Extension of Safety Assessment Tool For Construction Work Zone Phasing Plans

Final Report
August 2018

SWZDI
Smart Work Zone Deployment Initiative

Sponsored by
Smart Work Zone Deployment Initiative
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(Part of InTrans Project 18-535)

About SWZDI

Iowa, Kansas, Missouri, and Nebraska created the Midwest States Smart Work Zone Deployment Initiative (SWZDI) in 1999 and Wisconsin joined in 2001. Through this pooled-fund study, researchers investigate better ways of controlling traffic through work zones. Their goal is to improve the safety and efficiency of traffic operations and highway work.

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16. Abstract

Engineering practitioners must balance safety and mobility when evaluating different construction phasing alternatives for highway work zones. There is a need for practitioner guidance and practical tools to assess work zone safety impacts as such resources are currently lacking. The objective of the study was to extend a structured safety assessment tool that was previously developed for freeways, expressways, and rural two-lane highways to include other facilities such as arterials, signalized intersections, unsignalized intersections, multi-lane highways, and ramps. Using Missouri data, this study introduces five new crash prediction models for work zones on urban multi-lane highways, arterials, ramps, signalized intersections, and unsignalized intersections. All the work zone models in this report are proposed for the first time. These work zone models are implemented in a user-friendly spreadsheet tool that automatically selects the appropriate model based on user input. The tool predicts crashes by severity, and computes the crash costs for each construction phasing alternative.

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EXTENSION OF SAFETY ASSESSMENT TOOL FOR CONSTRUCTION ZONE WORK PHASING PLANS

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This research was conducted under the Smart Work Zone Deployment Initiative (SWZDI) and Federal Highway Administration (FHWA) Pooled Fund Study TPF-5(295), involving the following state departments of transportation:

- Iowa (lead state)
- Kansas
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EXECUTIVE SUMMARY

As the need for maintaining existing highway infrastructure continues to grow, practitioners must balance mobility and safety impacts in highway work zones. While there are many existing tools based on the Highway Capacity Manual (TRB 2010) to assess work zone mobility impacts, there are a limited number of tools available to evaluate work zone safety impacts. The need for a work zone safety assessment tool was underscored in a survey by Brown et al. (2016) in which practitioners indicated that they typically use engineering judgment to evaluate work zone safety and that they would utilize a work zone safety assessment tool if it were available. The Highway Safety Manual (HSM) (AASHTO 2010) provides limited guidance for work zone safety evaluation as it only presents work zone crash modification factors (CMFs) for freeway work zone length and duration based on data from 36 freeway work zones in California. In addition, there is a small number of CMFs for some work zone layout configurations and countermeasures in the CMF Clearinghouse (FHWA 2018).

To address the need for a tool to evaluate work zone safety impacts, a spreadsheet-based safety assessment tool was recently developed for freeways, expressways, and rural two-lane highways (Brown et al. 2016a). Data from Missouri were analyzed to develop the statistical models that were implemented in the tool. The tool predicts crashes by severity and crash costs for each work zone alternative based on input data provided by the user. The objective of this study was to extend the previously developed safety assessment tool to include other facilities such as arterials, signalized intersections, unsignalized intersections, multi-lane highways, and ramps in an effort to further facilitate the evaluation of work zone safety impacts by practitioners.

The research approach included the collection and analysis of work zone, traffic, crash, roadway, and intersection data from the Missouri Department of Transportation (MoDOT) database that included 120,797 work zones between 2011 and 2016. Work zones longer than 0.1 mile and duration greater than 10 days were included. These thresholds, of 0.1 mile and 10 days, were the same as those previously determined in Brown et al. (2016a). Since the MoDOT database includes only information regarding the footprint of the activity area and the entire work zone footprint is needed to link crashes to work zones, the length recommendations in the MUTCD (FHWA 2009) were used to locate the entire work zone footprint by determining the locations of the other independent work zone segments: advance warning area, transition area, buffer area, and termination area. An algorithm was developed to assign crashes to work zones at intersections. Crashes were assigned to intersections within 250 ft of the intersection on its approaches according to the HSM criterion. Descriptive statistics for the five facility types studied in this research are provided in Tables ES.1 to ES.5.

Table ES.1. Descriptive statistics of urban multi-lane highway work zone samples

Length, Duration, and AADT			
Variables	Average	Min	Max
Length of work zone, mi (km)	1.477 (2.377)	0.100 (0.161)	9.320 (14.999)
AADT (vehicles per day)	7,592	1,164	18,071
Work zone duration (days)	42.8	10.0	277.0
Number of observations		251	

Crashes			
Number of Crashes	All Crashes	PDO	Fatal-Injury
Sum	506	348	158
Average	2.016	1.386	0.629
Min/max	0/83	0/51	0/32

Table ES.2. Descriptive statistics of arterial work zone samples

Length, Duration, and AADT			
Variables	Average	Min	Max
Length of work zone, mi (km)	2.291 (3.687)	0.1 (0.161)	9.990 (16.077)
AADT (vehicles per day)	5,746	94	29,383
Work zone duration (days)	40.1	10.0	299.9
Urban/rural percent		55% / 45%	
Number of observations		3,138	

Crashes			
Number of Crashes	All Crashes	PDO	Fatal-Injury
Sum	4,682	3,429	1,253
Average	1.492	1.093	0.399
Min/max	0/60	0/48	0/26

Table ES.3. Descriptive statistics of ramp work zone samples

Length, Duration, and AADT			
Variables	Average	Min	Max
Length of work zone, mi (km)	0.277 (0.446)	0.11 (0.177)	0.820 (1.320)
AADT (vehicles per day)	6,487	112	64,755
Work zone duration (days)	46.1	10.0	280
Urban/rural percent		86% / 14%	
Number of observations		372	

Crashes			
Number of Crashes	All Crashes	PDO	Fatal-Injury
Sum	138	94	44
Average	0.371	0.253	0.118
Min/max	0/34	0/28	0/6

Table ES.4. Descriptive statistics of signalized intersection (4-leg) work zones samples

Length, Duration, and AADT

Variables	Average	Min	Max
Major leg AADT (vehicles per day)	11,373	1,213	36,561
Minor leg AADT (vehicles per day)	3,115	15	13,878
Work zone duration (days)	43.1	10.1	299.9
Urban/rural percent		93% / 7%	
Number of observations		2,484	

Crashes

Number of Crashes	All Crashes	PDO	Fatal-Injury
Sum	236	189	47
Average	0.095	0.076	0.019
Min/max	0/9	0/8	0/3

Table ES.5. Descriptive statistics of unsignalized intersection (4-leg) work zones samples

Length, Duration, and AADT

Variables	Average	Min	Max
Major leg AADT (vehicles per day)	3,575	66	46,198
Minor leg AADT (vehicles per day)	423	11	12,976
Work zone duration (days)	34.2	10.1	283.7
Urban/rural percent		37% / 63%	
Number of observations		8,060	

Crashes

Number of Crashes	All Crashes	PDO	Fatal-Injury
Sum	75	53	22
Average	0.0093	0.0066	0.0027
Min/max	0/10	0/8	0/2

Using these samples, negative binomial regression models were used to predict work zone crash frequency for the five facility types based on independent variables such as annual average daily traffic (AADT), work zone length, work zone duration, and urban/rural indicator. A summary of the variables included in each model is shown in Table ES.6. Although the models have some limitations with respect to high overdispersion values and low numbers of crashes at intersections, they are the first models to predict work zone crashes for these facility types and the best possible models for the chosen data. Future improvements to work zone data collection methods could improve knowledge of work zone safety impacts and enhance future tools.

Table ES.6. Independent variables in crash prediction models

	AADT (Segment)	AADT (Major Leg)	AADT (Minor Leg)	Duration	Length	Urban /Rural
Urban multi-lane highway	X			X	X	
Arterial	X			X	X	X
Ramp	X			X		
Signalized intersection (4-leg)		X	X	X		
Unsignalized intersection (4-leg)		X	X	X		

The models were incorporated into the previously developed user-friendly spreadsheet tool. The software graphical interface and an example of output are shown in Figures ES.1 and ES.2.

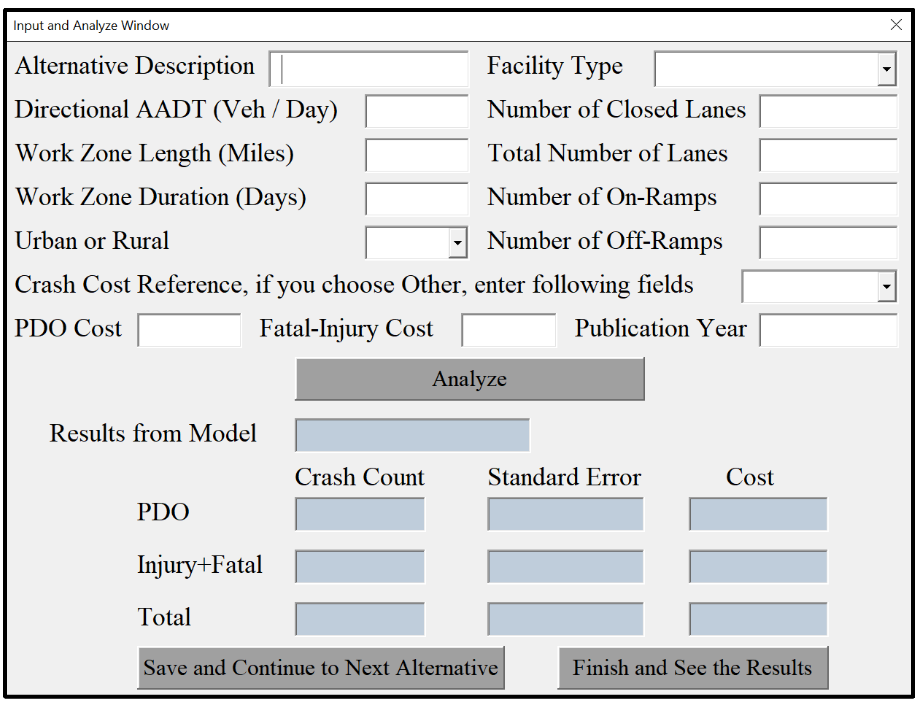


Figure ES.1. User input window for the enhanced work zone safety assessment tool

Alternatives Comparison			
	Output		
	Arterial	Ramp	Sig. Int.
Expected Number of PDO Crashes	4.26	0.02	0.08
Standard Error of PDO Estimation	2.064	0.141	0.283
Expected Number of Fatal and Injury Crashes	1.56	0.01	0.02
Standard Error of Fatal and Injury Estimation	2.495	0.101	0.157
Total Crash Cost; value in 2018	$656,832	$4,082	$8,864
Model Used:	Arterial	Ramp	Sig. Intsc. (4-Leg)
	Input		
	Arterial	Ramp	Sig. Int.
AADT	8000	2000	
Duration	90	45	120
Length	1.5		
Urban/Rural	Urban		
Number of Closed Lanes			
Total Number of Lanes			
Number of On-ramps			
Number of Off-ramps			
Number of Signalized Intersections			
Crash Cost Reference; Publication Year	HSM (2010)	HSM (2010)	HSM (2010)
PDO Crash Cost	$7,400	$7,400	$7,400
Fatal and Injury Crash Cost	$158,200	$158,200	$158,200
Facility Type	Arterial	Ramp	Sig. Intsc. (4-Leg)
Major Leg AADT (4-Leg Intsc.)			4000
Minor Leg AADT (4-Leg Intsc.)			500
Developed by University of Missouri-Columbia; TransZou			

Figure ES.2. Sample output of the enhanced work zone safety assessment tool

The developed software will provide transportation practitioners with a valuable tool to help them assess the safety impacts of work zones for different alternatives. Decision makers will be able to optimize for work zone safety impacts and mobility impacts by selecting the best construction phasing plan alternative.

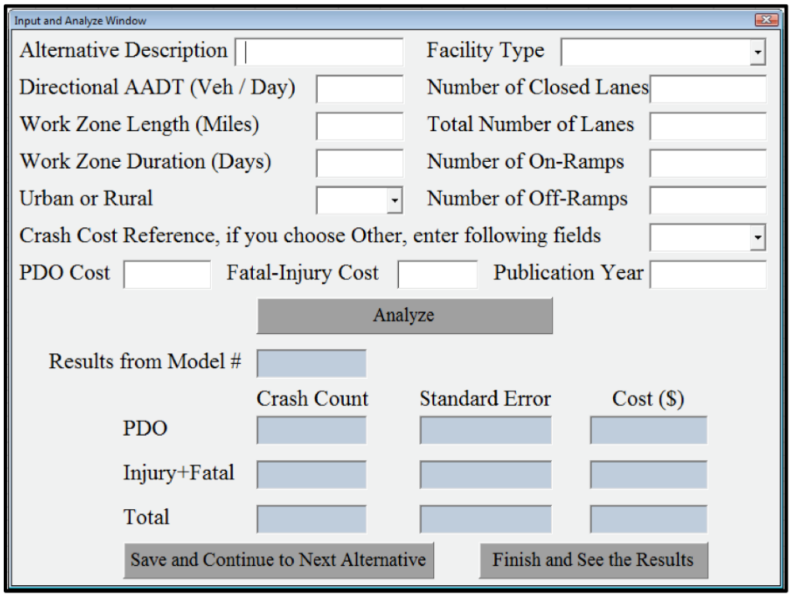
1. INTRODUCTION

As the nation's highway infrastructure continues to age, many state departments of transportation (DOTs) and other public agencies have focused more on maintaining their existing road network in lieu of expanding the highway network. The mitigation of mobility and safety impacts from highway rehabilitation projects requires careful consideration by practitioners. The Federal Highway Administration (FHWA) Work Zone Safety and Mobility Rule (Scriba et al. 2005) encourages agencies to develop procedures to assess safety and mobility impacts in work zones. DOTs need to assess safety impacts of work zones in order to find ways to mitigate them. Mitigation techniques include efficient scheduling of work activity, use of effective traffic management plans, and use of intelligent transportation system (ITS) technologies.

Work zones include many components that affect both traffic and safety. In 2014, nearly 10% of all congestion on freeways was due to the presence of work zones (FHWA 2017a). This is equivalent to 310 million gallons of fuel loss (FHWA 2017a). In terms of safety, in the US, every 5.4 minutes a work zone-related crash occurred in 2015 (96,626 annual crashes) (FHWA 2017b). Among these, 26.4% were injury crashes, 0.7% were fatal crashes and the rest were property damage only (PDO) crashes (FHWA 2107b).

While there are several existing tools based on the Highway Capacity Manual (TRB 2010) that can be used to assess the operational impacts of work zones, including Quick Zone, QUEWZ-98, and CA4PRS, there are few tools available to assess work zone safety impacts. A survey by Brown et al. (2016a) discussed the need for a comprehensive work zone safety evaluation tool. The survey asked representatives from DOTs, FHWA, and contractors about their best practices for work zone safety. The survey results showed that engineering judgement is often used to evaluate work zone safety. In addition, 90 percent of DOT and FHWA respondents and 83 percent of contractor respondents indicated that they would use a work zone safety assessment tool, if available.

Since many agencies typically assess work zone safety at a program level using engineering judgement, there is a need for a comprehensive tool to help practitioners quantify the safety impacts of different work zone phasing plans and lane closure scenarios at a project level. To help address this need, a project was recently completed to develop a work zone safety assessment tool for freeways, expressways, and rural two-lane highways (Brown et al. 2016a). The spreadsheet-based tool includes a user-friendly interface (Figure 1.1) and is available for download (Brown et al. 2016b).



Brown et al. 2016a

Figure 1.1. Work zone safety assessment tool data input window

To create the tool, statistical models were developed from the analysis of work zone, crash, traffic, and geometric data from Missouri. Variables that were found to impact the number of work zone crashes include annual average daily traffic (AADT), work zone length, work zone duration, and the number of total lanes, closed lanes, on-ramps, off-ramps, and signalized intersections. The tool provides the expected number of crashes by severity and total crash costs for each alternative as output (Figure 1.2).

Alternatives Comparison			
	Output		
	FW WZ	Exp WZ	RTL WZ
Expected Number of PDO Crashes	9.8	42.91	10.58
Standard Error of PDO Estimation	4.644	28.311	3.253
Expected Number of Fatal and Injury Crashes	3.16	15.7	2.24
Standard Error of Fatal and Injury Estimation	2.094	10.828	1.497
Total Crash Cost; value in 2016	$1,169,024	$5,720,784	$883,581
Model Used: #	6	10	14 & 15

Brown et al. 2016a

Figure 1.2. Example work zone safety assessment tool output

The objective of the study was to extend the previously developed structured safety assessment tool to include other facilities such as arterials, signalized intersections, unsignalized intersections, multi-lane highways, and ramps. Expansion of the tool to include other facility types will further facilitate the evaluation of work zone safety impacts by practitioners. The research approach included the collection and analysis of work zone and crash data from

Missouri for different construction phasing alternatives. These data were used to develop statistical models that were then coded into the enhanced spreadsheet tool. Attainment of the project objective will help to fill gaps in existing knowledge and provide transportation practitioners with a valuable tool to assist them in the evaluation of the safety impacts of construction work zones for different alternatives. Armed with better information regarding the anticipated safety impacts of different alternatives, decision makers will be able to more readily balance these impacts with mobility impacts and other factors to select the best construction phasing plan alternative.

This report describes process for enhancing the previously developed work zone safety assessment tool. The report includes the following chapters: introduction, background, data, model estimation methodology, model results, discussion of model results, software applications/examples, and conclusion.

2. BACKGROUND

2.1. Overview of Highway Safety Manual (HSM)

The Highway Safety Manual (HSM) (AASHTO 2010) is the national manual on highway safety just as the Highway Capacity Manual, the AASHTO Green Book, and the Manual of Uniform Traffic Control Devices (MUTCD) are national manuals on capacity/level-of-service, geometric design, and traffic control devices. With the advent of the HSM, transportation engineers now have a quantitative method for assessing safety along with other impacts such as capacity and delay. However, the first edition of HSM lacks several facility types and, despite the enormous effort expended in its creation, was developed with data from only a few select states. The quantitative methods presented for work zones are brief and based on limited research; the HSM methodology for work zones is based on 36 freeway work zones with high traffic volumes in California. A previous research study (Sun et al. 2014) calibrated HSM work zone models using data from Missouri and resulted in a calibration factor of 3.78, which is significantly larger than 1, thus undesirable.

2.2. Safety Performance Function (SPF) and Crash Modification Function (CMF)

In the HSM (AASHTO 2010), safety performance functions (SPFs) are used to predict crashes for a given set of base conditions based on exposure variables such as AADT and length. These crashes are then multiplied by crash modification factors (CMFs) to account for conditions different than base conditions and by a calibration factor to account for regional differences. The general method for this calculation is shown below (AASHTO 2010).

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

where:

$N_{predicted}$ is the predicted crash frequency for a site,
N_{SPF} is the predicted crash frequency for specified base conditions,
CMF_i is the crash modification factor i reflecting a prevailing site condition that differs from the base condition,
C is the calibration factor, which accounts for differences (jurisdictional and time period) between the sample used for SPF development and the one for which the crash frequency is currently being estimated.

For work zones, the HSM provides CMFs for work zone length and duration (AASHTO 2010):

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

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

These CMFs were developed from California data for 36 high impact freeway work zones in California.

2.3. Literature Review

This section provides a summary of recent literature related to work zone safety. Additional work zone safety literature prior to 2016 was summarized in the study by Brown et al. (2016a) to develop a work zone safety assessment tool. Brown et al. (2016a) conducted a survey for contractors and DOT representatives to assess the state of the practice of work zone safety. They also developed negative binomial crash prediction models for freeway, expressway, and rural two-lane work zones and coded the models into a spreadsheet-based assessment tool.

Edara et al. (2016) developed guidance for practitioners regarding the application and development of work zone CMFs. The developed guidance provided an overview of existing work zone CMFs and described the steps for evaluating work zones using existing CMFs and for developing new work zone CMFs.

Clark and Fontaine (2015) studied two years of Virginia work zone crashes. They reviewed work zone coded crashes (from crash reports) and found that only 23% of these crashes were directly related to the presence of work zones. Rahmani et al. (2016) developed crash prediction models for freeway work zones using negative binomial models.

La Torre et al. (2017) used a sample of 15,570 stationary work zones in Italy to perform an empirical Bayes (EB) before-and-after study. Their result showed a general increase in crash frequency due to the implementation of work zones. In this study, various lane closure scenarios for freeway work zones were determined and analyzed, and CMFs were calculated for the different scenarios. The average of CMFs they found were 1.33 for fatal and injury and 1.66 for property damage only crashes.

Theofilatos et al. (2017) did a meta-analysis on the studies that focused on the work zone crash frequency modeling. From various studies, they collected and compared the coefficients of work zone duration and length, as two main contributing factors. They found the average coefficients of length and duration to be 0.953 and 0.847, respectively.

Wei et al. (2017) categorized work zone-related crashes in Tennessee during 2005–2015 into three lighting conditions: daylight, dark-lighted, and dark-not-lighted. The study showed that by increasing the number of closed lanes the severity level increases during daylight but decreases at night. Also, drugs and alcohol were found to significantly increase the work zone-related crash severity in dark-not-lighted conditions, while having a limited effect on the other two lighting conditions.

Ullman et al. (2017) developed four work zone CMFs for queue warning systems in two different traffic conditions: queued and non-queued. Ullman et al. (2016) studied an end-of-queue (EOQ) warning system including a set of portable radar speed sensors, portable changeable message signs, and portable transverse rumble strips. Their result showed the significant positive effect of the system in reducing crashes (reduced by 44%).

3. DATA

The dependent variable in roadway SPFs is typically annual crash frequency. However, in this study, the dependent variable of crash prediction models is crash count for the work zone duration. There is a tremendous effort required for performing work zone safety studies, because different data sources need to be cleaned and then fused together. Three types of data are required: work zone characteristics such as length, duration, location, and type; work zone traffic characteristics; and work zone crash characteristics.

The data in this study were queried from the Missouri Department of Transportation (MoDOT) databases. Data from other states were requested, but unfortunately, the DOTs did not have proper data available. In the prior study (Brown et al. 2016a), 20 state DOTs were contacted to assess their availability of suitable work zone and crash data. The data received from other states either did not allow for the assignment of crashes to work zones or did not contain enough work zones for model development. In this study, efforts were made to obtain work zone and crash data from the Kansas Department of Transportation (KDOT) and Wisconsin Department of Transportation (WisDOT). KDOT provided some data for work zone crashes between 2011 and 2016. However, the data did not include AADT or data regarding work zone characteristics and thus could not be used for analysis. During the final stages of the project, WisDOT provided work zone and crash data for some freeway and expressway work zones in 2016 and 2017. Although the WisDOT data could not be incorporated into this project, it could potentially be used in the future to calibrate the previously developed models for freeway and expressway crashes in work zones. However, analysis of the WisDOT data would require review of individual crash reports to properly link the crashes to work zones.

Samples were extracted based on work zone thresholds of longer than 0.1 mile for continuous segments and duration greater than 10 days for both segments and intersections. These thresholds for minimum work zone length and duration were determined analytically from a previous study by Brown et al. (2016a). For intersections, crashes were assigned to intersections within 250 ft of the intersection on its approaches according to the HSM criterion. Typically, a work zone is divided into five independent segments: advance warning area, transition area, buffer area, activity area, and termination area based on MUTCD (FHWA 2009). In the MoDOT database, the only available information is the footprint of activity area. Since the entire work zone footprint was needed in this study for the safety analysis, the locations of the other work zone areas were determined based on the length recommendations in the MUTCD (FHWA 2009). Additional details regarding the assignment of crashes to work zones and sampling are provided later in this chapter.

3.1. Databases

A challenge in creating a work zone crash prediction model involves fusing three categories of data (i.e., work zone characteristics, crash characteristics, and road and traffic characteristics) from different databases to link work zones with crashes. Some of the data needed in each category include the following:

Work zone characteristics

- Travel-way ID
- Work zone dates and location (mile post)
- Cost of the project
- Lane closure
- Duration of the work zone
- Length of the work zone

Crash characteristics

- Travel-way ID
- Log-mile (the mile post on each travel-way)
- Date and time of the crash
- Number of injuries, fatalities, etc.
- Number of vehicles involved
- Type of collision

Road and traffic characteristics

- Travel-way ID
- Segment begin and end log-mile
- Average daily traffic (ADT) or AADT with seasonal adjustment factor
- Number of lanes
- Number of intersections
- Percent of heavy vehicles

Intersection database

- Intersection ID
- Leg travel-way ID
- Log-mile
- Signalized flag
- Number of legs

Figure 3.1 shows the data collection process:

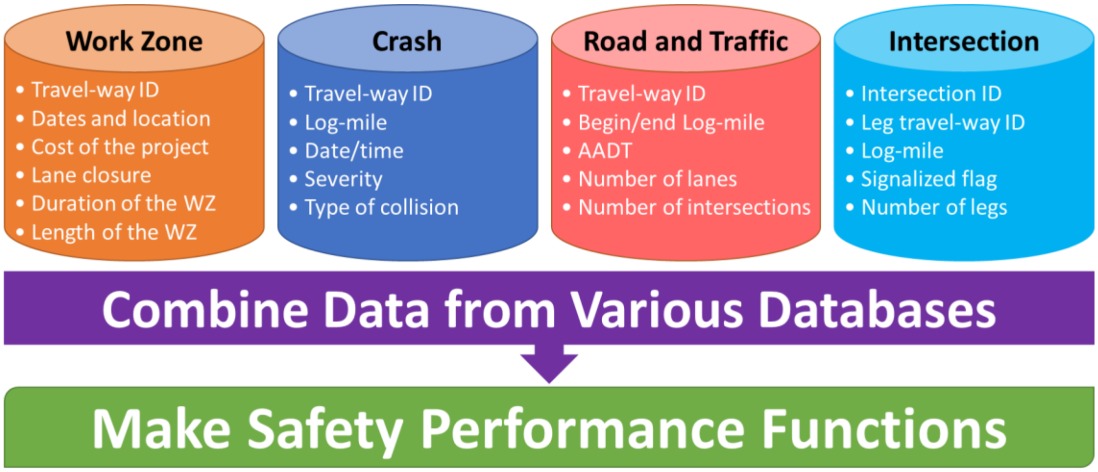


Figure 3.1. Work zone studies data collection process

In order to combine the information contained in the work zone, crash, road traffic, and intersection databases, data fusion was utilized. Due to the complexities in the data fusion and other data challenges, prior research has typically incorporated small sample sizes when developing work zone crash models. The work zone CMFs in the HSM were developed from a sample size of 36 work zones in a study by Khattak et al. (2002). The sample sizes used in this study are significantly larger than those used in prior work zone safety studies. This study used 251 multi-lane highway, 3,138 arterial, 372 ramp, 2,488 4-leg signalized intersection, and 8,060 4-leg unsignalized intersection work zones to develop 5 new work zone safety models. The data for work zones on 3-leg intersections was not adequate.

The work zone database contained the following information: unique work zone ID, a roadway segment ID, start and end date, time of work, and start and end location. Archived highway patrol reports were contained in the crash database. The crash reports included a column to indicate the presence of a work zone. However, this information was not used in this study to determine if a crash was related to a work zone because it was based upon a law enforcement officer's judgment at the scene and could therefore be inaccurate. For example an officer might not have been aware of the work zone if there were not visible work zone traffic control at the scene. Some crashes were related to work zones even though they were not coded in the crash reports as work zone-related crash. A FHWA study (FHWA 1996) assessed 4 work zones and determined that up to 77 percent of the work zone crashes were not coded as work zone-related crashes by law enforcement officers.

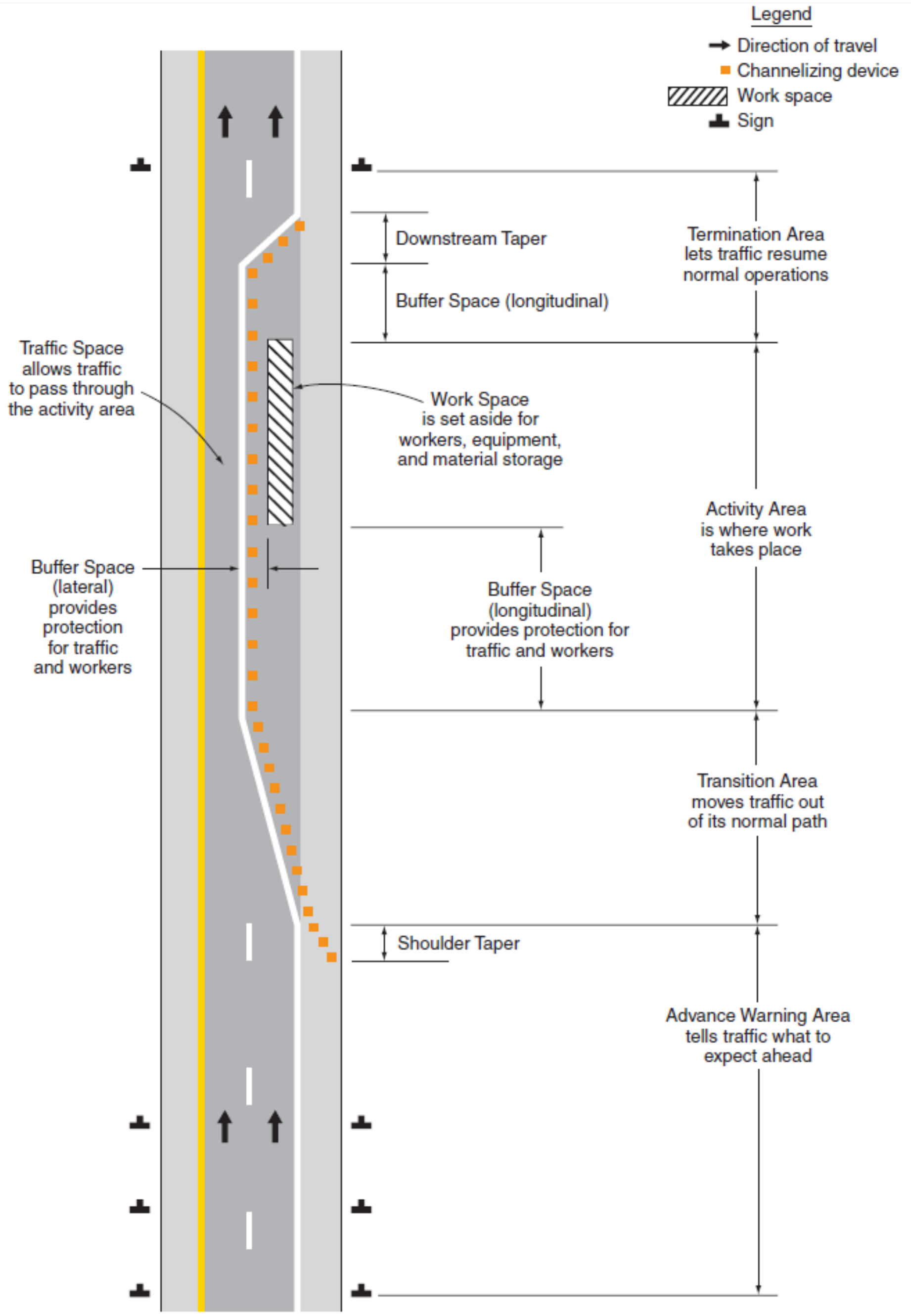
In this study, the crashes were assigned to the real footprint of work zones by using temporal-spatial matching as described in the following sections.

3.2. Assignment of Crashes to Work Zones

In the MoDOT work zone database, the footprint of a work zone is indicated by the beginning and end of the work area. To account for the crashes that happen in advance warning area, transition area, buffer area, and termination area of work zones, most studies in the literature considered a *constant length* before the start and after the end of each work zone. For example, the model used by the HSM classified all crashes within 0.5 mile (0.8 km) of the beginning and 0.5 mile (0.8 km) after the end of the work zone as work zone crashes To estimate the actual footprint of work zones, *including advance warning area, transition area, buffer area, activity area, and termination area*, the MUTCD-specified temporary traffic control plan lengths for roadway work zones were used in this study.

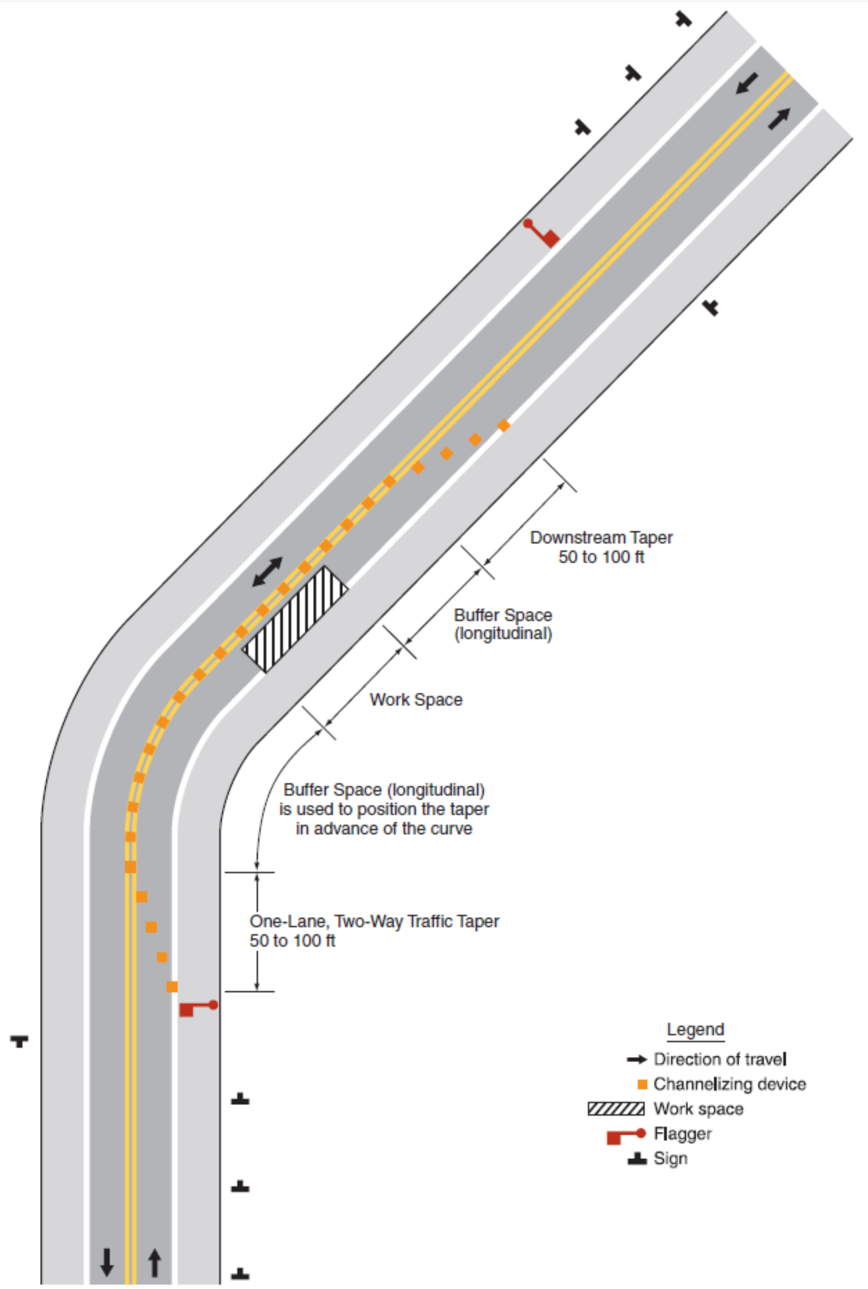
3.2.1. Crash Assignment to Roadway Work Zones (Based on MUTCD)

As described previously, the MUTCD-recommended distances were used to determine the footprint of the work zone and link crashes with work zones. The five different parts of the work zone are the advance warning area, transition area, buffer area, activity area, and termination area (FHWA 2009). In this study, the activity and buffer areas were considered together, and the remaining areas separate. Figure 3.2 shows the schematic plan of the parts of the work zone, and Figure 3.3 shows the MUTCD layout for a rural two-lane work zone.



FHWA 2009

Figure 3.2. Work zone components based on MUTCD



FHWA 2009

Figure 3.3. Rural two-lane schematic work zone parts, MUTCD

The procedure for determining the extents of the different work zone areas was described in Brown et al. (2016) and is summarized below.

- Advanced warning area is determined from Table 3.1.
- The buffer distance is calculated from Table 3.2 and could be included both before and after the work area.
- The transition area is computed from Table 3.3. Based on the MUTCD, the shoulder taper is

included in the advanced warning area.

- The total distance of the buffer area, transition area, and advance warning area is added to the beginning of the work area.
- The buffer area downstream of the work zone is the same distance as the buffer area upstream of the work zone.
- The termination area is 50–100 ft for each closed lane.
- The buffer area and termination area are added to the end of the work zone.

Table 3.1. Advanced warning area distances, MUTCD recommendations

Road Type	Distance Between Signs**		
	A	B	C
Urban (low speed)*	100 feet	100 feet	100 feet
Urban (high speed)*	350 feet	350 feet	350 feet
Rural	500 feet	500 feet	500 feet
Expressway / Freeway	1,000 feet	1,500 feet	2,640 feet

* Speed category to be determined by the highway agency

** The column headings A, B, and C are the dimensions shown in Figures 6H-1 through 6H-46 [of the MUTCD]. The A dimension is the distance from the transition or point of restriction to the first sign. The B dimension is the distance between the first and second signs. The C dimension is the distance between the second and third signs. (The “first sign” is the sign in a three-sign series that is closest to the temporary traffic control (TTC) zone. The “third sign” is the sign that is furthest upstream from the TTC zone.)

Source: FHWA 2009

Table 3.2. Buffer area, MUTCD recommendations

Stopping Sight Distance as a Function of Speed	
Speed*	Distance
20 mph	115 feet
25 mph	155 feet
30 mph	200 feet
35 mph	250 feet
40 mph	305 feet
45 mph	360 feet
50 mph	425 feet
55 mph	495 feet
60 mph	570 feet
65 mph	645 feet
70 mph	730 feet
75 mph	820 feet

* Posted speed, off-peak 85th-percentile speed prior to work starting, or the anticipated operating speed

Source: FHWA 2009

Table 3.3. Transition and termination area, MUTCD recommendations

Taper Length Criteria for Temporary Traffic Control Zones

Type of Taper	Taper Length
Merging Taper	at least L
Shifting Taper	at least 0.5 L
Shoulder Taper	at least 0.33 L
One-Lane, Two-Way Traffic Taper	50 feet minimum, 100 feet maximum
Downstream Taper	50 feet minimum, 100 feet maximum

Source: FHWA 2009

The formulas for determining taper length differ depending on the speed. Equation 4 gives the formula when the speed is 40 mph or less, and Equation 5 gives the formula when the speed is 45 mph or more.

$$L = \frac{WS^2}{60} \tag{4}$$

$$L = WS \tag{5}$$

where:

L = taper length in feet,
W = width of offset in feet, and
S = posted speed limit, or off-peak 85th-percentile speed prior to work starting, or the anticipated operating speed in mph

3.2.2. Crash Assignment to Work Zones on Intersections

3.2.2.1. Overview of Methodology

The work zone database includes work zones on roadway segments only; there is no available data for work zones on intersections. In addition, the intersection database is not indexed for each intersection. In fact, the intersection database contains a list of all “intersections legs” in the state of Missouri. So, each row of the database includes the information on ***ONE leg*** of an intersection.

To assign the work zones to the intersections, the following algorithm was devised. Note that the real footprint of the work zones were found by the MUTCD length recommendations mentioned in Section 3.2.1. Crashes were classified as intersection-related if they occurred on one of the intersection approaches with a distance less than 250 ft from the intersection.

3.2.2.2. Algorithm

The following algorithm was devised to link work zones, intersections, and crashes. In the algorithm symbols Ⓐ, Ⓑ, Ⓒ, and Ⓓ represent various datasets that were prepared.

1. For each work zone in the database:
   1.1. From the intersection database Ⓐ find the 'set of intersection legs inside the work zone by using the travel-way ID of the intersection legs and log-mile
      1.1.1. Find the legs with travel-way ID equal to work zone travel-way ID and $WZ\ begin\ logmile < leg\ logmile < WZ\ end\ logmile$
   1.2. From Ⓐ find the 'list of unique intersection IDs'Ⓑ
   1.3. For each intersection in Ⓑ find the 'list of all the legs of the intersection'Ⓒ
   1.4. For each intersection in Ⓑ
      1.4.1. From Ⓒ Find AADT of major and minor set of legs considering:
         1.4.1.1. One of major legs has maximum AADT, One minor of legs has the minimum AADT
         1.4.1.2. The leg on opposite side of the 1st major leg is the second major leg. The same for the minor leg.
         1.4.1.3. Find the average AADT for set of major legs and minor legs
      1.4.2. Find the crashes on each leg that have the same travel-way ID as the leg travel-way ID, which:
         $Leg\ logmile - 250 < Crash\ logmile < Leg\ logmile$
         $WZ\ start\ date < Crash\ date < WZ\ end\ date$
      1.4.3. Put the crashes on all legs in a list Ⓓ
      1.4.4. Aggregate all the crashes in Ⓓ by severity
2. For each intersection found in 1, add work zone and crash count information calculated in 1.4.1 and 1.4.4.

3.3. Sampling and Data Descriptive Statistics

There were 120,797 work zones in the MoDOT database between 2011 and 2016. As previously discussed, the work zones shorter than 0.1 miles or with a duration of less than 10 days were not included.

3.3.1. Urban Multi-Lane Highway Work Zones

An urban multi-lane highway is an undivided travel-way with two or more lanes for through traffic in each direction. The access control can be either limited/partial or none. The urban multi-lane highway segments were queried by using the facility type name as MULTI-LANE and area designation as URBAN or URBANIZED. Then, these segments were fused with the work zones by temporal-spatial matching. Table 3.4 shows the descriptive statistics of the sample of 251 urban multi-lane highway work zones used in this study. These work zones were collected between the years of 2011 and 2016. The average length and duration were 1.477 miles and 42.8 days, respectively. The AADT of the samples ranged from 1,164 to 18,071 veh/day with an average of 7,592 veh/day. About 70% of the crashes were property damage only (PDO), and the rest were fatal and injury crashes.

Table 3.4. Descriptive statistics of the urban multi-lane highway work zone sample

Length, Duration, and AADT

Variables	Average	Min	Max
Length of work zone, mi (km)	1.477 (2.377)	0.1 (0.161)	9.32 (14.999)
AADT (vehicles per day)	7,592	1,164	18,071
Work zone duration (days)	42.8	10.0	277.0
Number of observations		251	

Crashes

Number of Crashes	All Crashes	PDO	Fatal-Injury
Sum	506	348	158
Average	2.016	1.386	0.629
Min/max	0/83	0/51	0/32

3.3.2. Arterial Work Zones

Arterial roads were collected from the MoDOT database by querying the functional class name as PRINCIPAL ARTERIAL or MINOR ARTERIAL. Table 3.5 shows the descriptive statistics of the sample of 3,138 arterial work zones used in this study. These work zones were collected between the years of 2011 and 2016. The average length and duration were 2.291 miles and 40.1 days, respectively. The AADT of the samples ranged from 94 to 29,383 veh/day with an average of 5,746 veh/day. Around 55% of these arterials were in urban areas. About 73.24% of the crashes were property damage only, and the rest were fatal and injury crashes.

Table 3.5. Descriptive statistics of the arterial work zone sample

Length, Duration, and AADT			
Variables	Average	Min	Max
Length of work zone, mi (km)	2.291 (3.687)	0.1 (0.161)	9.990 (16.077)
AADT (vehicles per day)	5,746	94	29,383
Work zone duration (days)	40.1	10.0	299.9
Urban/rural percent		55% / 45%	
Number of observations		3,138	

Crashes			
Number of Crashes	All Crashes	PDO	Fatal-Injury
Sum	4,682	3,429	1,253
Average	1.492	1.093	0.399
Min/max	0/60	0/48	0/26

3.3.3. Ramp Work Zones

A ramp is a travel-way that allows movement from one travel-way to another travel-way. The ramp segments were queried by using the facility type name as RAMP. These segments were fused with work zones by temporal-spatial matching. Ramps are usually found at interchanges; however, some at-grade intersections may have ramps to reduce turning movements. Table 3.6 shows the descriptive statistics of the sample of 372 ramp work zones used in this study. These work zones were collected between the years of 2011 and 2016. The sample contained work zones longer than 0.1 miles with a duration of more than 10 days. The average length and duration were 0.277 miles and 46.1 days, respectively. The AADT of the samples ranged from 112 to 64,755 veh/day with an average of 6,487 veh/day. Around 84% of these ramps were in urban areas. About 68% of the crashes were property damage only, and the rest were fatal and injury crashes.

Table 3.6. Descriptive statistics of the ramp work zone sample

Length, Duration, and AADT			
Variables	Average	Min	Max
Length of work zone, mi (km)	0.277 (0.446)	0.11 (0.177)	0.820 (1.320)
AADT (vehicles per day)	6,487	112	64,755
Work zone duration (days)	46.1	10.0	280
Urban/rural percent		86% / 14%	
Number of observations		372	
Crashes			
Number of Crashes	All Crashes	PDO	Fatal-Injury
Sum	138	94	44
Average	0.371	0.253	0.118
Min/max	0/34	0/28	0/6

3.3.4. Signalized Intersection (4-Leg) Work Zones

The intersections that had some work zones on them were found using the methodology described in Section 3.2.2. Table 3.7 shows the descriptive statistics of the sample of 2,484 work zones on 4-leg signalized intersections used in this study. There was not enough data for 3-leg intersections. These work zones were collected between the years of 2011 and 2016. The average duration was 43.1 days. The major leg AADT of the samples ranged from 1,213 to 36,561 veh/day with an average of 11,373 veh/day. The minor leg AADT of the samples ranged from 15 to 13,878 veh/day with an average of 3,115 veh/day. Around 93% of these intersections were in urban areas. About 80% of the crashes were property damage only and the rest were fatal and injury crashes.

Table 3.7. Descriptive statistics of the signalized intersection (4-leg) work zones sample

Length, Duration, and AADT			
Variables	Average	Min	Max
Major leg AADT (vehicles per day)	11,373	1,213	36,561
Minor leg AADT (vehicles per day)	3,115	15	13,878
Work zone duration (days)	43.1	10.1	299.9
Urban/rural percent		93% / 7%	
Number of observations		2,484	

Crashes			
Number of Crashes	All Crashes	PDO	Fatal-Injury
Sum	236	189	47
Average	0.095	0.076	0.019
Min/max	0/9	0/8	0/3

3.3.5. Unsignalized Intersection (4-Leg) Work Zones

Table 3.8 shows the descriptive statistics of the sample of 8,060 work zones on 4-leg unsignalized intersections used in this study. There was not enough data for 3-leg intersections. These work zones were collected between the years of 2011 and 2016. The average duration was 34.2 days. The major leg AADT of the samples ranged from 66 to 46,198 veh/day with an average of 3,575 veh/day. The minor leg AADT of the samples ranged from 11 to 12,976 veh/day with an average of 423 veh/day. Around 37% of these intersections were in urban areas. About 71% of the crashes were property damage only and the rest were fatal and injury crashes.

Table 3.8. Descriptive statistics of the unsignalized intersection (4-leg) work zones sample

Length, Duration, and AADT

Variables	Average	Min	Max
Major leg AADT (vehicles per day)	3,575	66	46,198
Minor leg AADT (vehicles per day)	423	11	12,976
Work zone duration (days)	34.2	10.1	283.7
Urban/rural percent		37% / 63%	
Number of observations		8,060	

Crashes

Number of Crashes	All Crashes	PDO	Fatal-Injury
Sum	75	53	22
Average	0.0093	0.0066	0.0027
Min/max	0/10	0/8	0/2

4. MODEL ESTIMATION METHODOLOGY

The negative binomial model was used in this study for several reasons. First, the prior study by Brown et al. (2016), used the Akaike information criterion (AIC) to investigate various distributions such as negative binomial, zero-inflated negative binomial, Poisson and zero-inflated Poisson and found that the negative binomial model provided the best results. In addition, the majority of prior work zone safety studies (e.g., Pal and Sinha 1996, Venugopal and Tarko 2000, Tarko and Venugopal 2001, Khattak et al. 2002, Srinivasan et al. 2011, Ozturk et al. 2013, Yang et al. 2013, Sun et al. 2014) utilized the negative binomial model. Since previous studies have shown reliable results by using the negative binomial model in work zone crash frequency modeling, this study also utilized negative binomial models. For negative binomial models, the dispersion parameter α describes the degree to which the variance of the crash frequency data exceeds the mean crash frequency (Salkind 2006). Additional details regarding the negative binomial model are described in Brown et al. (2016).

Since many prior work zone safety studies used AADT, length, and duration of work zone (Pal and Sinha 1996, Elias and Herbsman 2000, Venugopal and Tarko 2000, Tarko and Venugopal 2001, Khattak et al. 2002, Ozturk et al. 2013, Yang et al. 2013, Sun et al. 2014) as explanatory variables, this study also follows the exponential functional form for all the three variables. Some prior work zone safety studies (Venugopal and Tarko 2000, Tarko and Venugopal 2001, Khattak et al. 2002, Srinivasan et al. 2008, Sun et al. 2014) also incorporated the urban/rural classification. Based on the knowledge developed in previous studies, the final functional forms for the models in this study were as follows:

- Urban multi-lane highway total crash model

$$N_{Total} = e^{\beta_0} AADT^{\beta_1} L^{\beta_2} D^{\beta_3} \tag{6}$$

- Arterial total crash model

$$N_{Total} = e^{\beta_0} AADT^{\beta_1} L^{\beta_2} D^{\beta_3} e^{\beta_4 * \text{Urban}} \tag{7}$$

- Ramp total crash model

$$N_{Total} = e^{\beta_0} AADT^{\beta_1} D^{\beta_2} \tag{8}$$

- Signalized intersection total crash model

$$N_{Total} = e^{\beta_0} AADT_{Major}^{\beta_1} AADT_{Minor}^{\beta_2} D^{\beta_3} \tag{9}$$

- Unsignalized intersection total crash model

$$N_{Total} = e^{\beta_0} AADT_{Major}^{\beta_1} AADT_{Minor}^{\beta_2} D^{\beta_3} \tag{9}$$

where the variables are as follows:

N_{Total}	– Total number of crashes;
$AADT$	– Annual average daily traffic (vehicles/day);
$AADT_{Major}$	– Intersection's major leg AADT (vehicles/day);
$AADT_{Minor}$	– Intersection's minor leg AADT (vehicles/day);
D	– Duration of observation (days);
L	– Segment length (miles);
Urban	– Dummy variable for work zone location, 1= urban, 0 = rural;

Variables were added sequentially, and maximum likelihood was used to estimate parameters.

5. MODEL RESULTS

This chapter summarizes the final results of modeling five different road functional types: urban multi-lane highway, arterial, ramp, signalized intersection (4-leg), and unsignalized intersection (4-leg). All of the models were developed using a variable-added-in-order method. In this method, variables are added to the model one by one. At each stage, a variable that improves the model the most is added, and the significance of variable and the resulting overall model performance are tested. If both statistical tests are passed, the variable remains in the model. Otherwise, it is dropped. The chi-square goodness-of-fit test was used to assess the suitability of the models. This test calculates a statistic based on the differences between two models with a smaller value indicating a better fit of the data (Yale University 1997). This process continues for adding other variables. Adding all the variables in all the five final models significantly improved the models' performance. The variables that were not significant were dropped from final models.

5.1. Urban Multi-Lane Highway Work Zone Model

This model was made by considering a constant overdispersion. Table 5.1 summarizes the estimated parameters of the model with following functional form:

$$N_{Total} = e^{\beta_0} AADT^{\beta_1} L^{\beta_2} D^{\beta_3} \tag{5}$$

Each variable added was statistically beneficial to the model. All explanatory variables were statistically significant at the 1% level. This model predicts the total number of crashes. From the collected data, 68.77% of them were PDO crashes, and the rest were fatal and injury crashes. The overdispersion was 1.5988, which was not satisfactory. However, the reason for the poor overdispersion was the nature of data. The low number of crashes and the small sample size increase the uncertainty of the predictions.

Table 5.1. Urban multi-lane highway model parameters for total number of crashes

Explanatory Variable	Parameter Estimates	Standard Error	p-value
Constant	-9.7757	1.9870	<.0001
AADT	0.7892	0.2170	<.0003
L	0.7648	0.0917	<.0001
D	0.8981	0.1209	<.0001
Overdispersion, $\boldsymbol{\alpha_0}$	1.5988	0.2729	
PDO/Fatal-injury percent	68.77% / 31.23%		
Number of Observations	251		

Figures 5.1 and 5.2 show the urban multi-lane highway model AADT and length cumulative residual (CURE) plots, respectively. These plots support the model's performance. A good model residual should be a random number around zero, following a normal distribution. The summation of such a random variable should follow a normal distribution with 95 percent of the

observations falling within two standard deviations of the mean. In the CURE plots shown in the following sections, the blue lines represent the cumulative residuals ordered by the independent variable while the red lines represent two standard deviations above and two standard deviations below zero.

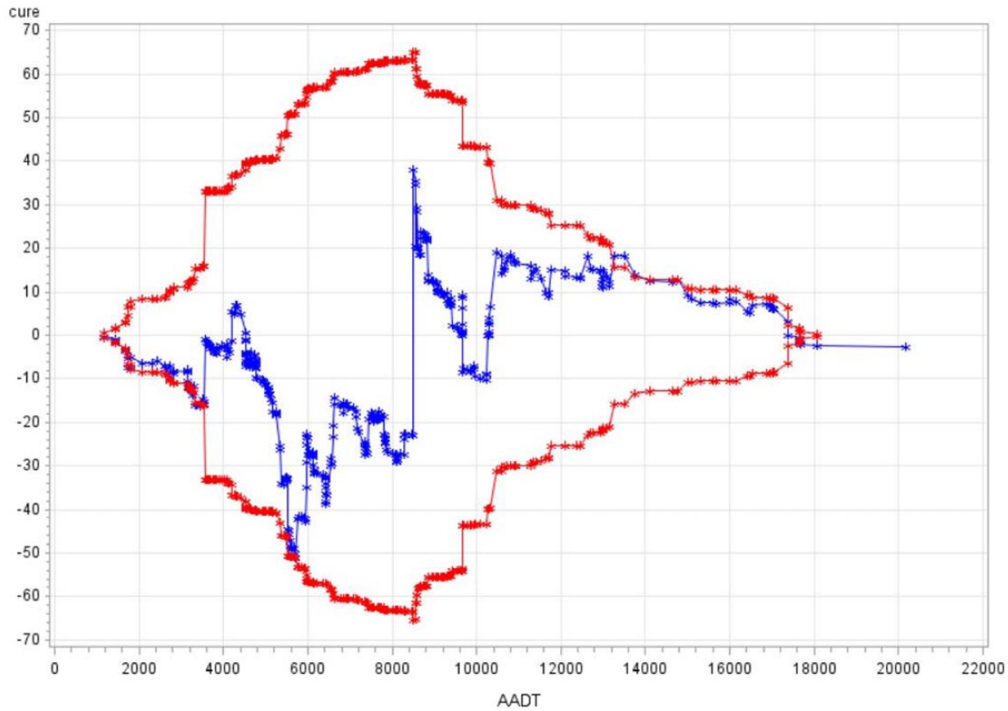


Figure 5.1. Urban multi-lane highway AADT CURE plot

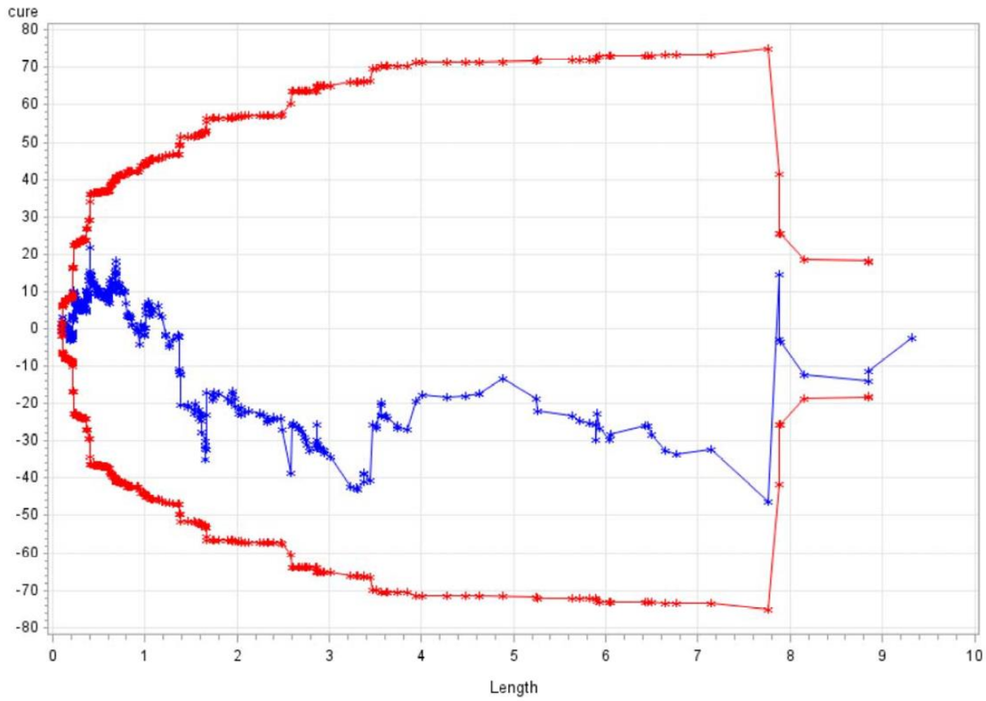


Figure 5.2. Urban multi-lane highway length CURE plot

Given that a CURE plot shows the sum of random variables (crash predictions), it is approximately normally distributed (Hauer 2015). In a normal distribution, about 95% of the probability mass should lie between two standard deviations from the mean. So the CURE plot should rarely go beyond the two confidence limits ($\mp 2\sigma^*$). With the same reasoning, if significantly more than 40% of the CURE plot lies between half of the standard deviation limits ($\mp 0.5\sigma^*$), the danger of overfitting problem exists. In an overfitted model, variables' coefficients do not show the underlying relationships and a small change in one independent variable could result in an exaggerated change in the dependent variable (Brown et al. 2016).

5.2. Arterial Work Zone Model with Length-Modified Overdispersion

This model was made by considering a length modified overdispersion as it showed better results comparing to the constant overdispersion. Table 5.2 summarizes the estimated parameters of arterial model with the following functional form:

$$N_{Total} = e^{\beta_0} AADT^{\beta_1} L^{\beta_2} D^{\beta_3} e^{\beta_4 * \text{Urban}} \tag{7}$$

Each variable added was statistically beneficial to the model (using the $\aleph^2$ test) and all explanatory variables were statistically significant at the 1% level. Since $e^{(0.749)} = 2.1149$, urban arterials have 2.1149 times the frequency of crashes compared to rural roads. This model predicts the total number of crashes. From the collected data, 73.24% of the crashes were PDO crashes, and the rest were fatal and injury crashes. The overdispersion was $\frac{2.8745}{L}$, which was not satisfactory. The reason for the poor overdispersion was the nature of data. The low number of crashes in the sample increases the uncertainty of the predictions.

Table 5.2. Arterial model parameters for total number of crashes

Explanatory Variable	Parameter Estimates	Standard Error	p-value
Constant	-11.5029	0.3931	<.0001
AADT	0.9088	0.0434	<.0001
L	0.6190	0.0325	<.0001
D	0.9103	0.0395	<.0001
Urban	0.7490	0.0812	
Overdispersion, $\boldsymbol{\alpha_0}$	2.8745	0.1654	
PDO / Fatal-injury percent	73.24% / 26.76%		
Number of Observations	3,138		

Figures 5.3 and 5.4 show the arterial model AADT and length CURE plots, respectively. These two plots go beyond the boundaries and in some range of AADT show the over-prediction or underestimation problem. However, due to the low average number of crashes (1.49 crashes per work zone from Table 3.5), improving the model was not possible. Therefore, the sample includes all the available Missouri data between years 2011 and 2016.

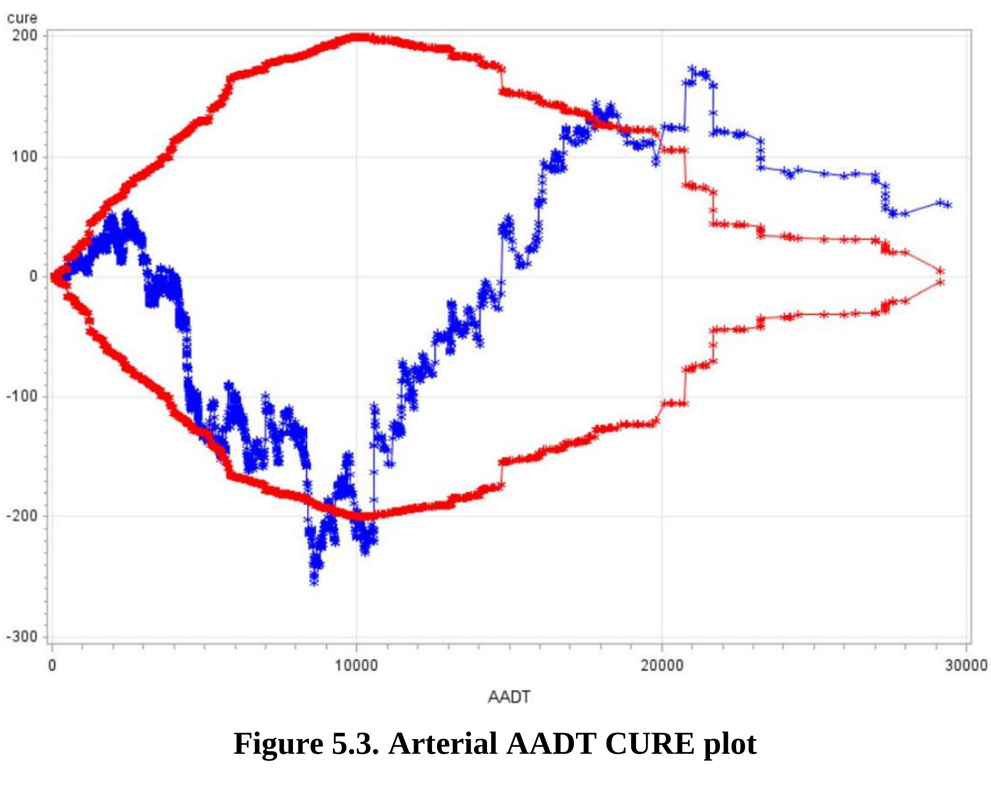


Figure 5.3. Arterial AADT CURE plot

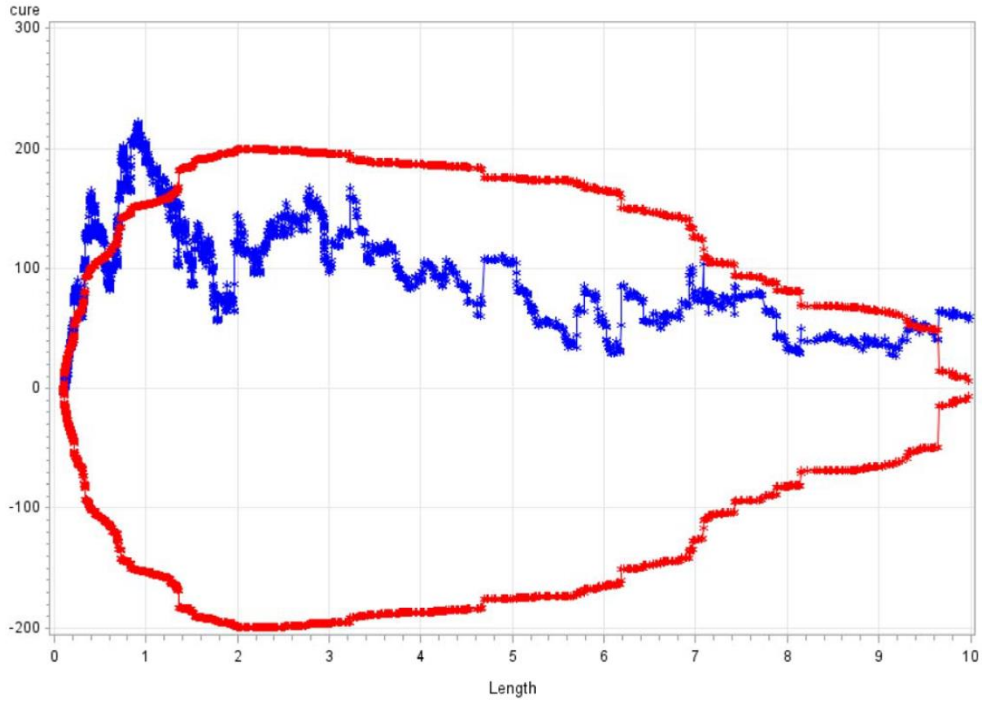


Figure 5.4. Arterial length CURE plot

5.3. Ramp Work Zone Model

This model was made by considering a constant overdispersion. Table 5.3 summarizes the estimated parameters of the ramp model with the following functional form:

$$N_{Total} = e^{\beta_0} AADT^{\beta_1} D^{\beta_2} \quad (8)$$

Table 5.3. Ramp model parameters for total number of crashes

Explanatory Variable	Parameter Estimates	Standard Error	p-value
Constant	-20.9478	2.0636	<.0001
AADT	1.6561	0.1895	<.0001
D	1.1940	0.1880	<.0001
Overdispersion, $\boldsymbol{\alpha_0}$	1.4733	0.5728	
PDO / Fatal-injury percent	68.12% / 31.88%		
Number of Observations	372		

Work zone AADT and duration were statistically significant at 1% level. The length of ramps ranged from 0.11 to 0.82 miles with an average of 0.28 miles and standard deviation of 0.15 miles. Due to low diversity in the data, work zone length was not statistically significant for addition to the model. About 86% of the work zones in the sample of 372 ramps were in urban areas. The data did not show noteworthy differences between urban and rural work zones on ramps. From the collected data, 68.12% of the crashes were PDO crashes, and the rest were fatal and injury crashes. The overdispersion was 1.4733, which was not satisfactory. The reason for the poor overdispersion was the nature of data. Due to the low number of crashes (0.37 crash per work zone), and the small sample size, the uncertainty of the predictions increases.

Figure 5.5 shows the ramp model AADT CURE plot. The AADT CURE shows the over-prediction problem for the range of low AADTs (decreasing trend). However, due to the low average number of crashes and small sample size, improving the model was not possible. Therefore, the sample includes all the available Missouri data between years 2011 and 2016.

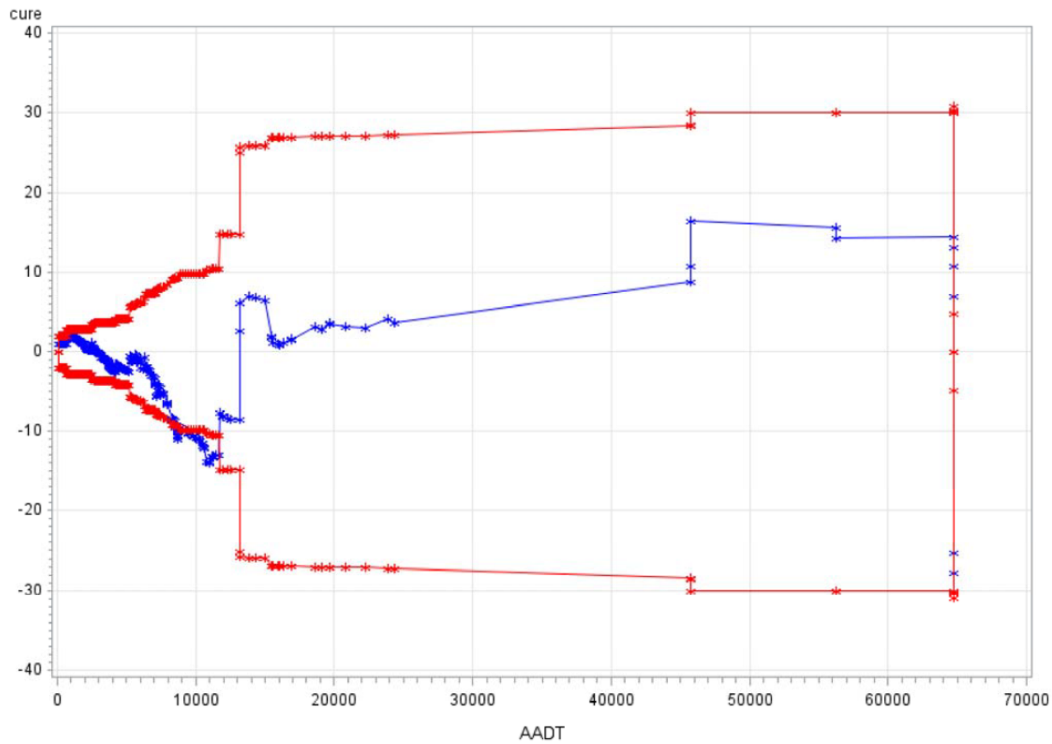


Figure 5.5. Ramp AADT CURE plot

5.4. Signalized Intersection (4-Leg) Work Zone Model

Table 5.4 summarizes the estimated parameters of the model for work zones on a signalized intersection (4-leg) with following functional form:

$$N_{Total} = e^{\beta_0} AADT_{Major}^{\beta_1} AADT_{Minor}^{\beta_2} D^{\beta_3} \quad (9)$$

Table 5.4. Signalized intersection (4-leg) model parameters for total number of crashes

Explanatory Variable	Parameter Estimates	Standard Error	p-value
Constant	-12.5905	2.0603	<.0001
$AADT_{Major}$	0.4297	0.2365	0.0694
$AADT_{Minor}$	0.3293	0.1544	0.0331
D	0.9805	0.1196	<.0001
Overdispersion, $\boldsymbol{\alpha_0}$	11.5069	1.8422	
PDO / Fatal-injury percent	80.08% / 19.92%		
Number of Observations	2,484		

Major leg AADT, minor leg AADT, and duration were statistically significant at 10%, 5%, and 1% level, respectively. From the collected data, 80.08% of the crashes were PDO crashes, and the rest were fatal and injury crashes. The average crash rate of work zones on signalized intersections is too low (0.09 crash per work zone). One possible explanation for such a small crash rate is that two of the approaches may be closed in the presence of a work zone. The model overdispersion was 11.5, which is not satisfactory. It shows the very low accuracy of the model. The reason for this poor overdispersion was the very low crash rate.

Figures 5.6 and 5.7 show the intersection major and minor leg AADT CURE plots, respectively. The AADT CURE plots show the over-prediction problem for most ranges of AADTs (decreasing trend). Most of the work zones in the database have no crashes. For these work zones on signalized intersections, the model predicts very small number of crashes, but not zero. This explains the over-prediction problem in CURE plots.

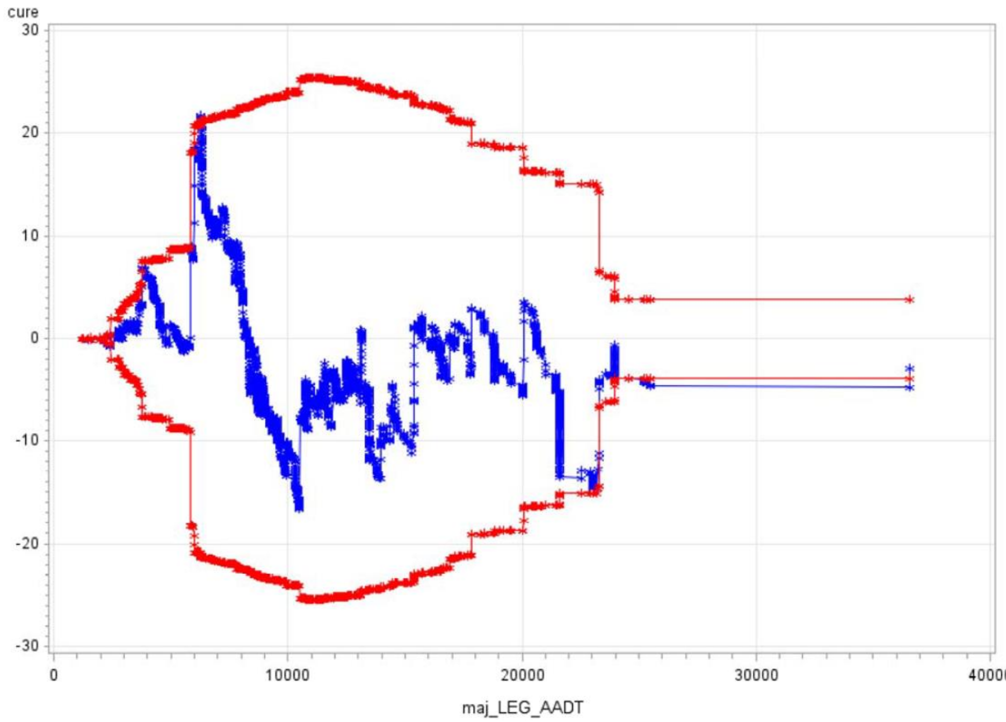


Figure 5.6. Signalized intersection (4-leg) major leg AADT CURE plot

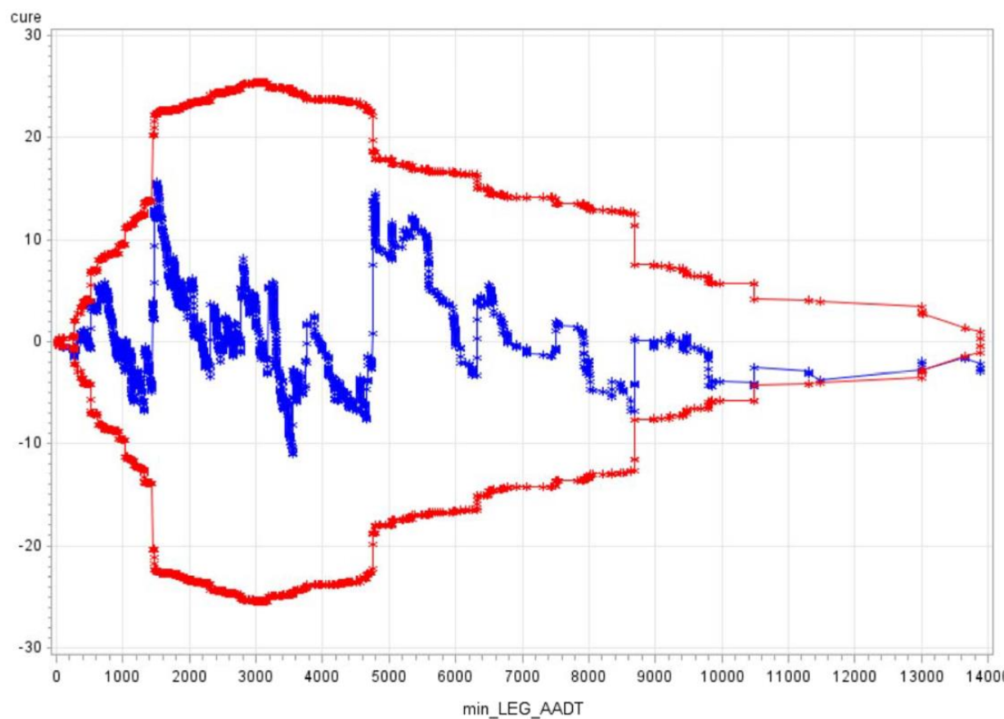


Figure 5.7. Signalized intersection (4-leg) minor leg AADT CURE plot

5.5. Unsignalized Intersection (4-Leg) Work Zone Model

Table 5.5 summarizes the estimated parameters of the model for work zone on an unsignalized intersection (4-leg) with following functional form:

$$N_{Total} = e^{\beta_0} AADT_{Major}^{\beta_1} AADT_{Minor}^{\beta_2} D^{\beta_3} \tag{9}$$

Table 5.5. Unsignalized intersection (4-leg) model parameters for total number of crashes

Explanatory Variable	Parameter Estimates	Standard Error	p-value
Constant	-14.2582	1.348	<.0001
$AADT_{Major}$	0.4397	0.2430	0.0704
$AADT_{Minor}$	0.2861	0.2128	0.1788
D	1.1635	0.1714	<.0001
Overdispersion, $\boldsymbol{\alpha_0}$	16.0845	5.4854	
PDO / Fatal-injury percent	70.67% / 29.92%		
Number of Observations	8,060		

Major leg AADT, minor leg AADT, and duration were statistically significant at 10%, 20%, and 1% level, respectively. From the collected data, 70.67% of the crashes were PDO crashes, and the rest were fatal and injury crashes. The average crash rate of work zones on signalized intersections is too low (0.009 crash per work zone). Most of the time in presence of a work zone, two of the approaches are closed. That is a possible explanation for such a small crash rate. The model overdispersion was 16.1, which is not desirable. It shows the low accuracy of the model. The reason for this poor overdispersion was the very low crash rate.

Figures 5.8 and 5.9 show the intersection major and minor leg AADT CURE plots, respectively. The AADT CURE plots show the over-prediction problem for most ranges of AADTs (decreasing trend). Most of the work zones in the database have no crashes. For these work zones on unsignalized intersections, the model predicts very small number of crashes, but not zero. This explains the over-prediction problem in CURE plots.

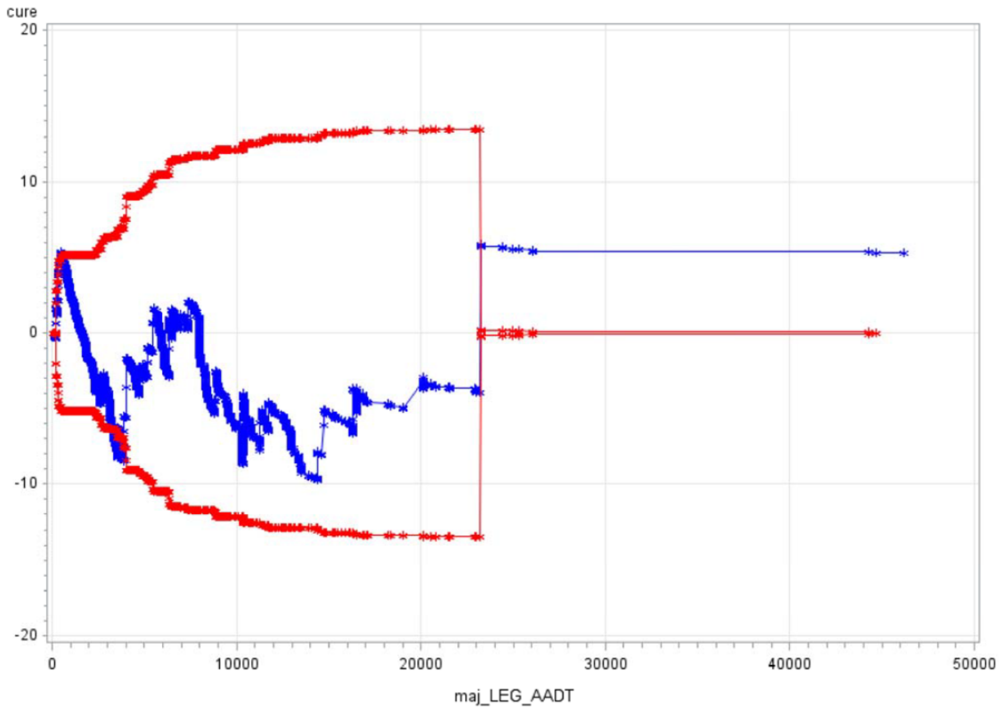


Figure 5.8. Unsignalized intersection (4-leg) major leg AADT CURE plot

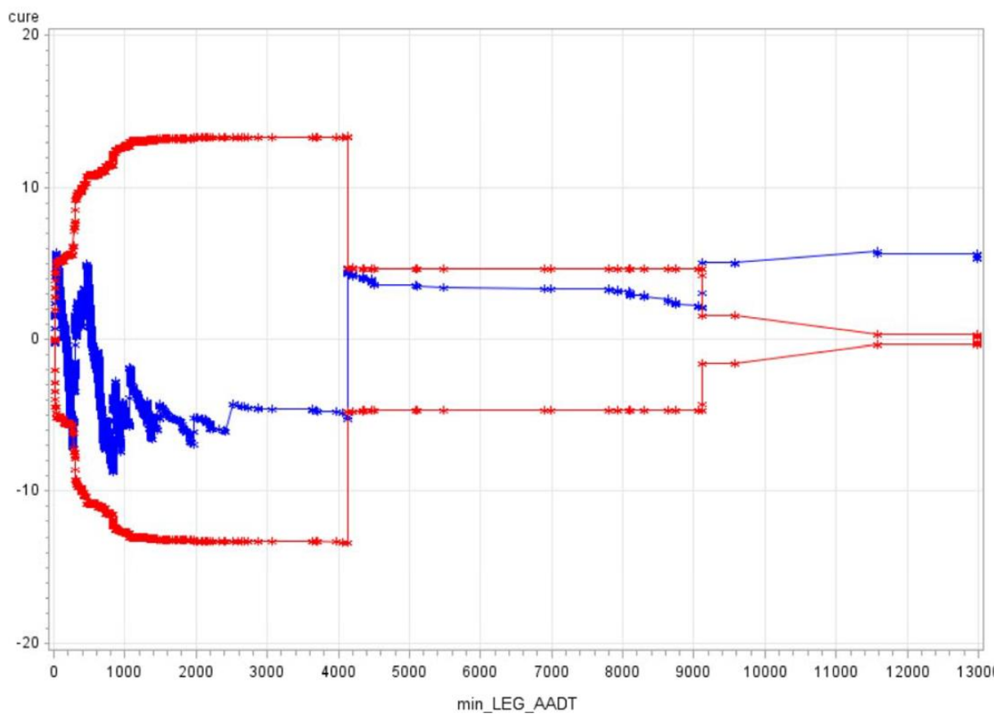


Figure 5.9. Unsignalized intersection (4-leg) minor leg AADT CURE plot

6. DISCUSSION AND SUMMARY

Tables 6.1 and 6.2 summarize the descriptive statistics of various samples used in this study. The range of variables for each facility type is important as the models are usable in these ranges. In Table 6.1, urban multi-lane highways and arterials have the highest and lowest crash frequencies (per mile per year), respectively. Table 6.2 shows that the crash frequencies for the signalized and unsignalized samples are very low. One possible explanation is that at the work zones on intersections, two approaches are sometimes closed to traffic. The ramp and arterial work zones have highest and lowest crash severity, respectively.

Table 6.1. Urban multi-lane highway (UMLH), arterial (Art), ramp (Rmp) modeling sample descriptive statistics

Sample	Size	Crash Rate $\frac{crash}{WZ}$	Crash Freq. (/mi/year)* $\frac{Crash\ Rate}{Avg.D \times Avg.L}$	% of Fatal and Injury	Range of Data: AADT, Veh/Day	Range of Data: Length, mi	Range of Data: Duration, Days
UMLH	251	2.02	11.66	31.2 %	(1,164, 18,071)	(0.1, 9.3)	(10, 277)
Art	3,138	1.49	5.92	27.8 %	(94, 29,383)	(0.1, 10)	(10, 300)
Rmp	372	0.37	10.58	31.9 %	(112, 64,755)	(0.1, 0.8)	(10, 280)

* Based on average duration in years and average length in miles

Table 6.2. Signalized 4-leg intersection (4SG) and unsignalized 4-leg intersections (4ST) modeling sample descriptive statistics

Sample	Size	Crash Rate $\frac{crash}{WZ}$	Crash Freq. (/year)* $\frac{Crash\ Rate}{Avg.D}$	% of Fatal and Injury	Range of Data: $AADT_{Major}$, Veh/Day	Range of Data: $AADT_{Minor}$, Veh/Day	Range of Data: Duration, Days
4SG	2,488	0.095	0.80	19.9	(1,213 , 36,561)	(15 , 13,878)	(10 , 300)
4ST	8,060	0.0093	0.099	29.3	(66 , 46,198)	(11 , 12,976)	(10 , 284)

* Based on average duration in years

Overdispersion typical of a good model is a number close to zero (less than 1). In the highway safety literature, certain safety performance functions have overdispersions such as 0.1, 0.2, 0.3, etc. Table 6.3 shows the overdispersion values of the work zone crash models developed in this study. The models all have overdispersion values larger than 1. Could these models still be useful?

Table 6.3. Overdispersion values for the developed models

Model	Overdispersion
UMLH	1.60
Art	2.87
Rmp	1.47
Signalized Intersection (4-Leg)	11.51
Unsignalized Intersection (4-Leg)	16.08

There is a noteworthy difference between work zone safety and general safety studies. In general safety studies, e.g., SPF for freeway segments, the researcher is free to collect data from many locations and for multiple years. As a result, the derived database includes a large number of crashes. Conversely, a work zone study's data is restricted by both population size and the data collection duration as work zones are occasional events on roadway systems with a defined duration. The nature of these restrictions, leads to having many zero crashes and a low number of work zone crashes in the database. As a result, work zone crash prediction models generally have lower accuracy in comparison to general SPFs. Note that all the facility types studied in this research are the first in the safety literature.

7. SOFTWARE APPLICATIONS AND EXAMPLES

This chapter gives an overview of the spreadsheet tool, provides some directions on its use, and presents some example applications.

7.1. Safety Tool Software Overview

To facilitate the evaluation of safety impacts of work zone phasing alternatives, the models created in this study were added to the user-friendly spreadsheet tool that was previously developed by Brown et al. (2016a) for freeways, expressways, and rural two-lane highways. A practitioner provides the input for each work zone phasing alternative in a user-friendly graphical user interface (GUI). After the user chooses the appropriate facility type (freeway, expressway, rural two-lane highway, urban multi-lane highway, arterial, ramp, 4-leg signalized intersections, and 4-leg unsignalized intersections) the software selects the proper and the most accurate model to calculate the results. For each alternative, the software provides the number of crashes by severity, standard error, and crash costs as output.

For crash costs, the practitioner has the option to use the HSM 2010 crash costs or specify his or her own crash cost values. The HSM crash cost values are $7,400 and $158,200 for PDO and fatal and injury crashes, respectively. The user can define crash costs either through the “User Defined” option which applies the values entered on the “User Defined Crash Cost” worksheet (Figure 7.1) or the “Other” option, which requires values to be provided in the GUI interface. In addition to the crash costs by severity, the user provides the year used as the basis for the costs. The HSM 2010 crash costs are based on a study that utilized 2001 data. The software applies the discount rate collected from governmental sources to transform the crash cost values to the current year. The discount rates used by the software are provided in Table 7.1. A constant discount rate was assumed for each five-year period. A discount rate of 0.75% was used for the years 2010 to the present as the software was initially developed in 2015.

Table 7.1. Discount rates used in the software

Year	Yearly Discount Rate
Before 1994	3.32%
1995–1999	3.04%
2000–2004	2.43%
2005–2009	3.75%
2010–Present	0.75%

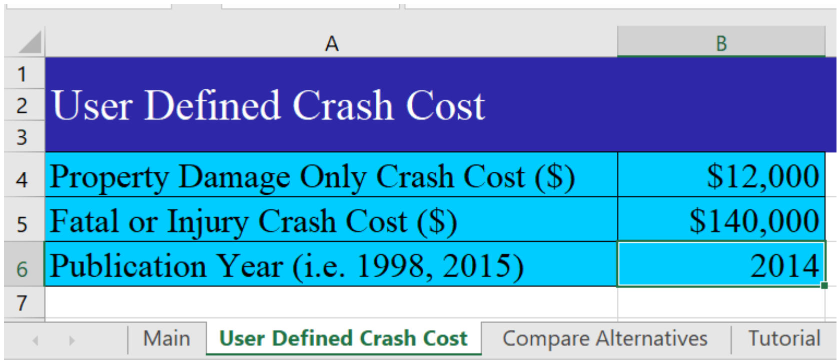


Figure 7.1. User defined crash cost sheet

7.2. Software Instructions

This section provides brief instructions on the use of the software. A complete tutorial is provided in Appendix A. This software was developed using visual basic in the Microsoft Excel for Windows environment. When the spreadsheet file is opened, the main page of the software (Figure 7.2) is presented to the user.

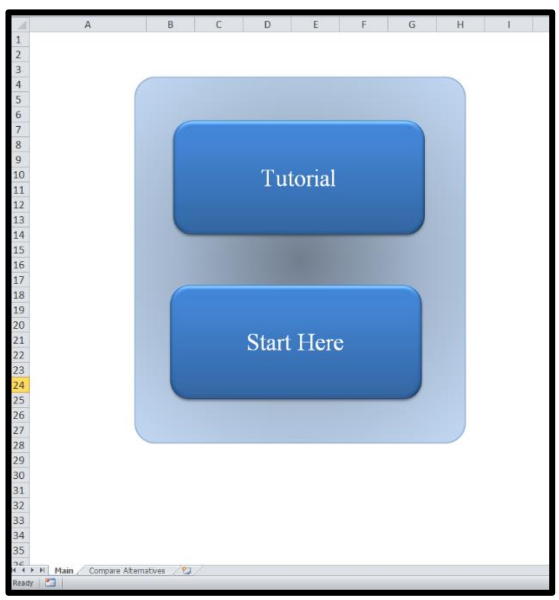


Figure 7.2. Software main page

By clicking on "Tutorial," the user can review detailed instructions on the use the software. The user clicks on "Start Here" to begin entering data through the "Input and Analyze" window (Figure 7.3).

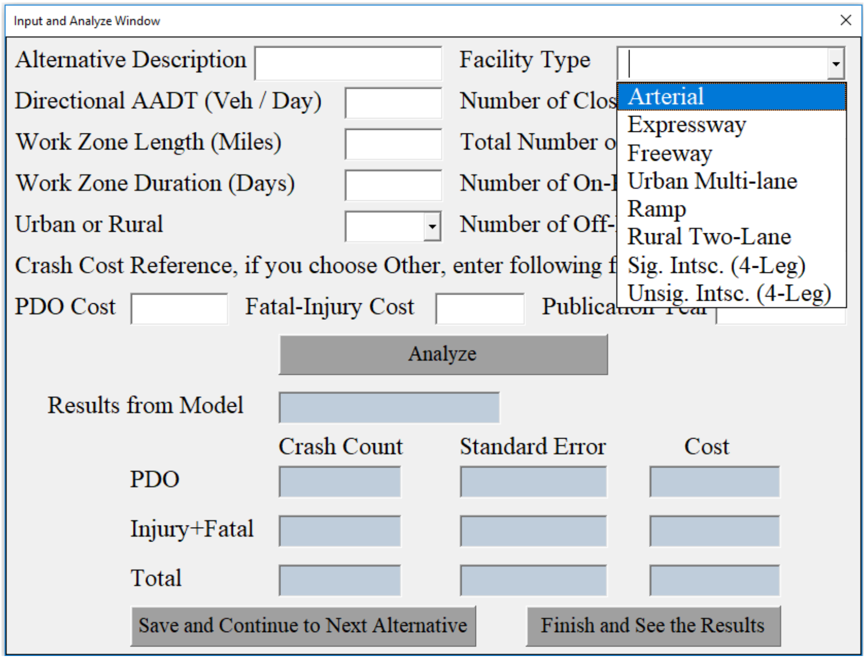


Figure 7.3. Software "Input and Analyze" window

The user can provide a description for the work zone phasing alternative in the first input field. After the facility types are selected, the appropriate input variables for that facility type are displayed on the window (See Figures 7.4 to 7.11).

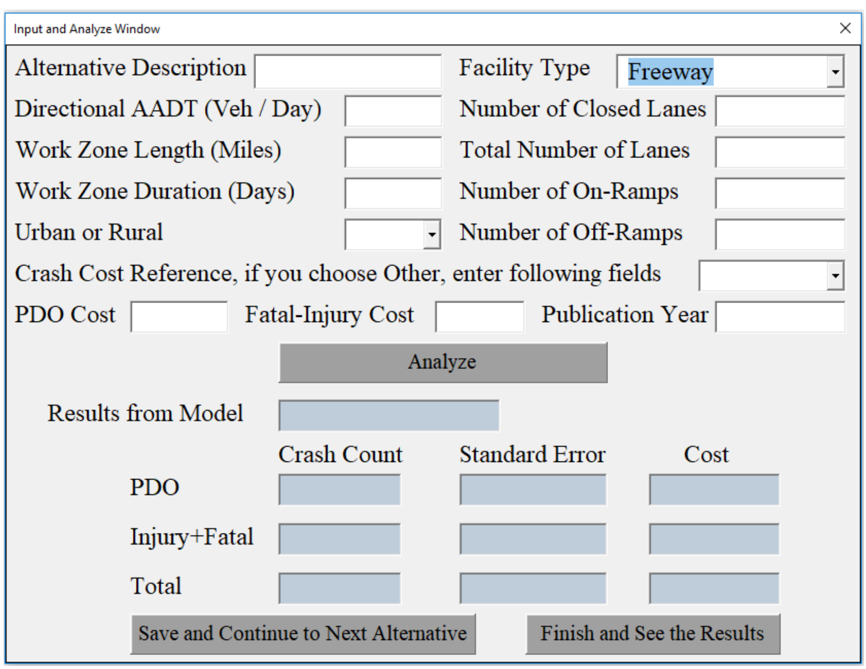


Figure 7.4. Freeway work zone required variables

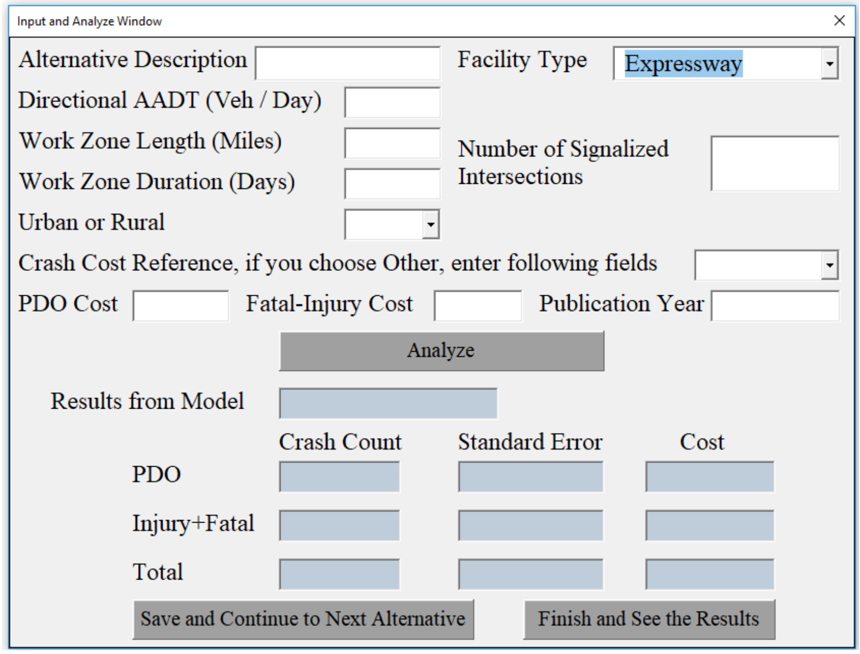


Figure 7.5. Expressway work zone required variables

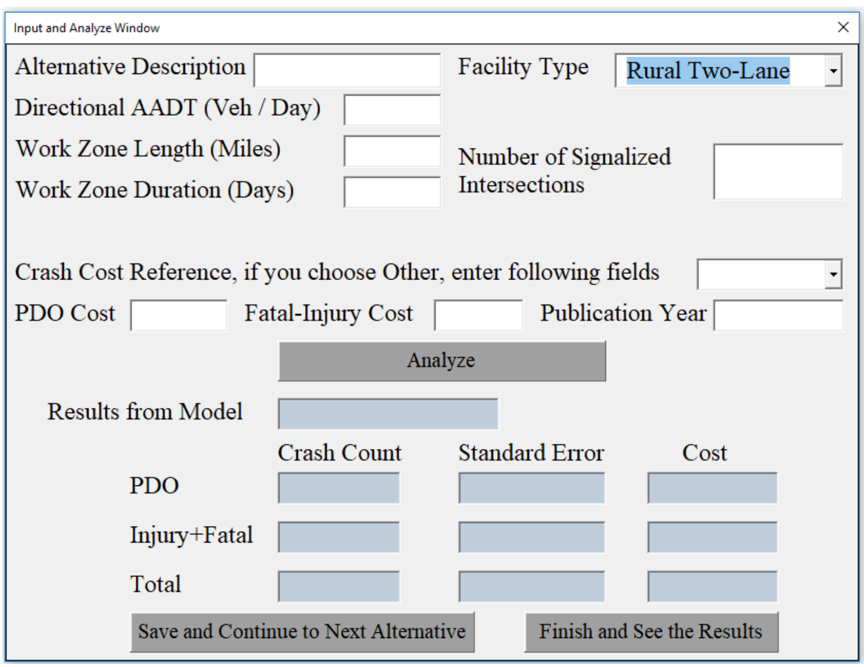


Figure 7.6. Rural two-lane work zone required variables

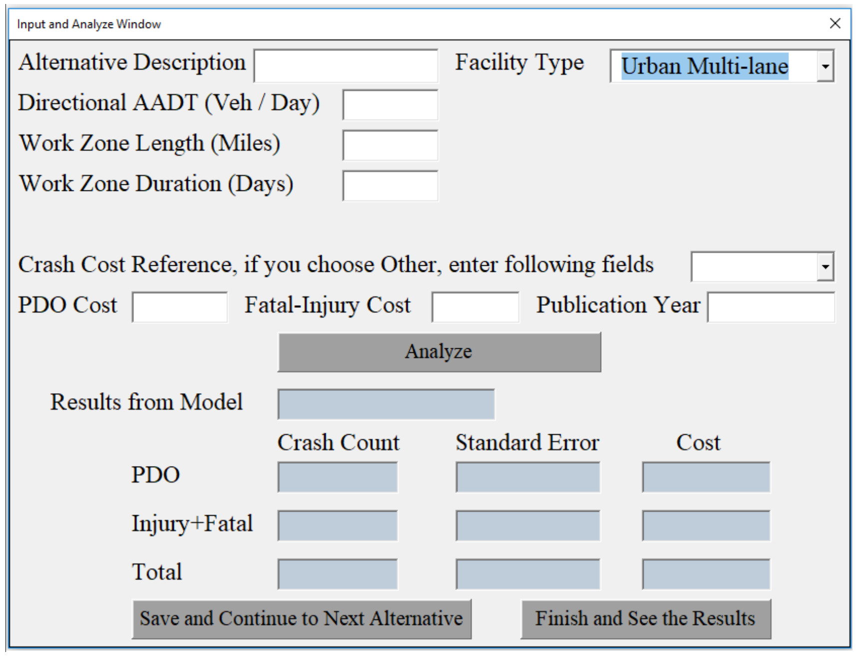


Figure 7.7. Urban multi-lane highway work zone required variables

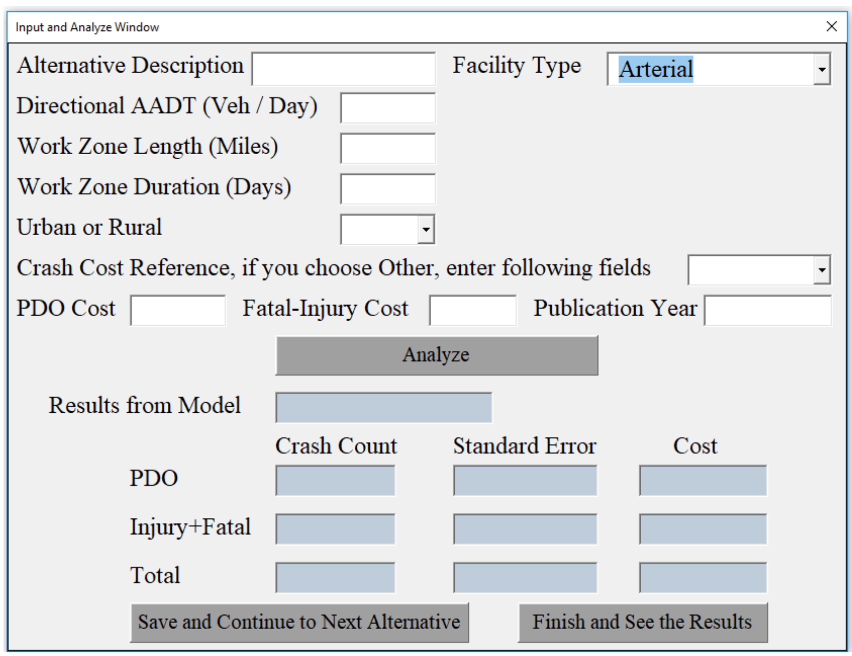


Figure 7.8. Arterial work zone required variables

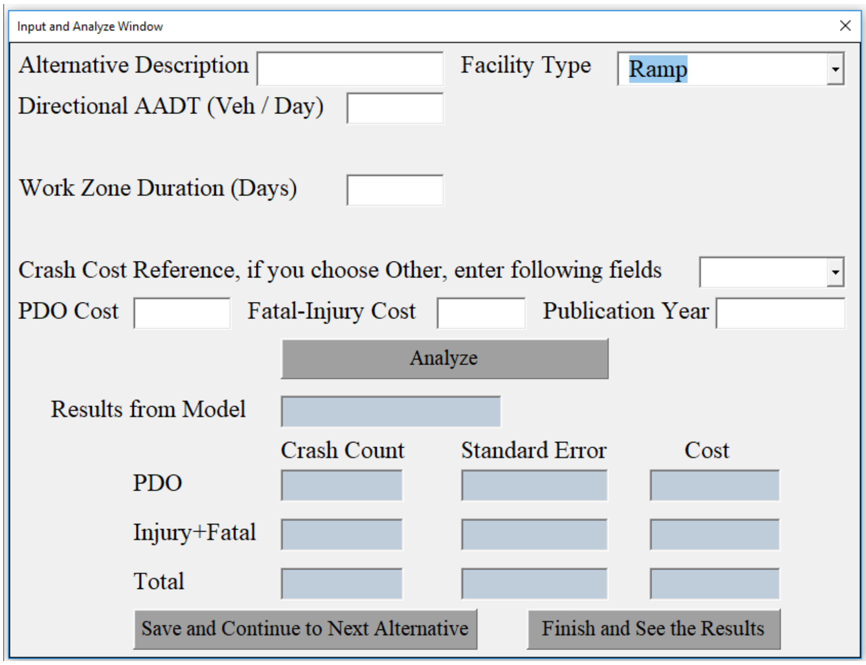


Figure 7.9. Ramp work zone required variables

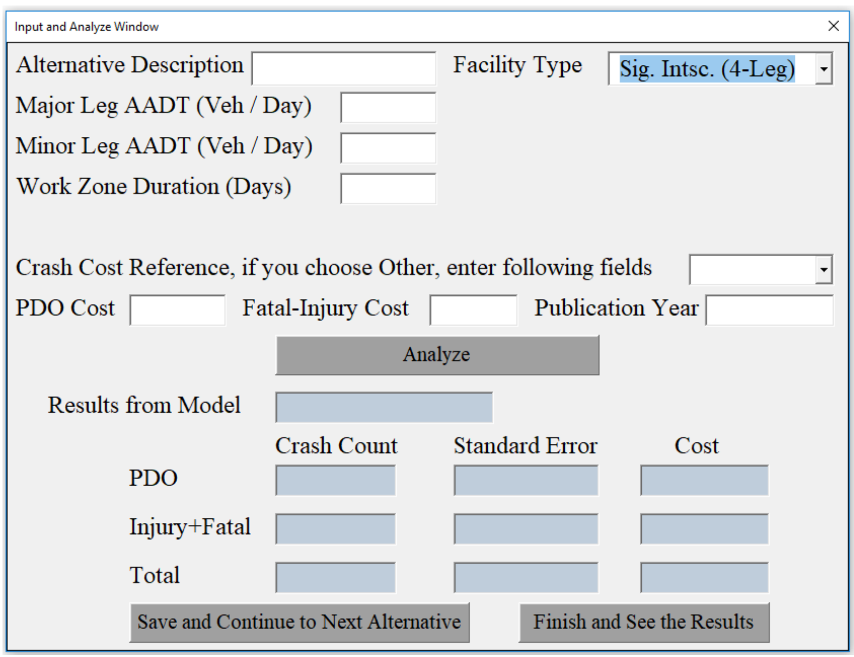


Figure 7.10. Work zones on signalized intersection (4-leg) required variables

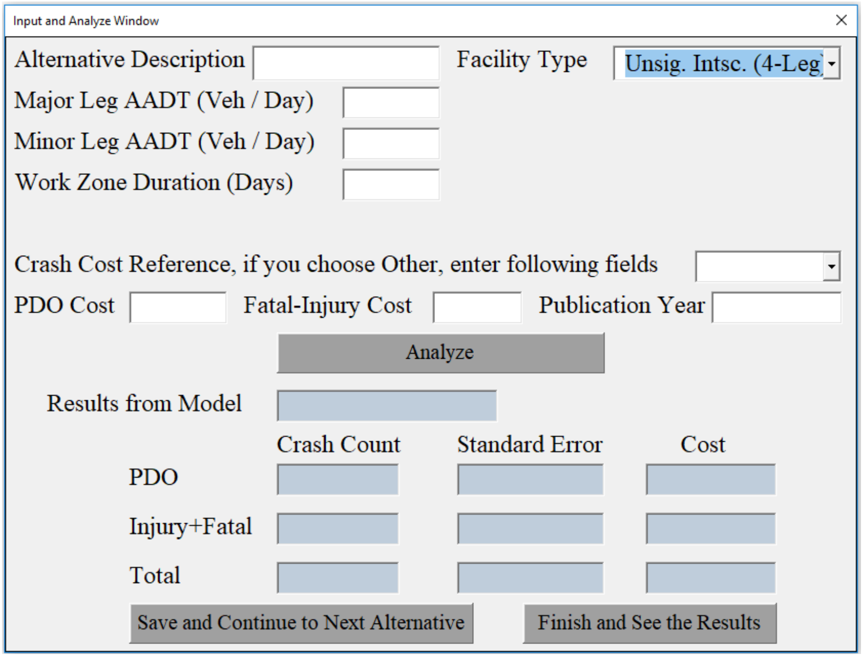


Figure 7.11. Work zones on unsignalized intersection (4-leg) required variables

After providing input data for the work zone alternative, the user selects the desired method for calculating crash costs and provides crash cost data if the "Other" option is selected. (Figure 7.12).

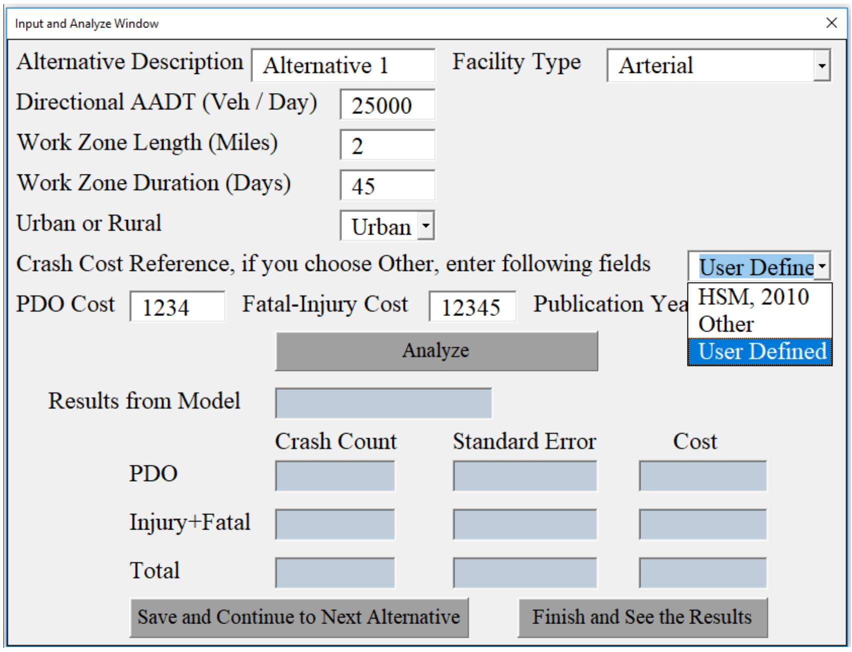


Figure 7.12. Software crash cost

The user then clicks "Analyze" to display the output as shown in Figure 7.13.

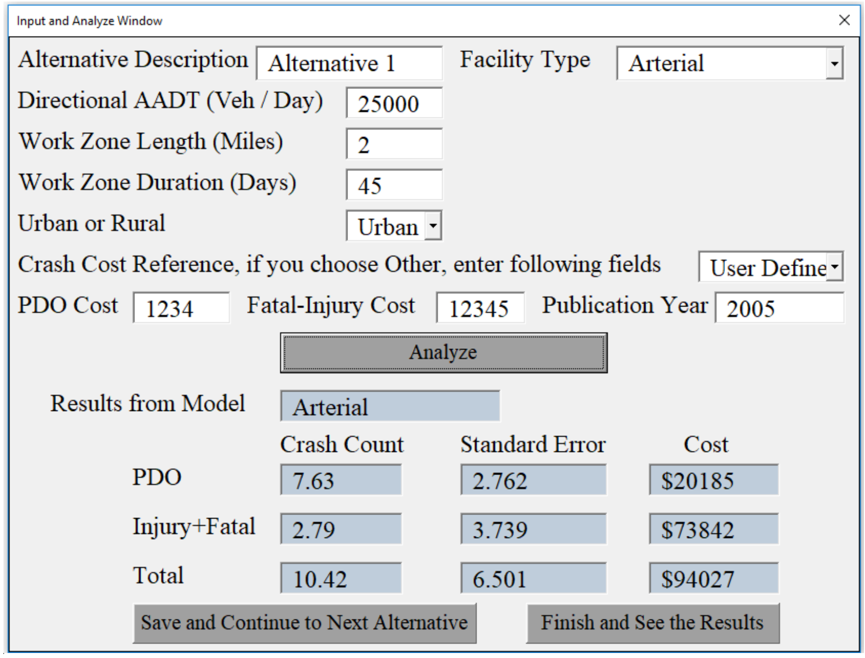


Figure 7.13. Software results

The "Input and Analyze Window" then populates the output fields, including model description, crash count by severity, standard error, and the equivalent total crash costs for the specified year. After the user clicks "Save and Continue to Next Alternative," the results are copied to the spreadsheet, and a blank "Input and Analyze" window opens to allow the user to provide data for the next alternative plan. The process is repeated for each alternative plan, and the user selects "Finish and See the Results" after entering data for the last alternative. The results are then displayed in the "Compare Alternatives" worksheet of the spreadsheets (Figure 7.14). An echo of the input data is also provided to allow the user to verify the accuracy of the input data.

Alternatives Comparison		
	Output	
	Alternative 1	Alternative 2
Expected Number of PDO Crashes	7.63	10.66
Standard Error of PDO Estimation	2.762	3.265
Expected Number of Fatal and Injury Crashes	2.79	3.9
Standard Error of Fatal and Injury Estimation	3.739	5.075
Total Crash Cost; value in 2018	$94,027	$131,422
Model Used:	Arterial	Arterial
	Input	
	Alternative 1	Alternative 2
AADT	25000	25000
Duration	45	65
Length	2	2
Urban/Rural	Urban	Urban
Number of Closed Lanes		
Total Number of Lanes		
Number of On-ramps		
Number of Off-ramps		
Number of Signalized Intersections		
Crash Cost Reference; Publication Year	User Defined (2005)	User Defined (2005)
PDO Crash Cost	$1,234	$1,234
Fatal and Injury Crash Cost	$12,345	$12,345
Facility Type	Arterial	Arterial
Major Leg AADT (4-Leg Intsc.)		
Minor Leg AADT (4-Leg Intsc.)		
		Developed by University of Missouri-Columbia; TransZou

Figure 7.14. Sample output of the software

7.3. Sample Applications

This section shows sample applications for using the safety tool described in this study, including work zone safety screening, work zone phasing alternative evaluation, and work zone scheduling comparison.

7.3.1. Urban Multi-Lane Example

A state transportation agency is considering a pavement rehabilitation of a 5-mile corridor of an urban multi-lane highway with the directional AADT of 8,000 vehicles per day. The agency has short-listed two alternatives. The first alternative involves doing the rehabilitation in 65 days, and the second alternative reduces the duration to 40 days by using a novel methodology. The agency is using crash costs provided in the HSM.

The input screen for Alternative 1 is shown in Figure 7.15, and the output for both alternatives is shown in Figure 7.16. Figure 7.16 shows that the second alternative has 2.42 and 1.10 fewer

PDO and fatal and injury crashes, respectively. The Alternative 1 estimated crash cost is $452,955 (= $1,280,592–$827,637) more than the Alternative 2 estimated crash cost.

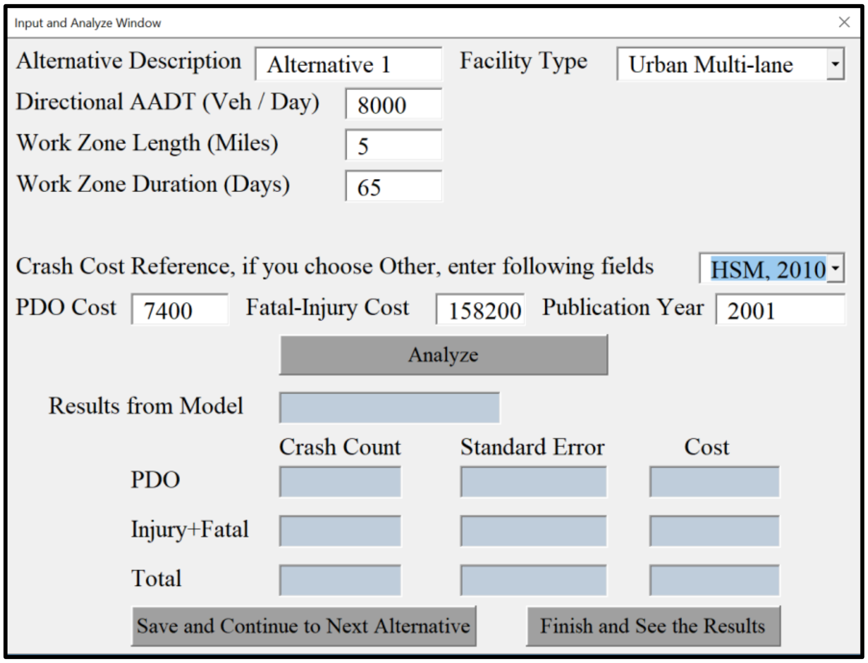


Figure 7.15. Urban multi-lane example, software input

Alternatives Comparison		
	Output	
	Alternative 1	Alternative 2
Expected Number of PDO Crashes	6.84	4.42
Standard Error of PDO Estimation	2.615	2.102
Expected Number of Fatal and Injury Crashes	3.11	2.01
Standard Error of Fatal and Injury Estimation	4.31	2.91
Total Crash Cost; value in 2018	$1,280,592	$827,637
Model Used:	Urban Multi-lane Highway	Urban Multi-lane Highway
	Input	
	Alternative 1	Alternative 2
AADT	8000	8000
Duration	65	40
Length	5	5
Urban/Rural	Urban	Urban
Number of Closed Lanes		
Total Number of Lanes		
Number of On-ramps		
Number of Off-ramps		
Number of Signalized Intersections		
Crash Cost Reference; Publication Year	HSM (2010)	HSM (2010)
PDO Crash Cost	$7,400	$7,400
Fatal and Injury Crash Cost	$158,200	$158,200
Facility Type	Urban Multi-lane	Urban Multi-lane
Major Leg AADT (4-Leg Intsc.)		
Minor Leg AADT (4-Leg Intsc.)		
	Developed by University of Missouri-Columbia; TransZou	

Figure 7.16. Urban multi-lane example, software output

7.3.2. Arterial Example

An agency plans to rehabilitate a two-mile segment on an urban arterial. The anticipated work zone duration is 120 days. The agency would like to evaluate the use of demand management strategies to reduce the AADT from 12,000 veh/day to 6,000 veh/day. Their schedule is to finish the work in 120 days. The estimated crash costs are $10,000 for PDO crashes and $125,000 for fatal and injury crashes based on the year 2014.

Figure 7.17 shows the input window for Alternative 1. The “Other” option is used for entering crash costs in this example. The results for both alternatives are shown in Figure 7.18 and indicate a crash cost savings of $263,754 by reducing the AADT by half.

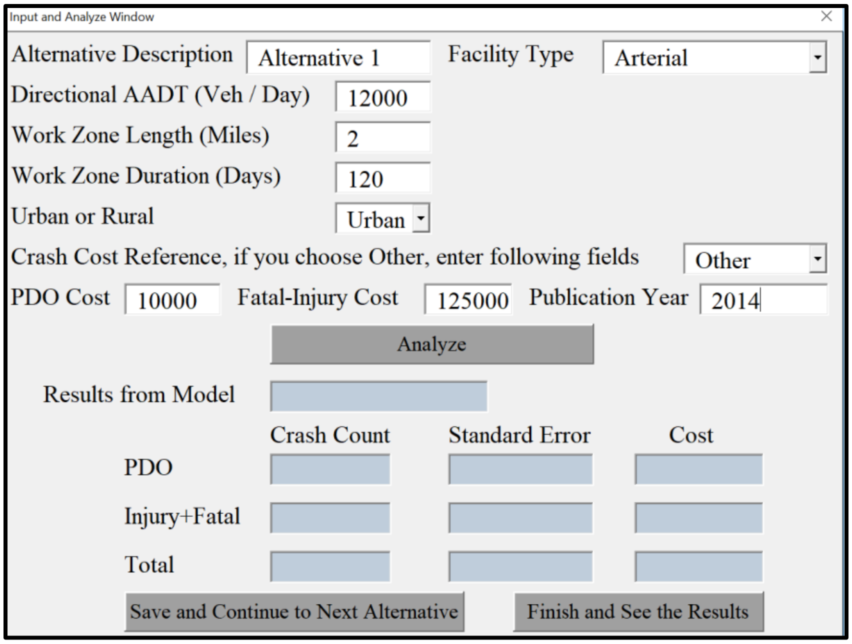


Figure 7.17. Arterial example, software input

Alternatives Comparison		
	Output	
	Alternative 1	Alternative 2
Expected Number of PDO Crashes	9.56	5.09
Standard Error of PDO Estimation	3.092	2.256
Expected Number of Fatal and Injury Crashes	3.49	1.86
Standard Error of Fatal and Injury Estimation	4.582	2.614
Total Crash Cost; value in 2018	$564,610	$300,856
Model Used:	Arterial	Arterial
	Input	
	Alternative 1	Alternative 2
AADT	12000	6000
Duration	120	120
Length	2	2
Urban/Rural	Urban	Urban
Number of Closed Lanes		
Total Number of Lanes		
Number of On-ramps		
Number of Off-ramps		
Number of Signalized Intersections		
Crash Cost Reference; Publication Year	Other (2014)	Other (2014)
PDO Crash Cost	$10,000	$10,000
Fatal and Injury Crash Cost	$125,000	$125,000
Facility Type	Arterial	Arterial
Major Leg AADT (4-Leg Intsc.)		
Minor Leg AADT (4-Leg Intsc.)		
Developed by University of Missouri-Columbia; TransZou		

Figure 7.18. Arterial example, software output

7.3.3. Ramp Example

An agency wants to participate in a bid for rehabilitating a 2-lane ramp with the AADT of 25,500 vehicles per day. Their schedule is to finish the work in 90 days. An alternative construction method would reduce the duration of the work to 55 days. The estimated crash costs in their state based on a study published in 2010 are $6,000 and $125,000 for PDO and fatal and injury crashes, respectively.

Figure 7.19 shows the input window for Alternative 1. The “Other” option is used for entering crash costs in this example. The results for both alternatives are shown in Figure 7.20 and indicate a crash cost savings of $71,648 with the accelerated schedule.

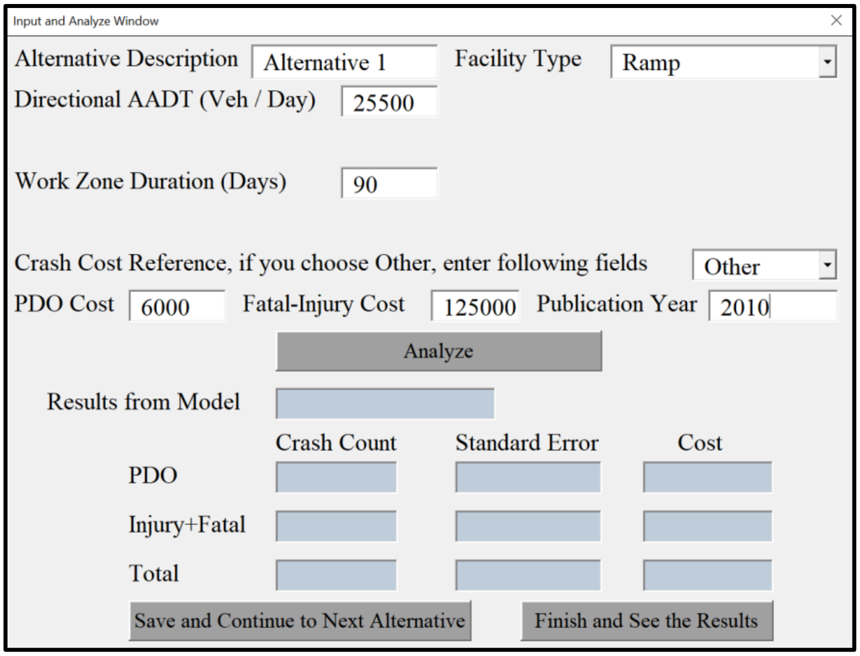


Figure 7.19. Ramp example, software input

Alternatives Comparison		
	Output	
	Alternative 1	Alternative 2
Expected Number of PDO Crashes	2.33	1.29
Standard Error of PDO Estimation	1.526	1.136
Expected Number of Fatal and Injury Crashes	1.09	0.6
Standard Error of Fatal and Injury Estimation	1.685	1.063
Total Crash Cost; value in 2018	$159,483	$87,835
Model Used:	Ramp	Ramp
	Input	
	Alternative 1	Alternative 2
AADT	25500	25500
Duration	90	55
Length		
Urban/Rural		
Number of Closed Lanes		
Total Number of Lanes		
Number of On-ramps		
Number of Off-ramps		
Number of Signalized Intersections		
Crash Cost Reference; Publication Year	Other (2010)	Other (2010)
PDO Crash Cost	$6,000	$6,000
Fatal and Injury Crash Cost	$125,000	$125,000
Facility Type	Ramp	Ramp
Major Leg AADT (4-Leg Intsc.)		
Minor Leg AADT (4-Leg Intsc.)		
Developed by University of Missouri-Columbia; TransZou		

Figure 7.20. Ramp example, software output

7.3.4. Signalized Intersection (4-Leg) Example

In this example, an agency is considering intersection improvements at two signalized intersections. Funding is only available for one of the intersections. The agency would like to incorporate an estimation of crash costs during construction into its analysis. The first intersection has a major AADT of 14,500 veh/day; minor AADT of 5,000 veh/day; and construction duration of 180 days. The input values for the second intersection are 7,700 veh/day; 8,400 veh/day; and 210 days for major AADT, minor AADT, and duration, respectively. The agency would like to use the crash cost values from the HSM.

Figure 7.21 shows the input window for Intersection 1. The results for both intersections are shown in Figure 7.22 and show that Intersection 2 has a higher crash cost of $57,617 compared to a crash cost of $48,927 for Intersection 1.

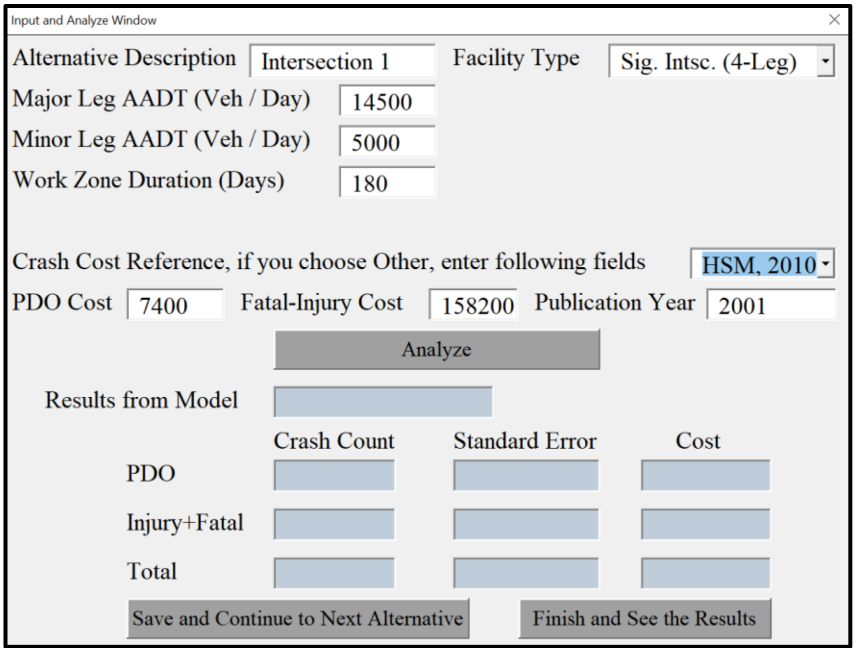


Figure 7.21. Signalized intersection (4-leg) example, software input

Alternatives Comparison		
	Output	
	Intersection 1	Intersection 2
Expected Number of PDO Crashes	0.45	0.52
Standard Error of PDO Estimation	0.671	0.721
Expected Number of Fatal and Injury Crashes	0.11	0.13
Standard Error of Fatal and Injury Estimation	0.499	0.57
Total Crash Cost; value in 2018	$48,927	$57,617
Model Used:	Sig. Intsc. (4-Leg)	Sig. Intsc. (4-Leg)
	Input	
	Intersection 1	Intersection 2
AADT		
Duration	180	210
Length		
Urban/Rural		
Number of Closed Lanes		
Total Number of Lanes		
Number of On-ramps		
Number of Off-ramps		
Number of Signalized Intersections		
Crash Cost Reference; Publication Year	HSM (2010)	HSM (2010)
PDO Crash Cost	$7,400	$7,400
Fatal and Injury Crash Cost	$158,200	$158,200
Facility Type	Sig. Intsc. (4-Leg)	Sig. Intsc. (4-Leg)
Major Leg AADT (4-Leg Intsc.)	14500	9700
Minor Leg AADT (4-Leg Intsc.)	5000	8400
Developed by University of Missouri-Columbia; TransZou		

Figure 7.22. Signalized intersection (4-leg) example, software output

7.3.5. Unsignalized Intersection (4-Leg) Example

An agency is planning improvements to an unsignalized intersection. The agency would like to evaluate two alternatives that include changes in project duration and implementing demand management strategies to reduce AADT. In the first alternative, the input values are 11,500 veh/day for major leg AADT; 2,000 veh/day for minor leg AADT; and 365 days for work zone duration. The second alternative reduces AADT values to 8,000 veh/day for the major leg and 1,000 veh/day for the minor leg. In addition, the project duration is reduced to 200 days. The estimated crash costs are $12,000 for PDO crashes and $140,000 for fatal and injury crashes based on the year 2014.

Figure 7.23 shows the input window for Alternative 1. The “User Defined” option is used for entering crash costs in this example. The results for both alternatives are shown in Figure 7.24 and indicate a crash cost savings of $12,315 with Alternative 2.

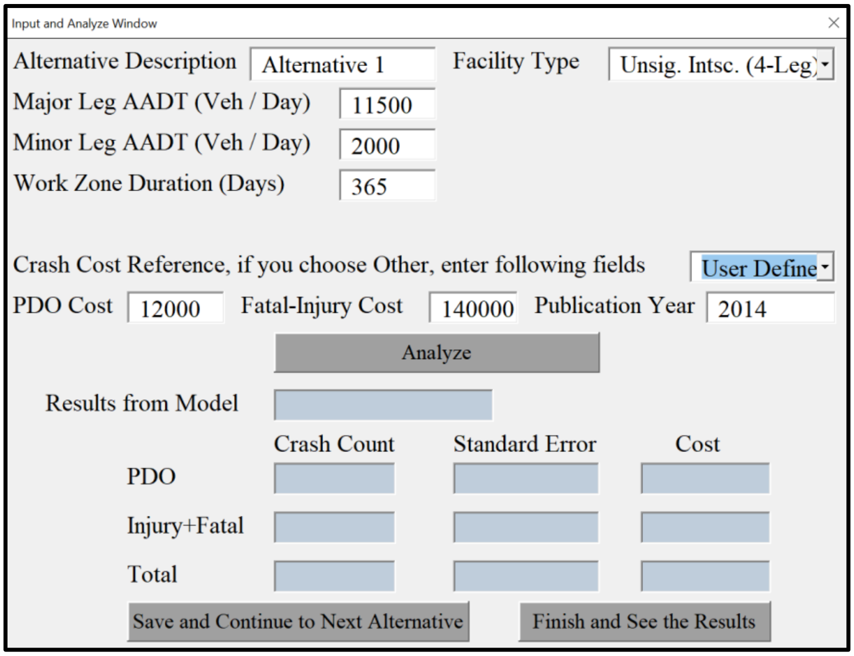


Figure 7.23. Unsignalized intersection (4-leg) example, software input

Alternatives Comparison		
	Output	
	Alternative 1	Alternative 2
Expected Number of PDO Crashes	0.23	0.08
Standard Error of PDO Estimation	0.48	0.283
Expected Number of Fatal and Injury Crashes	0.1	0.03
Standard Error of Fatal and Injury Estimation	0.511	0.211
Total Crash Cost; value in 2018	$17,792	$5,477
Model Used:	Unsig. Intsc. (4-Leg)	Unsig. Intsc. (4-Leg)
	Input	
	Alternative 1	Alternative 2
AADT		
Duration	365	200
Length		
Urban/Rural		
Number of Closed Lanes		
Total Number of Lanes		
Number of On-ramps		
Number of Off-ramps		
Number of Signalized Intersections		
Crash Cost Reference; Publication Year	User Defined (2014)	User Defined (2014)
PDO Crash Cost	$12,000	$12,000
Fatal and Injury Crash Cost	$140,000	$140,000
Facility Type	Unsig. Intsc. (4-Leg)	Unsig. Intsc. (4-Leg)
Major Leg AADT (4-Leg Intsc.)	11500	8000
Minor Leg AADT (4-Leg Intsc.)	2000	1000
		Developed by University of Missouri-Columbia; TransZou

Figure 7.24. Unsignalized intersection (4-leg) example, software output

8. CONCLUSION

This study addressed the need for practitioner guidance to evaluate work zone safety impacts. The HSM provides only freeway work zone CMFs for work zone duration and work zone length based on California data. In addition, the CMF Clearinghouse (FHWA 2018) provides a limited number of CMFs for some work zone layout configurations and countermeasures. In a prior study by Brown et al. (2016a), work zone crash prediction models for freeway, expressway, and rural two-lane highway work zones were developed and implemented in a user-friendly safety assessment tool. This study was an extension of Brown et al. (2016a) through the incorporation of newly developed models for other facility types into the tool.

Work zone safety studies present many different challenges, including obtaining appropriate data, fusing the data from multiple sources, and addressing the presence of many work zones with short lengths and durations. Data from a large population of work zones in Missouri were used in this study, since they were the best suited and most complete among what was available to the research team. Crashes were linked to work zones through the use of temporal-spatial matching. The assignment of crashes to work zones on segments applied the methodology developed in the prior study (Brown et al. 2016) in which the limits of the work zone advance warning area, transition area, buffer area, and termination area were determined from the lengths presented in the MUTCD (FHWA 2009). The assignment of crashes to work zones at intersections was based on a new algorithm developed in this study. Only work zones with a length longer than 0.1 miles and duration greater than 10 days were considered in the analysis.

The overdispersion values for models for multi-lane highway, arterial, ramp, 4-leg signalized intersections, and 4-leg unsignalized intersections work zones were 1.60, 2.87, 1.47, 11.51, and 16.08, respectively. In addition, the collected data for 4-leg signalized and unsignalized intersections showed very low crash counts and crash frequencies. A possible explanation for the low crash rates at intersection work zones is that work zones at intersections sometimes involve closures with traffic diversions. The work zone study data is restricted by population size and number of observed crashes, which heavily affected the models' accuracy. The DOTs work zone data collection could be improved by including information of all advance warning area, transition area, buffer area, and termination area. Also, recording information regarding specific work zone activities could help to investigate relationships between those activities and work zone crashes.

In this study, the first crash prediction models for the work zones on urban multi-lane highways, arterials, ramps, signalized intersections, and unsignalized intersections were established based on data from Missouri. These models were implemented in a user-friendly work zone safety assessment tool for practitioners that also includes previously developed crash prediction models for freeways, expressways, and rural multi-lane highways. The enhanced tool will enable transportation practitioners to assess the safety impacts of construction work zones for different alternatives quantitatively and more effectively. Decision makers will have the means to more readily balance work zone safety and mobility impacts when evaluating options for work zone phasing.

Future research to expand this study could include the use of Empirical Bayes or even full Bayes to better address regression-to-the-mean. A significant endeavor is needed to incorporate the Bayes methodology since each work zone site would need to be calibrated and modeled using HSM SPFs. Another useful expansion would be to utilize data from multiple states to account for regional differences in geography, climate, and driver behavior.

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APPENDIX A. SOFTWARE TUTORIAL

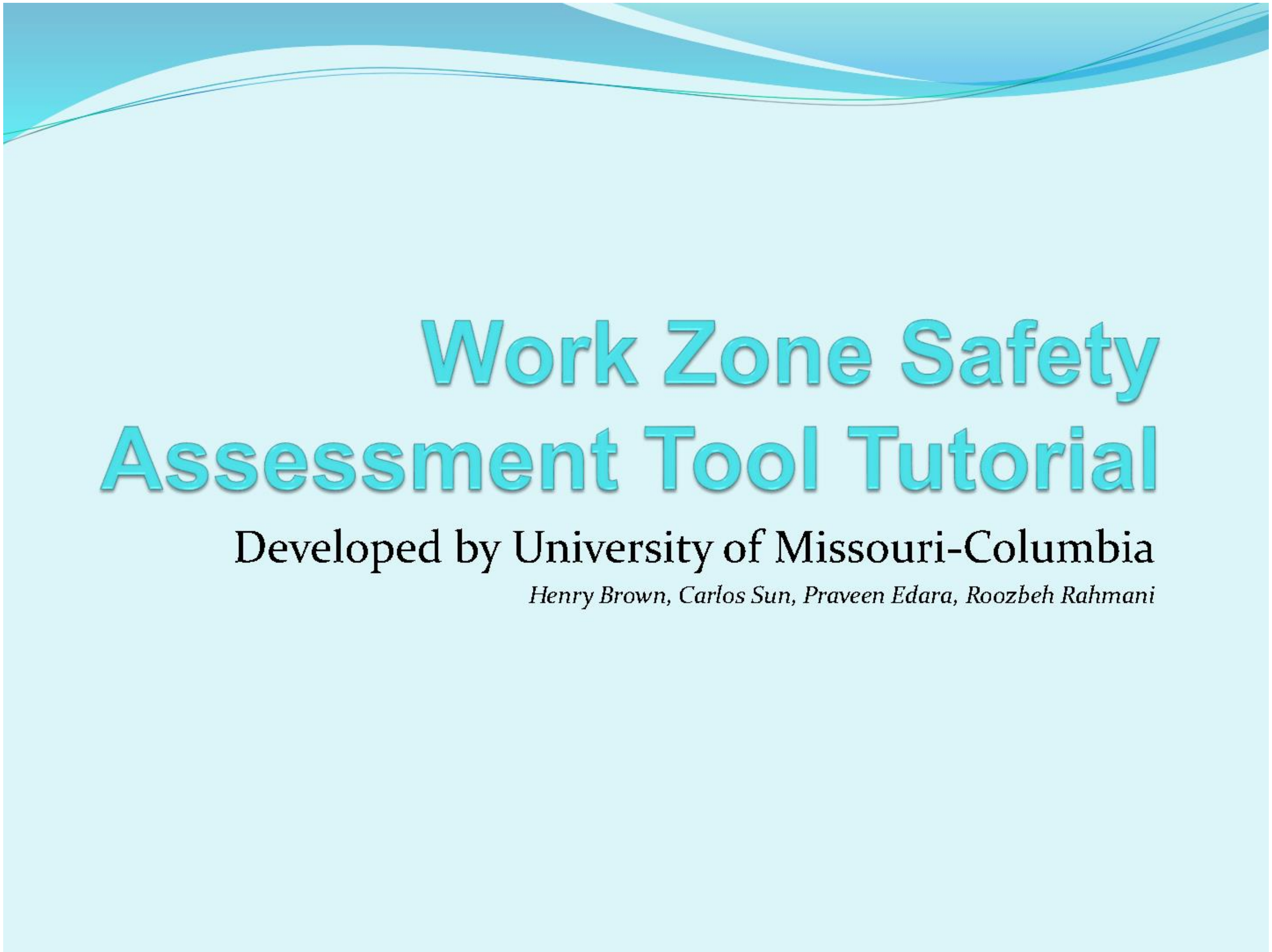


Figure A.1. Tutorial overview

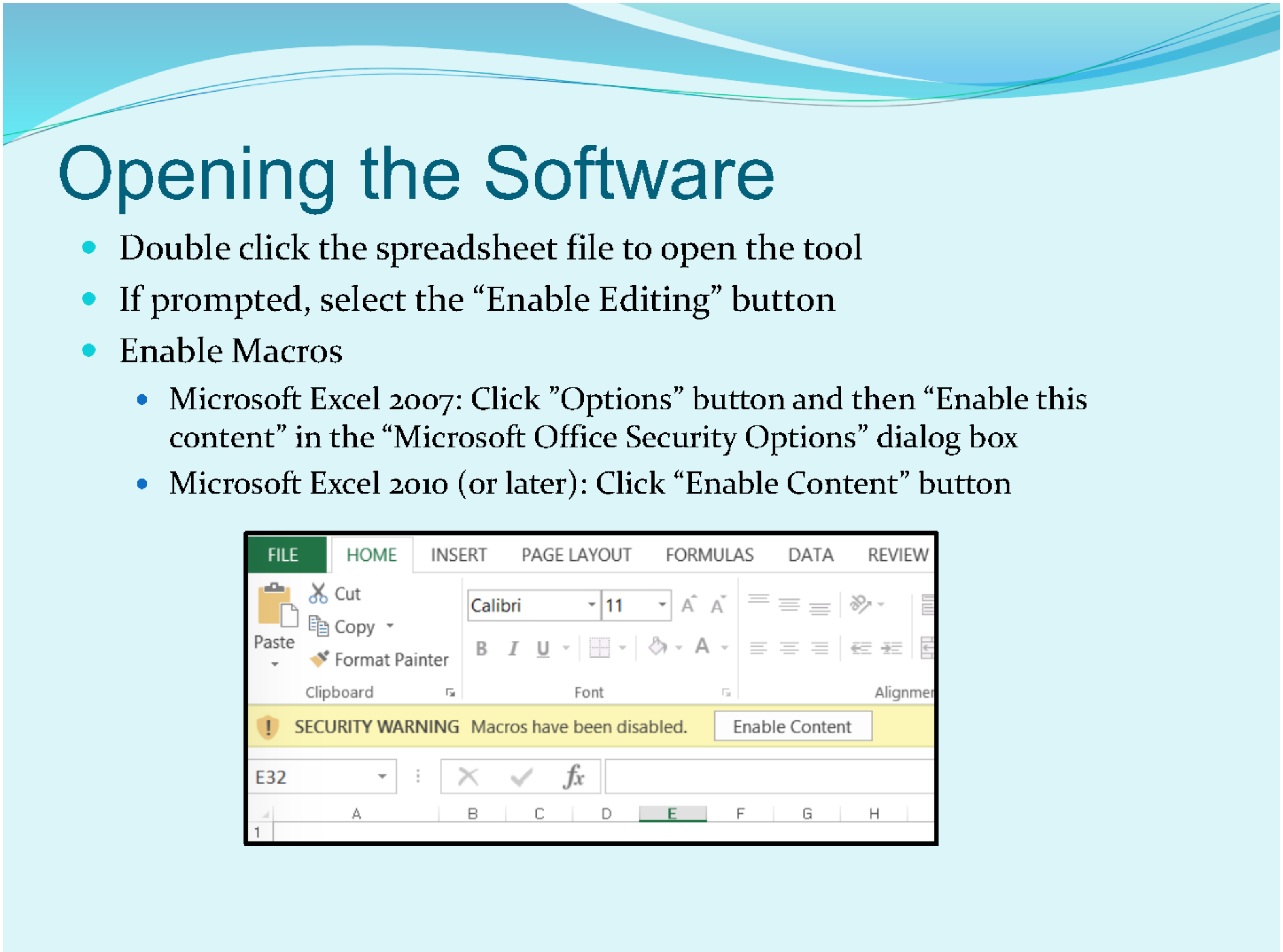


Figure A.2. Opening the software

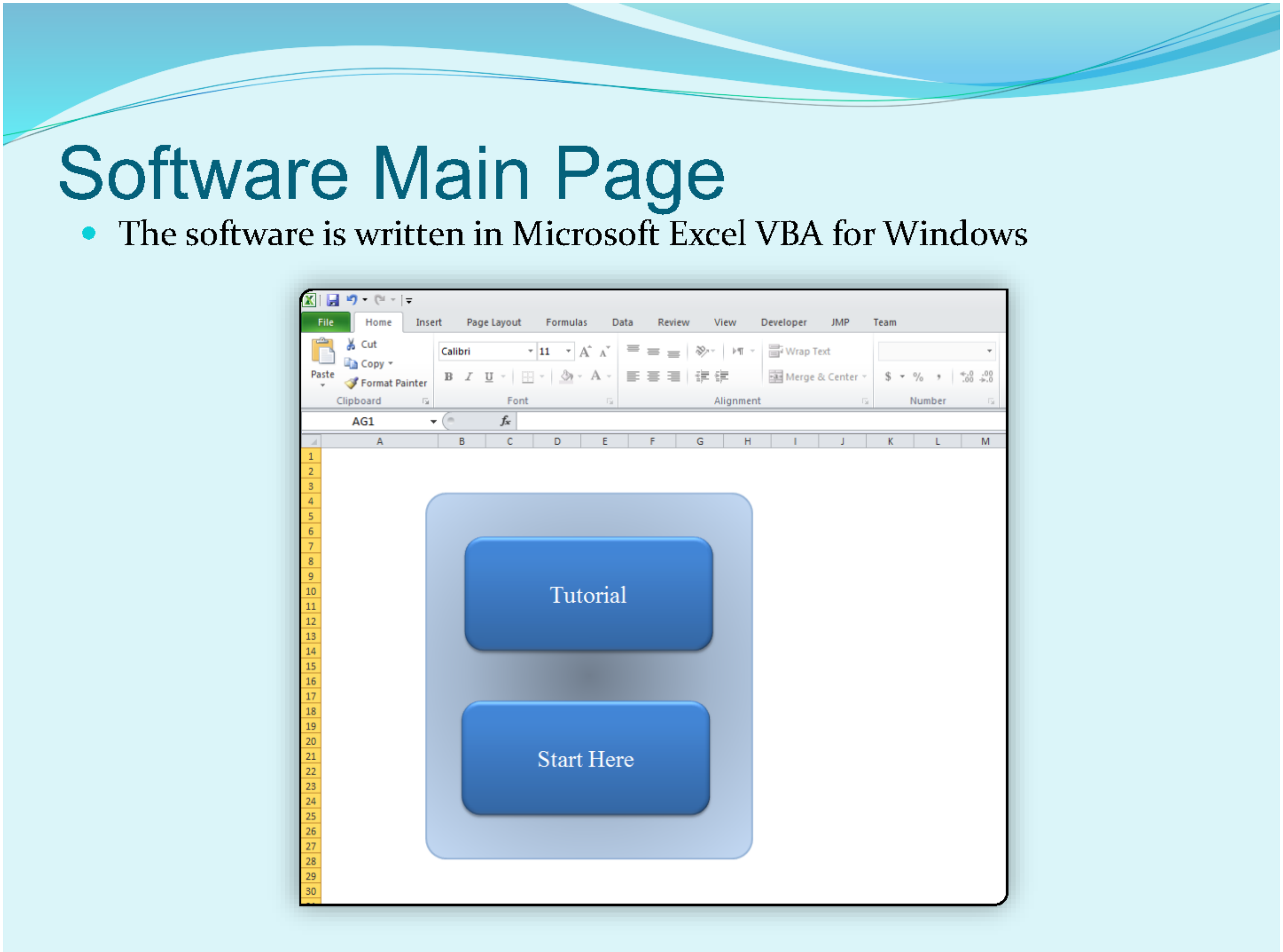


Figure A.3. Software main page

- By clicking on 'Tutorial' button user can see the software tutorial and by clicking on 'Start Here', the window for input data and analysis is opened

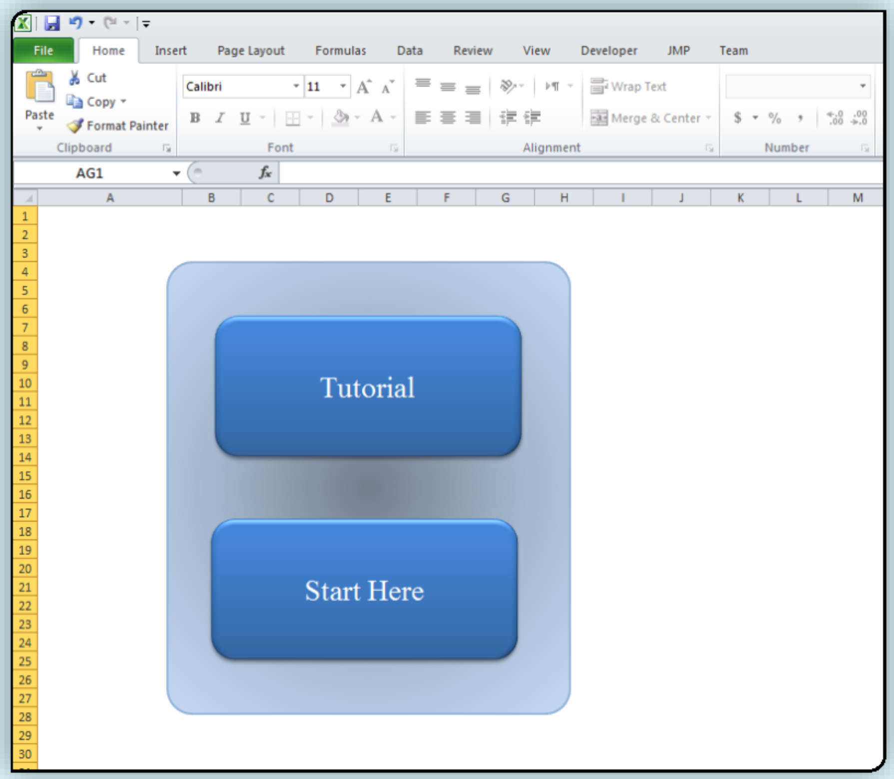


Figure A.4. Starting analysis or tutorial

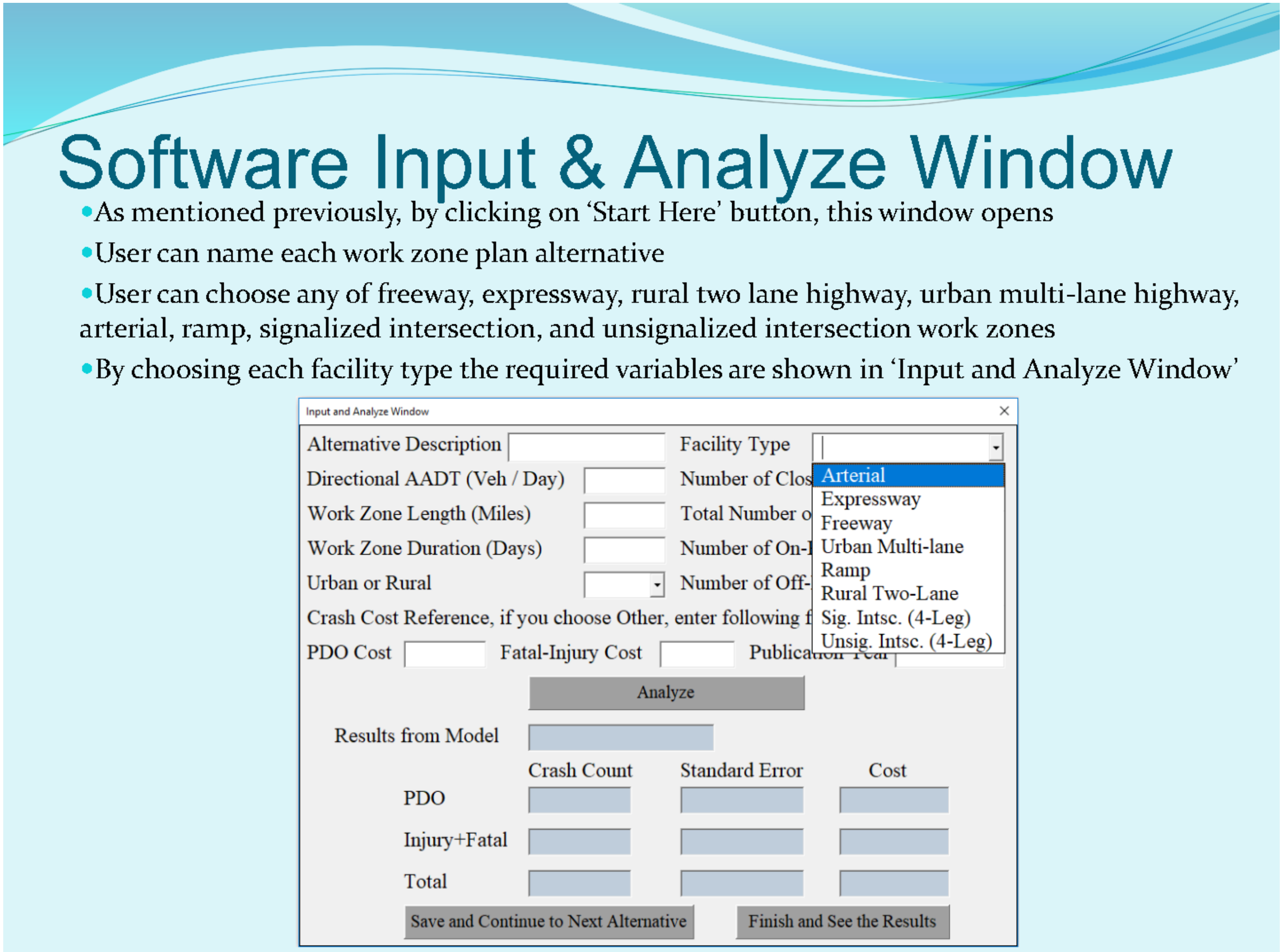


Figure A.5. Software input and analyze window

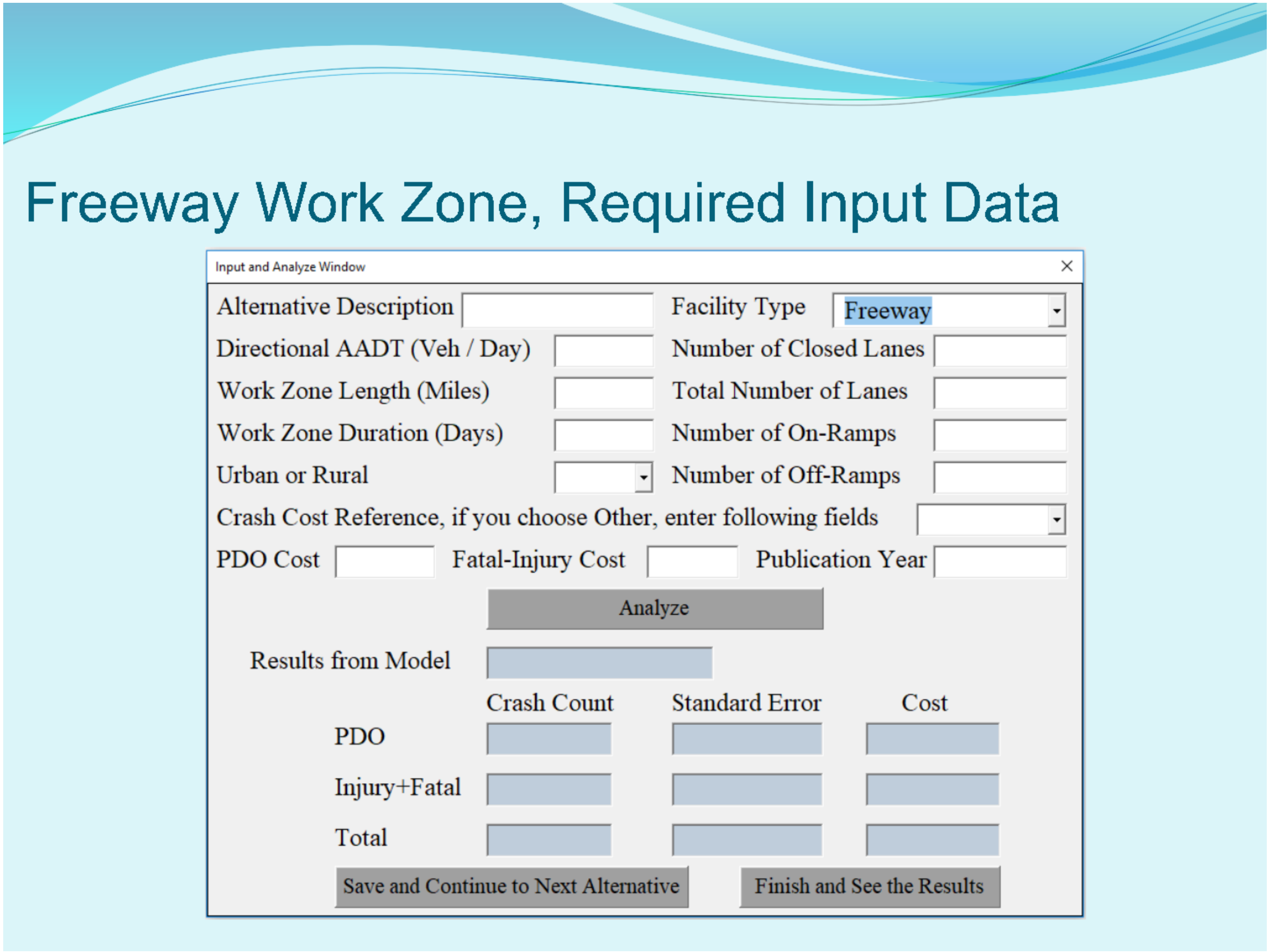


Figure A.6. Input window for freeway work zones

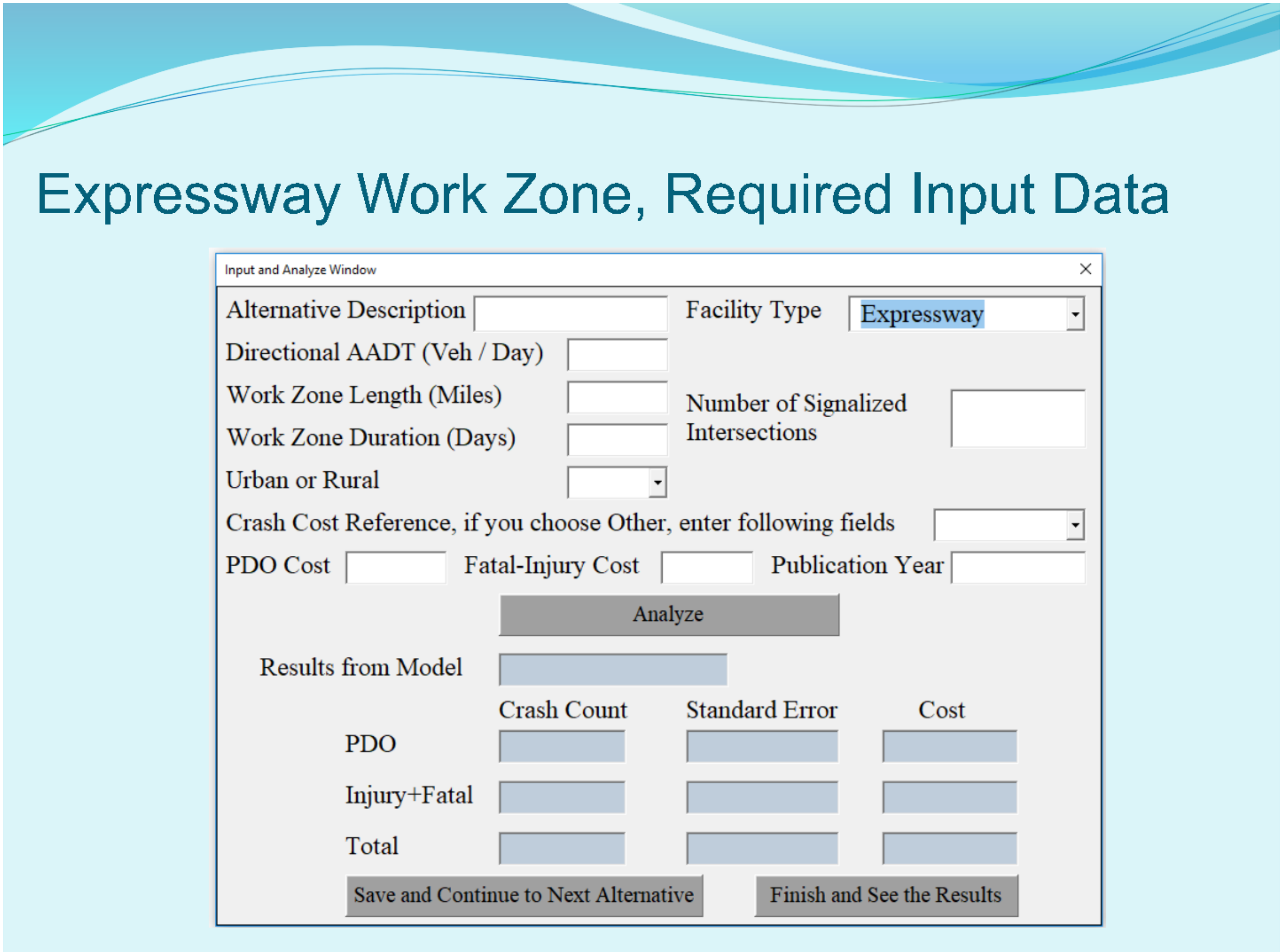


Figure A.7. Input window for expressway work zones

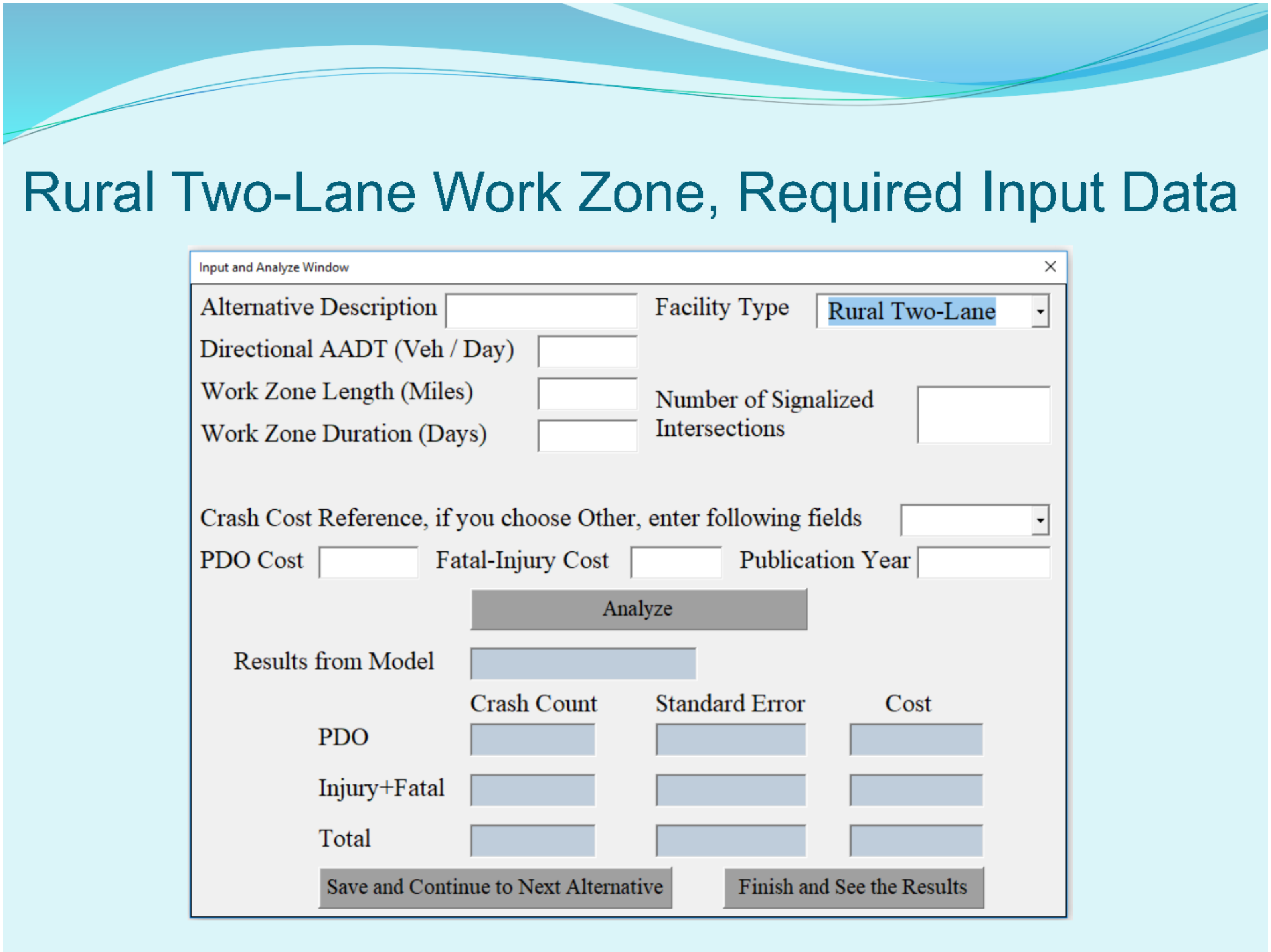


Figure A.8. Input window for rural two-lane work zones

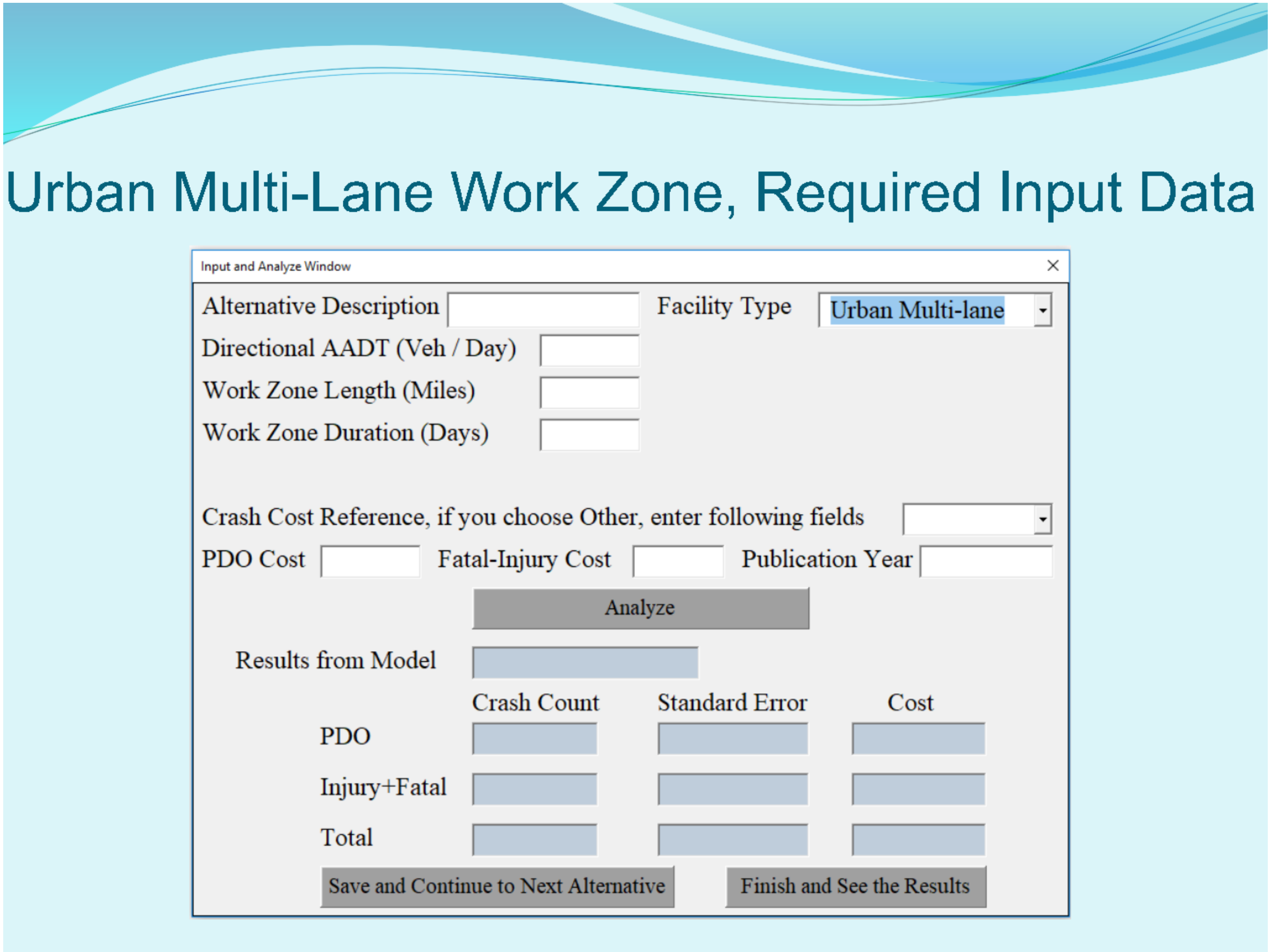


Figure A.9. Input window for urban multi-lane work zones

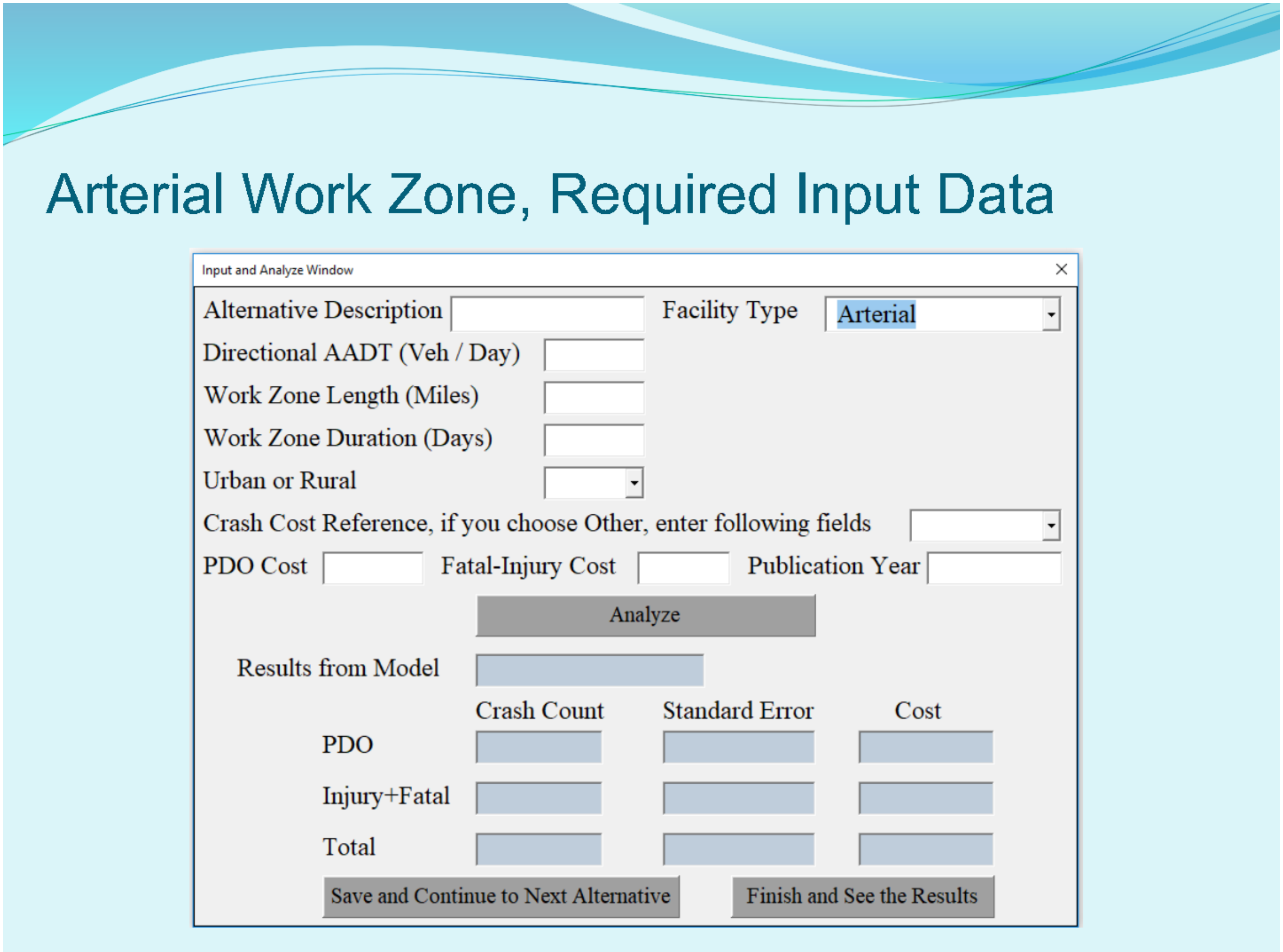


Figure A.10. Input window for arterial work zones

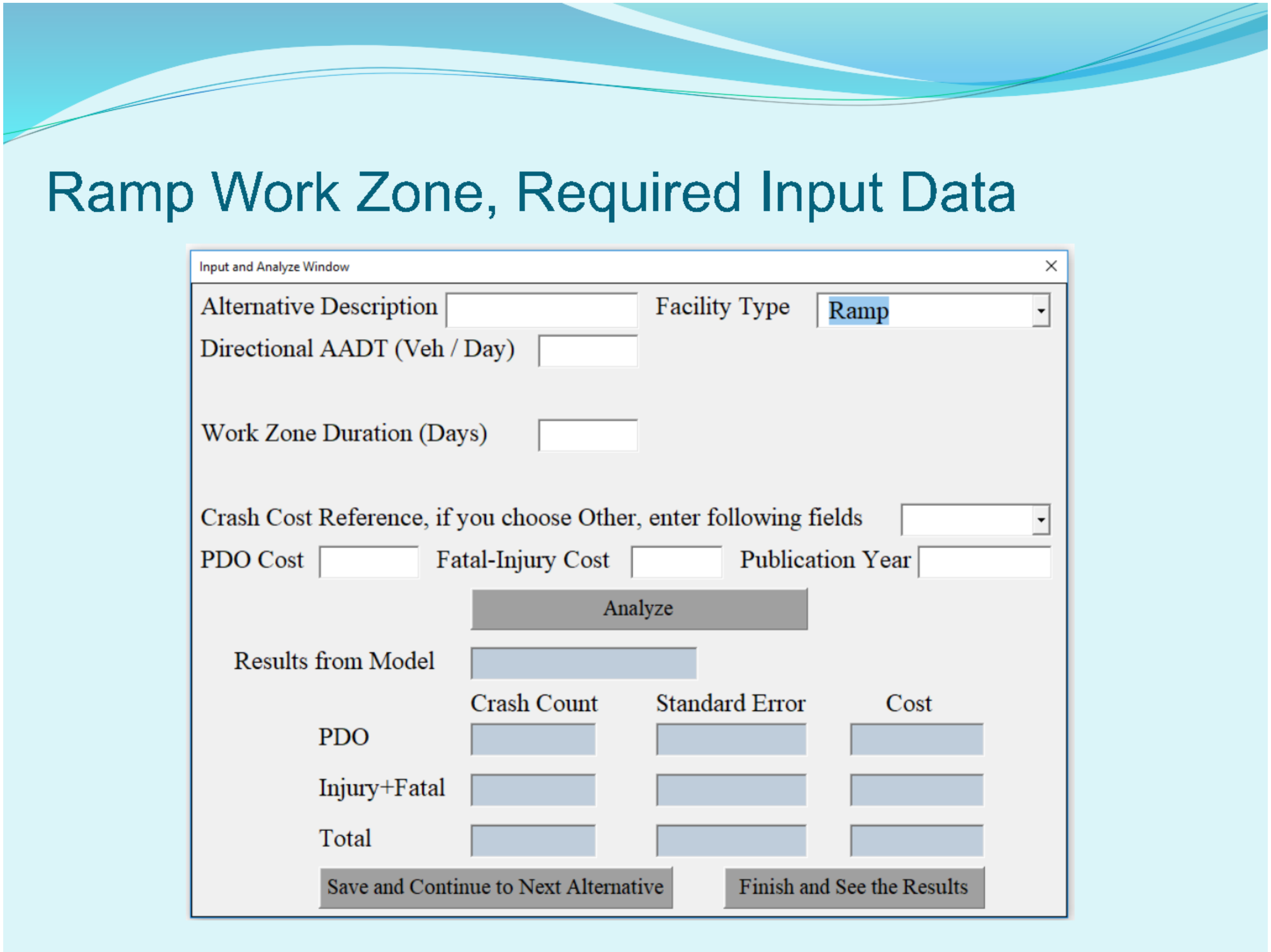


Figure A.11. Input window for ramp work zones

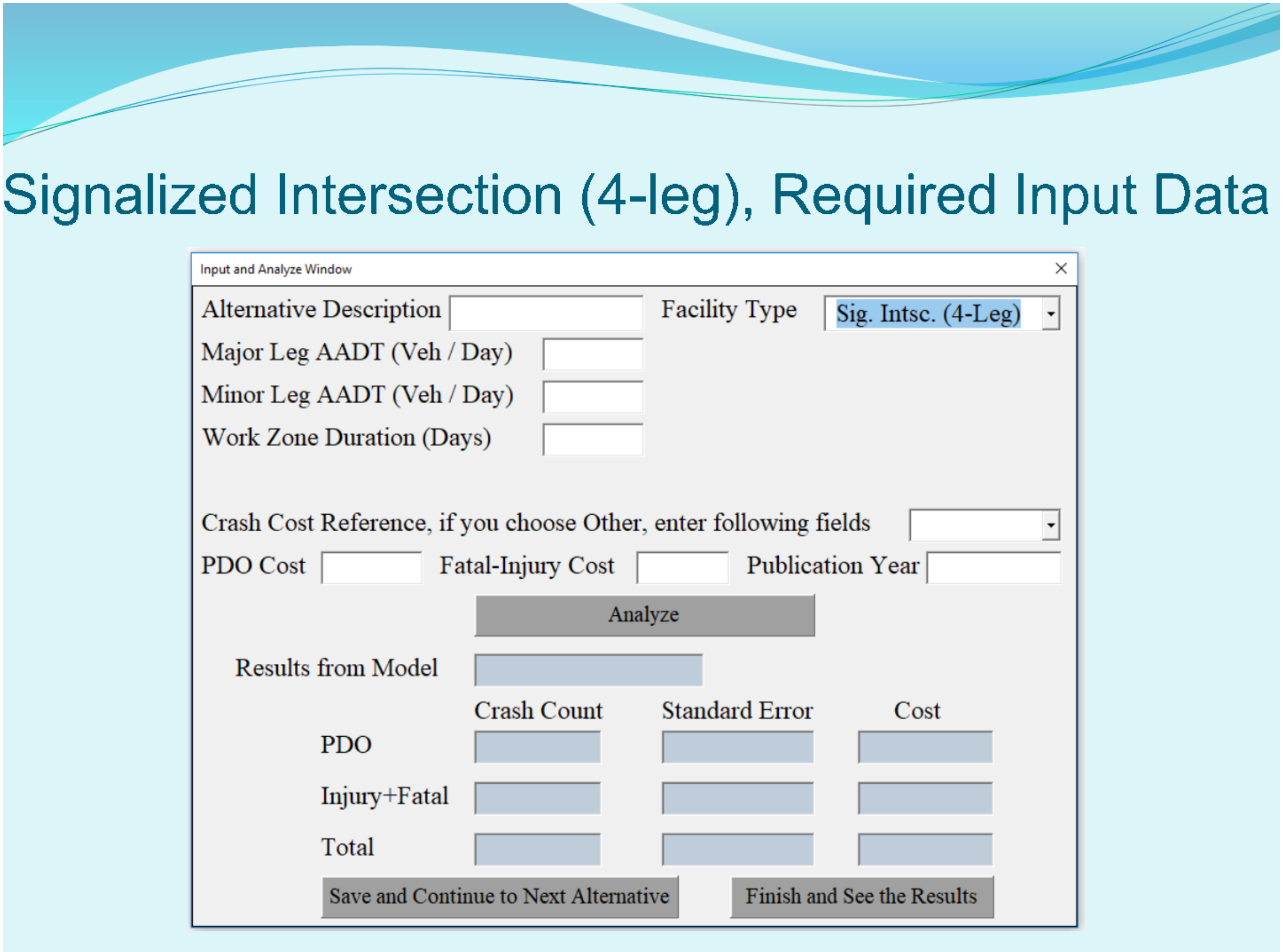


Figure A.12. Input window for signalized intersection (4-leg) work zones

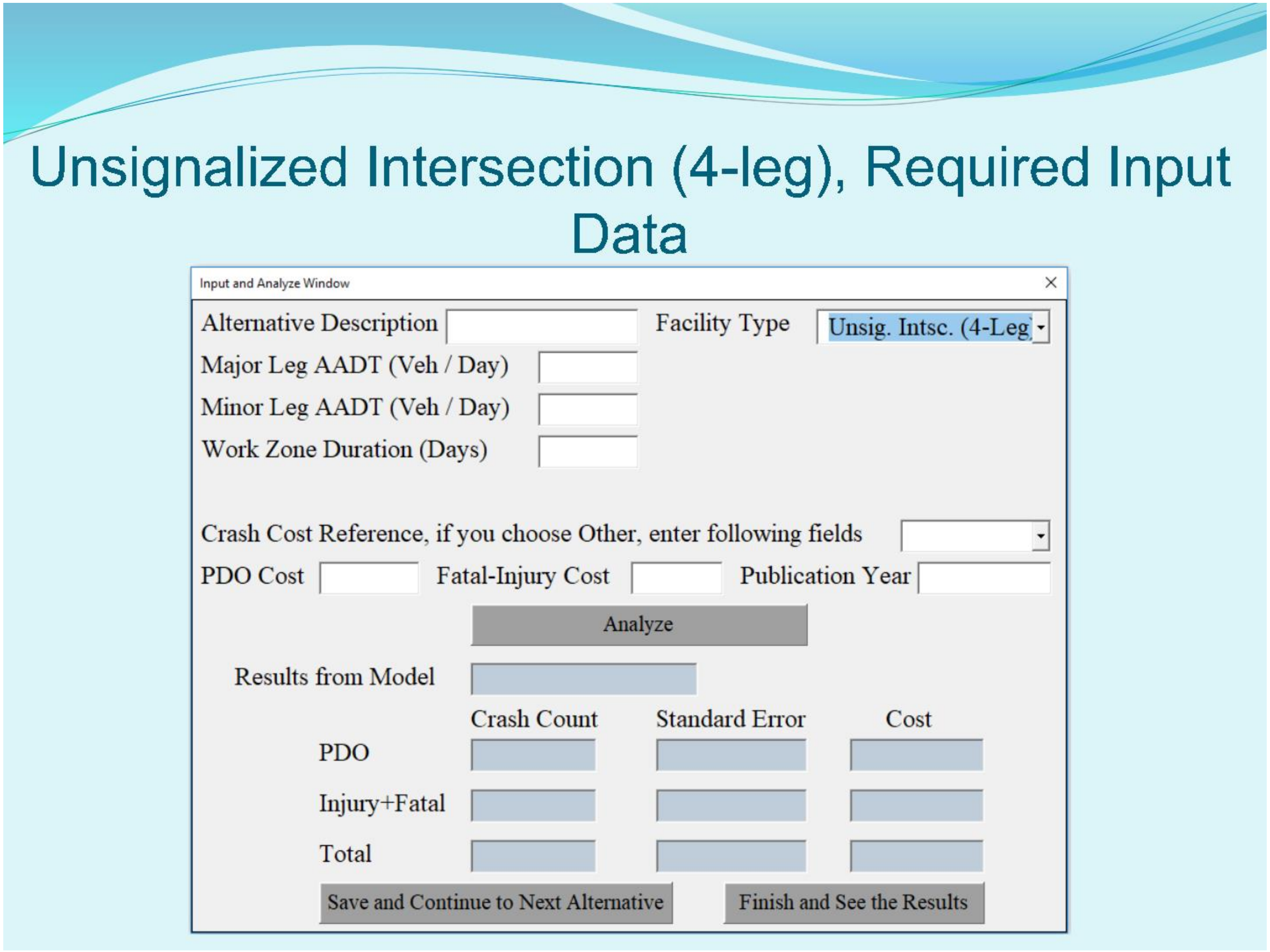
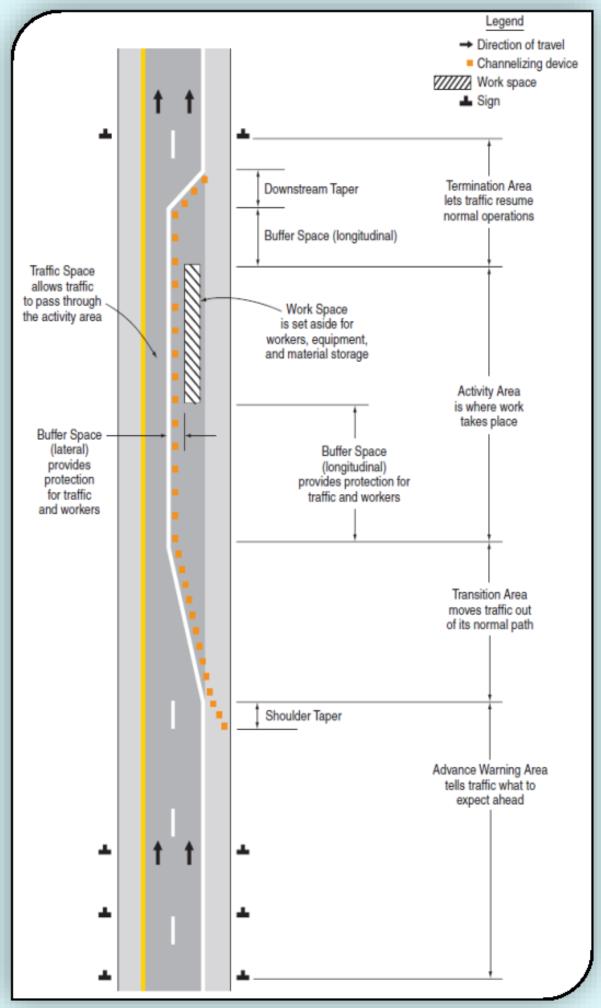


Figure A.13. Input window for unsignalized intersection (4-leg) work zones

Definitions of Input Variables

- AADT is directional Annual Average Daily Traffic and its unit is vehicles per day.
- $AADT_{Major}$ is directional Annual Average Daily Traffic of intersection major leg. Its unit is vehicles per day.
- $AADT_{Minor}$ is directional Annual Average Daily Traffic of intersection major leg. Its unit is vehicles per day.
- Length is the length of Work Area of the work zone in miles
- Duration is the work zone duration in days
- Work zone urban-rural indicator (urban if the city population is more than 5,000 and rural otherwise)
- Number of closed lanes in one direction due to the work zone
- Total number of lanes in one direction where work zone is located
- Number of on-ramps and off-ramps in work area of the work zone (transition and termination areas are not included)
- Number of signalized intersections in work area of the work zone (transition and termination areas are not included)



Work zone components based on MUTCD (2009)

Figure A.14. Definition of input variables

Freeway and Expressway Models

FW 1	$N_C = \mathrm{e}^{-12.40} AADT^{0.88} L^{0.60} D^{1.01} e^{0.23 * \frac{Closed\ Lanes}{Number\ of\ Lanes}} e^{0.38 * Urban} e^{-1.14 * Injury} \ , \ \alpha = 0.35$
FW 2	$N_C = \mathrm{e}^{-13.17} AADT^{0.94} L^{0.45} D^{1.03} e^{0.34 * \frac{Closed\ Lanes}{Number\ of\ Lanes}} e^{0.52 * Urban} e^{-1.14 * Injury} \ , \ L < 6 \ , \ \alpha = 0.36$
FW 3	$N_C = \mathrm{e}^{-12.51} AADT^{0.89} L^{0.65} D^{1.00} e^{0.21 * \frac{Closed\ Lanes}{Number\ of\ Lanes}} e^{0.35 * Urban} e^{-1.13 * Injury} \ , \ \alpha = \frac{0.89}{L}$
FW 4	$N_C = \mathrm{e}^{-13.52} AADT^{0.98} L^{0.46} D^{1.04} e^{0.32 * \frac{Closed\ Lanes}{Number\ of\ Lanes}} e^{0.41 * Urban} e^{-1.14 * Injury} \ , \ L < 6 \ , \ \alpha = \frac{0.49}{L}$
FW 5	$N_C = \mathrm{e}^{-12.19} AADT^{0.86} L^{0.65} D^{1.00} e^{0.15 * \frac{Closed\ Lanes}{Number\ of\ Lanes}} e^{0.38 * Urban} e^{-1.14 * Injury} \ , \ \alpha = \frac{34.39}{L * D}$
FW 6	$N_C = \mathrm{e}^{-13.45} AADT^{0.97} L^{0.47} D^{1.02} e^{0.29 * \frac{Closed\ Lanes}{Number\ of\ Lanes}} e^{0.44 * Urban} e^{-1.13 * Injury} \ , \ L < 6 \ , \ \alpha = \frac{20.59}{L * D}$
FW 7	$N_C = \mathrm{e}^{-13.42} AADT^{0.96} L^{0.77} D^{1.01} e^{0.10 * \frac{On-ramps}{L}} e^{0.12 * \frac{Off-ramps}{L}} e^{0.21 Urban} e^{-1.12 * Injury} \ , \ \alpha = 0.30$
FW 8	$N_C = \mathrm{e}^{-12.94} AADT^{0.89} L^{0.83} D^{1.01} e^{0.10 * \frac{On-ramps}{L}} e^{0.18 * \frac{Off-ramps}{L}} e^{0.27 Urban} e^{-1.12 * Injury} \ , \ \alpha = \frac{45.14}{L * D}$
Exp 1	$N_C = \mathrm{e}^{-11.93} AADT^{0.83} L^{0.60} D^{1.00} e^{0.21 * \frac{Signal}{L}} e^{0.66 * Urban} e^{-1.02 * Injury} \ , \ \alpha = 0.72$
Exp 2	$N_C = \mathrm{e}^{-10.94} AADT^{0.66} L^{0.66} D^{1.10} e^{0.43 * \frac{Signal}{L}} e^{-1.01 * Injury} \ , \ Rural \ , \ \alpha = 0.41$
Exp 3	$N_C = \mathrm{e}^{-11.60} AADT^{0.89} L^{0.59} D^{0.96} e^{0.20 * \frac{Signal}{L}} e^{-1.03 * Injury} \ , \ Urban \ , \ \alpha = 0.83$
Exp 4	$N_C = \mathrm{e}^{-14.37} AADT^{1.15} L^{0.38} D^{1.05} e^{0.16 * \frac{Signal}{L}} e^{-1.10 * Injury} \ , \ Urban \ , \ L < 6 \ , \ \alpha = 0.70$

Figure A.15. Freeway and expressway models

Rural Two-Lane, Urban Multi-Lane, Arterial, Ramp, and Intersection Models

Rural two-lane 1	$N_C = \mathrm{e}^{-12.08} AADT^{0.86} L^{0.84} D^{0.94} e^{0.53*\frac{Signal}{L}} e^{-0.64*Injury}\ ,\ \alpha = 2.51$
Rural two-lane 2	$N_{PDO} = \mathrm{e}^{-12.43} AADT^{0.93} L^{0.79} D^{0.93} e^{0.57*\frac{Signal}{L}}\ ,\ \alpha = 2.75$
Rural two-lane 3	$N_{Inj} = \mathrm{e}^{-12.18} AADT^{0.75} L^{0.94} D^{0.95} e^{0.50*\frac{Signal}{L}}\ ,\ \alpha = 2.00$
Urban multi-lane	$N_{Total} = \mathrm{e}^{-9.78} AADT^{0.79} L^{0.76} D^{0.90}\ ,\ \alpha = 1.60$
Arterial	$N_{Total} = \mathrm{e}^{-11.50} AADT^{0.91} L^{0.62} D^{0.91} e^{0.75*Urban}\ ,\ \alpha = 2.87$
Ramp	$N_{Total} = e^{-20.95} AADT^{1.66} D^{1.19}\ ,\ \alpha = 1.47$
Sig. Intsc. (4-Leg)	$N_{Total} = e^{-12.59} AADT_{Major}^{0.43} AADT_{Minor}^{0.33} D^{0.98}\ ,\ \alpha = 11.51$
Unsig. Intsc. (4-Leg)	$N_{Total} = e^{-14.26} AADT_{Major}^{0.44} AADT_{Minor}^{0.29} D^{1.16}\ ,\ \alpha = 16.08$

Figure A.16. Rural two-lane, urban multi-lane, arterial, ramp, and intersection models

Crash Equivalent Cost

- The software computes the equivalent crash cost of any alternative.
- Crash costs from HSM (AASHTO 2010) are built-in. The HSM crash costs are in 2001 dollars.
- The "Other" option allows the user to enter his or her own crash cost estimates from any other studies. These values must be entered for each alternative.
- The "User Defined" option is useful when the user wants to consider a crash cost reference multiple times. This option uses the values that the user enters in the "User Defined Crash Cost" worksheet.
- The publication year is needed to convert the values to current value.
- Based on the declared US discount rate, ***the software transforms previous values to current year value. For years after 2015 software considers 0.75% discount rate.***

Year	Yearly Discount Rate
Before 1994	3.32%
1995-1999	3.04%
2000-2004	2.43%
2005-2009	3.75%
After 2010	0.75%

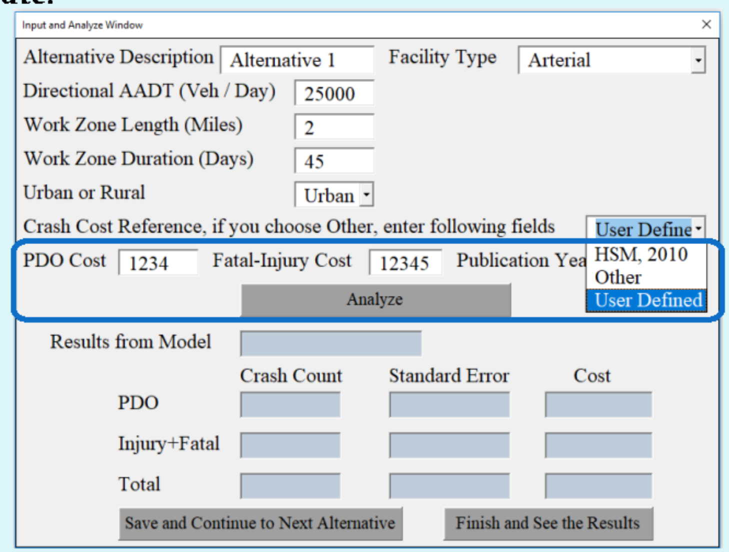


Figure A.17. Crash equivalent cost

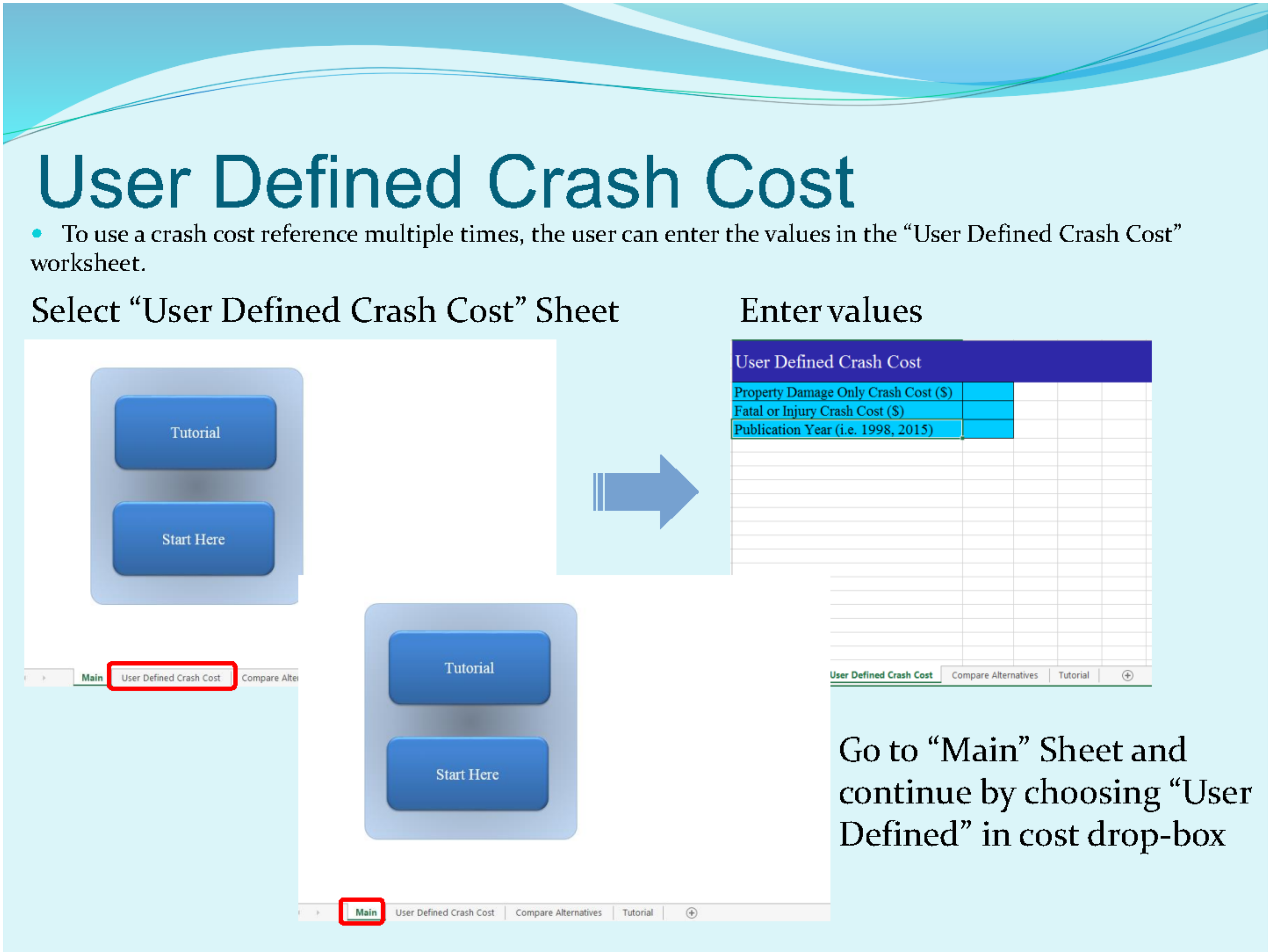


Figure A.18. User defined crash cost

Analyze

- After entering all mentioned variables above, the user should click on 'Analyze' button. Results are shown in the bottom half of the window.
- After clicking on 'Analyze' button, the user should click on 'Save and Continue to Next Alternative' button to start entering the next work zone alternative plan.
- For the last alternative instead of 'Save and Continue to Next Alternative' button user should select the 'Finish and See the Results' button to close the window and go to the results page.

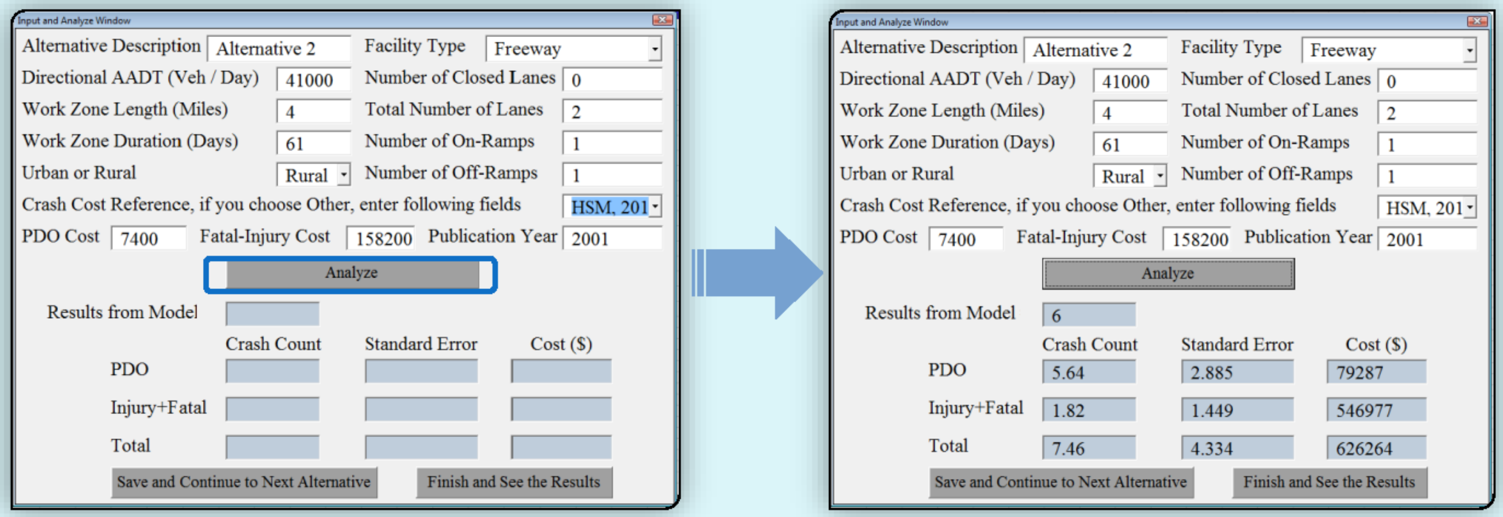


Figure A.19. Analysis window

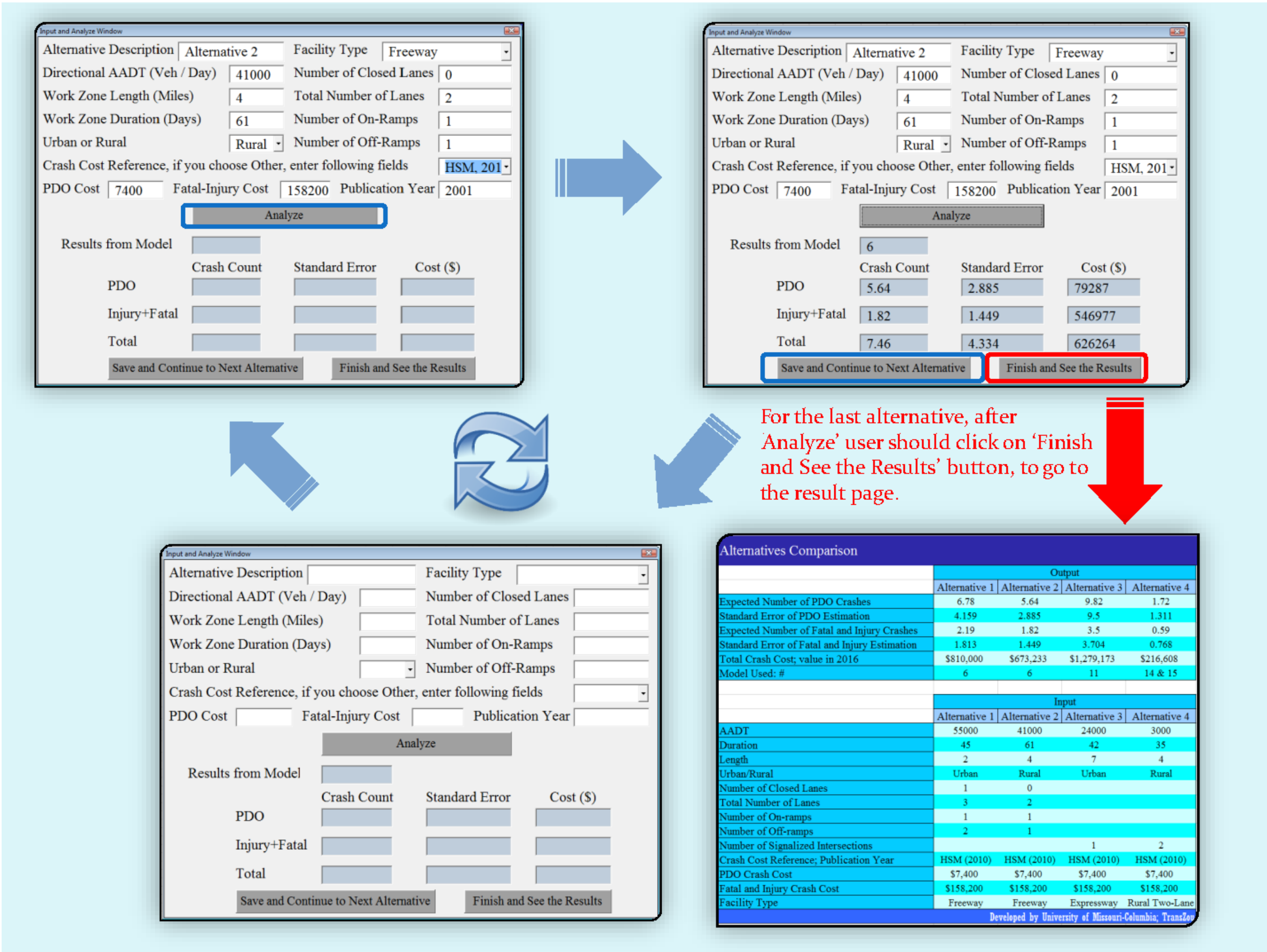


Figure A.20. Comparison of alternatives