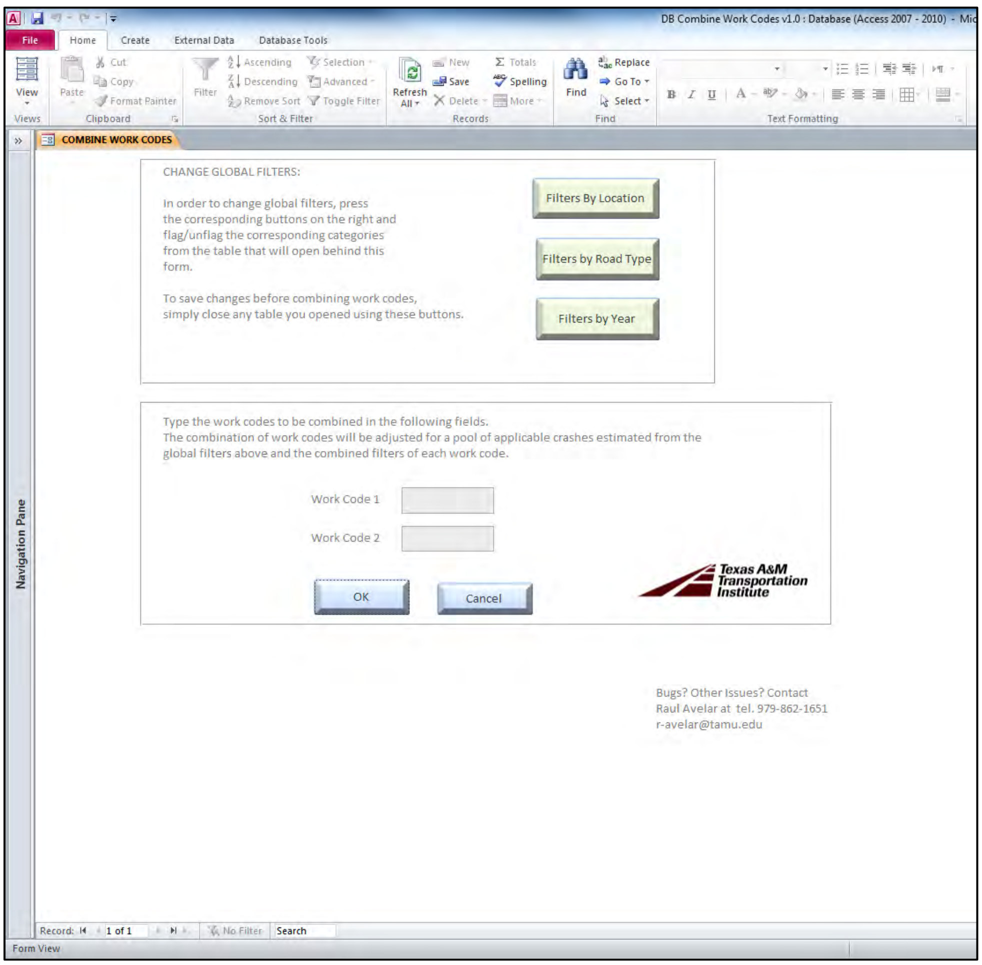
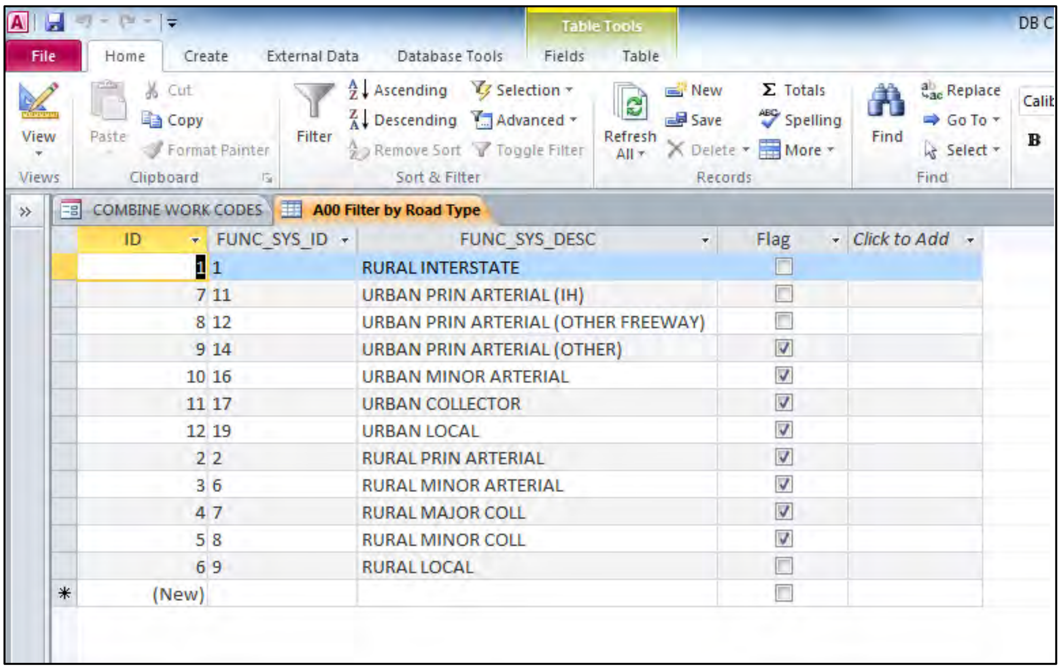


Figure 10. Main Form in Database File.

The area of this form presents the user with three buttons, each allowing the user to set global filters as discussed earlier in this chapter. For example, when pressing the second button, the table corresponding to the filters for facility type/ roadway character opens as shown in Figure 11. On this table, the user should set the flags that apply to the sites where the application of the combined work codes is intended.



ID	FUNC_SYS_ID	FUNC_SYS_DESC	Flag	Click to Add
1	1	RURAL INTERSTATE	☐	
7	11	URBAN PRIN ARTERIAL (IH)	☐	
8	12	URBAN PRIN ARTERIAL (OTHER FREEWAY)	☐	
9	14	URBAN PRIN ARTERIAL (OTHER)	☑	
10	16	URBAN MINOR ARTERIAL	☑	
11	17	URBAN COLLECTOR	☑	
12	19	URBAN LOCAL	☑	
2	2	RURAL PRIN ARTERIAL	☑	
3	6	RURAL MINOR ARTERIAL	☑	
4	7	RURAL MAJOR COLL	☑	
5	8	RURAL MINOR COLL	☑	
6	9	RURAL LOCAL	☐	
(New)			☐	

Figure 11. Table of Filters by Road Type in Database File.

After closing the tables where global filters were applied, the user should type in the work codes to be combined. For example, Figure 12 shows the form with the inputs necessary to estimate the combined effectiveness of work codes 107 and 122.

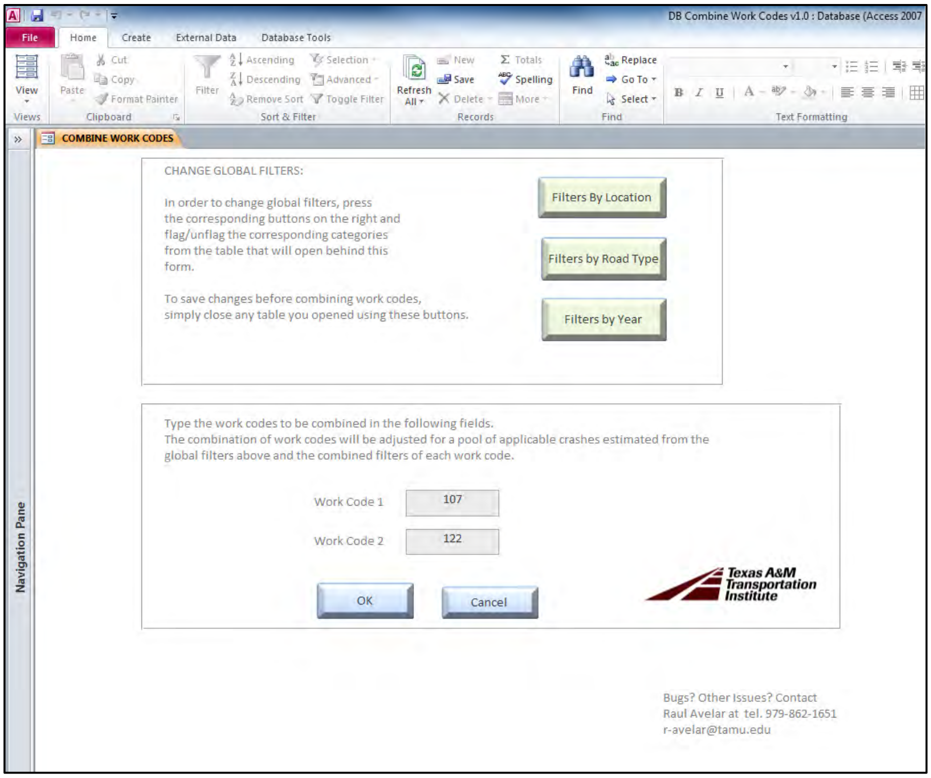


Figure 12. Inputs in Main Form to Combine Work Codes 107 and 122.

After pressing the OK button, the user receives an auditory confirmation (i.e. a beep) which indicates that the queries are being processed. When the calculations are finalized, the user is presented with the report shown in Figure 13.

There are two parts to this report. The right side presents the user with a Venn diagram containing the adjusted CRFs relative to the set of applicable crashes of the two combining work codes. In the case shown in Figure 13, the given CRFs (35 and 10) are unchanged in the Venn diagram since both these work codes share the same set of applicable crashes. That is not generally the case for other work codes. Below this diagram, there is a graphic represetation of the range of feasible values for the combination of CRFs, showing the CRFs value under the assumption of independent effects. A red arrow indicates the selected value using the weighting scheme in the previous section of this chapter. The right side of this report shows the same metrics described in the previous paragraph but relative to total crashes, as defined by the global filters.

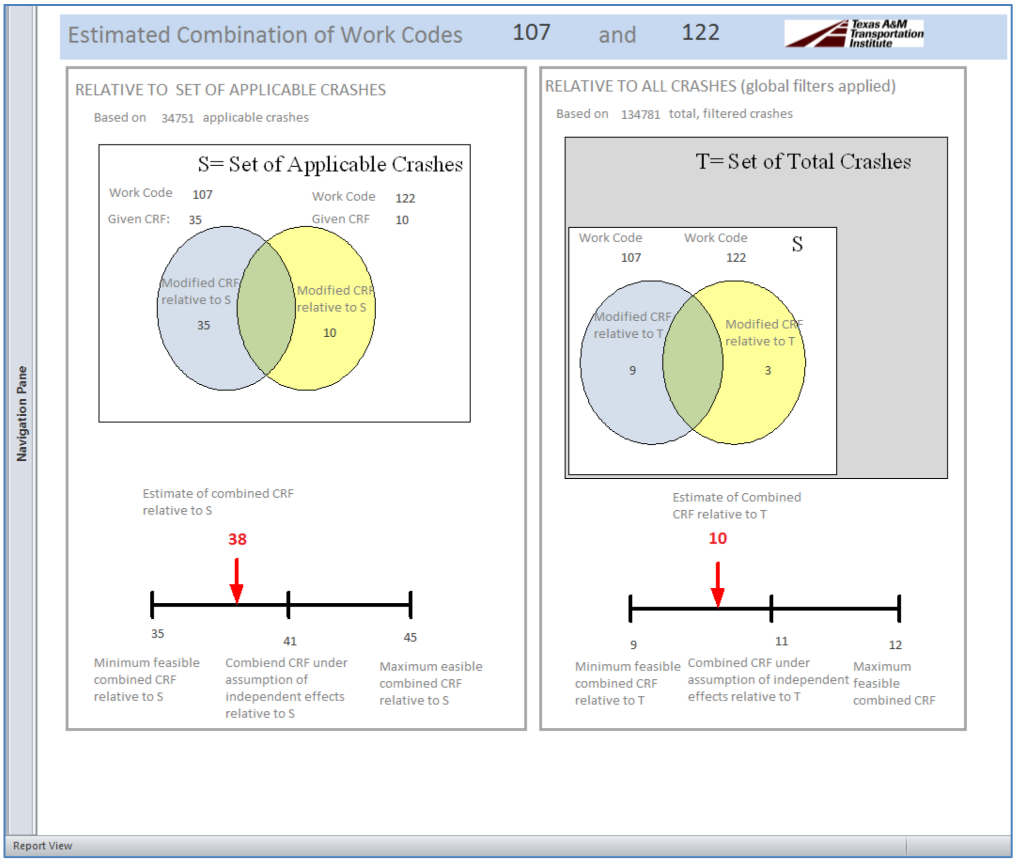


Figure 13. Report of the Estimation of Combining Work Codes 107 and 122.

CONCLUSIONS AND RECOMMENDATIONS

The research team assessed the current TxDOT procedure for combining work codes. In order to recommend enhancements to the procedure, the research team performed a meticulous analysis of the statistical properties of various combinations of CRFs. This analysis yielded valuable insights about certain theoretical features to be considered when combining CRFs. More importantly, this analysis yielded a path to compute a range of feasible values for combining CRFs that depends solely on their values and the degree of coincidence between their individual set of applicable crashes. The research team incorporated all these considerations into an enhanced procedure.

The recommended updated procedure requires two steps: 1) computing a range of feasible values for the combination of CRFs, and 2) incorporating statistical and reliability considerations in selecting a point estimate within the range identified in step 1. Step 2 is contingent on the availability of data and information about the statistical attributes and reliability of CRFs associated with current work codes. Future research should compile such information to be incorporated in a more robust step 2 of this methodology.

At this time, step 2 was determined as simply a weighted average of the three estimates obtained in step 1. The fixed weights were selected considering that the resulting point estimates would tend to be more conservative than assuming that the effects of the combined work codes are statistically independent. The research team developed a database tool as companion to this technical memorandum to help facilitate the implementation of this procedure.

Future research should expand the work codes already included in the database tool, as well as a revisit of the CRFs associated with the current work codes, so as to incorporate statistical and reliability considerations into step 2 of the procedure recommended in this work. Finally, future research should expand the functionality of the current database tool to save point estimates of some common combinations of CRFs in order to allow the combination of more than two CRFs. However, the research offers caution with this recommendation, as it is expected that the degree of uncertainty (and bias) tends to increase with every additional CRFs combined. In that regard, the research team recommends work toward increasing the robustness of step 2 prior to any work toward combining additional (multiple) CRFs using the current methodology.

CHAPTER 4. CONCLUSIONS

This report identified the current TxDOT WCs and companion supporting literature. In many cases, the Texas values were aligned with national values. In some cases, the WC description was very specific and there were not any national CMFs or CRFs that exactly matched that description. General findings during this review of the literature are as follows:

- Current emphasis of TxDOT WCs primarily addresses total crashes; however, the national performance measures are shifting towards emphasis on reducing fatal and serious injury crashes. Consequently, TxDOT may consider expanding the current WCs to incorporate this specific type of crash severity.
- Recent literature for CMFs and CRFs tends to include a variety of severity and crash types (where statistically viable) along with some measure of reliability (usually a standard error). Statistically rigorous evaluations that incorporate the standard error are more likely to reliably estimate safety performance and this will extend to effective expenditure of value project funds. A future research goal may be to expand the TxDOT WCs to incorporate levels of reliability.
- In most cases, the TxDOT WC values were aligned with those from national research. In select instances, however, the TxDOT value for total crashes was greater than the national average for total crashes (or in some cases for injury crashes). If TxDOT does elect to expand the WCs to include injury and fatal values as well as reliability (the previous two recommendations), a priority for identifying WCs to evaluate may be to select the WCs that had values that were not similar to those reported nationally.

In addition to the literature review, the report outlines the statistical analysis conducted by the researchers so as to assess an effective technique for combining work codes. Chapter 3 summarizes this information. Key items to note include the following:

- A two-step procedure can be used to efficiently combine the TxDOT WCs, though currently a combination of two WC values is the focus of the analysis. The method identified in Chapter 3 includes: 1) computing a range of feasible values for the combination of CRFs, and 2) incorporating statistical and reliability considerations in selecting the point estimate of the range.

- The existing TxDOT procedure for combining WCs provides similar values as that proposed in this analysis for many cases. The TxDOT method currently includes an economic weighting factor in the procedure; however, the researchers recommend that this factor be applied as part of a benefit-cost evaluation after the work codes have been combined.
- The simple multiplication of CMFs, as currently presented in the AASHTO Highway Safety Manual, is suitable for treatment combinations where the safety effects are generally independent. When the affected crashes begin to overlap, however, an alternative procedure should be considered.
- The detailed assessment required for identifying the varying weighting assignments for TxDOT WCs can be manually computationally challenging. As a result, the research team automated this procedure to help facilitate evaluations by TxDOT analysts.

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