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Design of Construction Work Zones on High-Speed Highways

TRANSPORTATION RESEARCH BOARD
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SUMMARY

Driving through construction work zones is an increasingly common part of the transportation experience. The combination of two long-term trends has increased the expanse and importance of work zones: (1) functional obsolesce and physical deterioration of aging highways; (2) increasingly intense use (i.e., ongoing growth in daily traffic volumes and loadings) of these same facilities. To varying degrees, ongoing reconstruction activities require alteration of traffic patterns and the introduction of new features to the driving environment. Whereas permanent roads are designed solely to facilitate safe and efficient traffic movement, roadways in work zones must also accommodate mechanized and labor-intensive construction activity. The transportation and construction functions are often at cross-purposes, with previous research indicating that crash rates in work zones are generally higher than those for the same site during normal operations.

Until fairly recently, work zone design generally consisted of developing temporary traffic control plans. While temporary traffic control is critical to work zone safety and operational efficiency, the work zone challenge cannot be met with temporary traffic control alone. Transportation management and the design of supporting infrastructure for work zones are also necessary to mitigate the potential negative impacts of work zones.

Numerous existing publications provide insight and guidance on various aspects of designing construction work zones on high-speed highways. On a national basis, three publications were found to be widely referenced. The *Manual on Uniform Traffic Control Devices* (*MUTCD*) is a national standard used to develop temporary traffic control plans. The *Roadside Design Guide* is published by the American Association of State Highway and Transportation Officials (AASHTO) and devotes a chapter to Traffic Barriers, Traffic Control Devices, and Other Safety Features for Work Zones. This chapter provides considerable information on hardware details and the functional performance requirements (e.g., crashworthiness). *A Policy on Geometric Design of Highways and Streets* (*Green Book*), also published by AASHTO, provides limited guidance on work zone design and recommends providing geometrics and traffic control devices that are as nearly comparable to those for normal operating situations as practical, while providing room for the contractor to work effectively. Taken together, these publications provide a wealth of useful information but do not address many routine work zone design decisions. Identifying and addressing these knowledge gaps were central themes of this research.

The subject of speed is inextricably connected to work zones. There is a widely held perception that speed is one of the most significant factors in road crashes. This perception is especially strong with regard to work zones. Speed reduction measures are a prominent topic in work zone practice and published research. Perceived speed-safety linkages stem, in part, from relationships between vehicle speed and operator capability. For permanent roadways, there is evidence indicating that crash probability is related to

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speed deviation above and below the mean speed. Crash rates are lowest for vehicles traveling near the mean speed.

Based on information summarized in the two previous paragraphs, this research was directed toward the development of two products: (1) Design Decision Guidance for Construction Work Zones on High-Speed Highways, and (2) Work Zone Speed Prediction Model. These objectives were accomplished.

As survey of state DOTs was conducted as part of the research. The survey yielded information in two areas: current state of work zone design practices and priority subjects for improving work zone design. Both sets of input were valuable. Existing state DOT practice were a key input to developing the design guidance. The priorities expressed in the survey were used to identify topics worthy of rigorous effort.

The Design Decision Guidance (design guidance) was prepared as a stand-alone, hard copy appendix to the final report. The design guidance provides information not otherwise available in nationally-referenced publications. It is intended for consideration by transportation agencies in developing policies and procedures related to work zone safety and mobility. The design guidance is also intended for use by transportation agency and consultant personnel involved in the planning, design and review of construction work zones on high-speed highways. It is not recommended for adoption as a standard.

The design guidance is written in a manner (i.e., terminology, format and conventions) similar to the AASHTO *Green Book* and consists of the following chapters:

1. Introduction;
2. Design Controls and Principles;
3. Conceptual Design and Planning of Work Zones;
4. Roadway Design;
5. Roadside Design and Barrier Placement;
6. Ancillary Design Information.

The information was developed using various methods and information sources including previous research, design guidance for permanent roads, state DOT work zone guidance publications and focused studies. In a number of areas (e.g., sight distance, cross section features, superelevation distribution method), there is a reasonable basis for designing construction work zones with guidelines different than the criteria typically used for permanent roads. A critical distinction between construction work zones and permanent roads is exposure. Construction work zones have finite service lives, which significantly reduces total exposure in comparison to permanent features. Since exposure is a key predictor of safety performance, it is explicitly and implicitly considered in design decisions.

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The development of design aids for the placement of temporary concrete barriers in construction work zones was a research emphasis area. Better guidance in this area was the top priority of state DOT survey respondents. Historically, work zone barrier placement decisions were made through either subjective judgment or application of the clear zone convention. Where the clear zone approach is used, practice and policies vary substantially on the design clear zone dimension (width) used for work zones. To provide an alternative method of assessing barrier placement in construction work zones, this research developed estimated benefit-cost ratios for a series of common work zone scenarios. Several analysis methods were considered. The Roadside Safety Analysis Program (RSAP) was selected as the best available analysis tool even though the RSAP documentation does not indicate the program is intended for application to work zones. In consultation with the RSAP development team, selective departures and alterations were made from the default RSAP procedures to more closely represent the distinctive characteristics of work zones and to compensate for program errors. The results are graphic plots of the estimated benefit-cost ratios for each scenario, with speed limit and exposure as variables. A narrative description, plan and cross-section view is provided for each scenario.

The Work Zone Speed Prediction Model estimates free flow vehicle speeds through two types of construction work zones on four lane freeways: single lane closures and median crossovers. The user interface is a Microsoft Excel spreadsheet, selected because of its wide availability. Input values are entered into cells by the user and results are displayed in labeled cells. The model uses an Artificial Neural Network which (as outlined in section 4.2.1) is a mathematical system based on the biological nervous system. For this particular application, the user provides two inputs (speed approaching work zone, type of work zone) that apply to the entire work zone and 14 inputs (primarily geometric and traffic control variables) for each representative location along the work zone. The model works in either the metric or US Customary system of units, as selected by the user.

To develop the model, free flow speeds were collected at 17 work zones, 10 in Pennsylvania and 7 and Texas. Spot speeds were collected at 119 locations at the 17 sites (including a location upstream of the work zone). Approximately 200 observations were made at each location for a total of about 24,000 speed observations. Using the model for conditions (e.g., curve radii, lane widths, posted speeds) that are outside the range of observed conditions is discouraged. The user interface provides guidance notes on appropriate ranges for various inputs and warnings when values are entered outside the range.

For each work zone, three sets of speed models are created: all vehicles, cars only, and trucks only. Each is displayed on a separate Excel worksheet. For each of the three models, the 15th, 50th and 85th percentile speeds are predicted at each location where inputs are provided. A graphic plot (speed profile) is also generated. The model is provided on a compact disc (CD) that is included with the final report. A User Manual was prepared is also included in electronic format on the same CD.

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The research report consists of five chapters. The Introduction (Chapter 1) provides background information related to work zones and specifically work zone design, including relevant guidance publications. The research scope and priorities are also identified. Chapter 2 is the Work Zone Literature Review and summarizes most of the recent relevant research publications. Numerous studies have been conducted, sometimes with conflicting findings. The methodologies and data for individual studies were evaluated. From this overview, several general conclusions were reached. For example, although results among studies vary, the preponderance of evidence indicates that the imposition of a work zone on a roadway is likely to diminish safety. There were many research findings that were neither refuted nor affirmed by other studies. As the research advanced, specific reported findings were considered in view of how the underlying study was conducted and the extent to which it was collaborated. Research findings were sought that established relationships between design decisions and performance results (e.g., safety, traffic flow). A very limited number of findings in this category were identified. A number of seemingly-reliable work zone safety characteristics, such as the distribution of work zone crash by type and severity, were identified and reported.

Chapter 3, Current Work Zone Design Guidance, is an inventory of potentially-relevant publications, which are divided into national and state categories. The publications in the former category are the AASHTO *Green Book*, AASHTO *Roadside Design Guide*, *Highway Capacity Manual* and *MUTCD*. The latter group were the publications and documents obtained from state DOTs through a survey and agency Web sites. Through the review of these documents, the research team was able to identify gaps in current guidance. Additionally, a review of state documents led to conclusions on areas of needed coverage, the range of practice in specific areas and unique and innovative approaches.

Chapter 4, Methodology and Findings, is a detailed summary of how the two research products were developed. The bases for the Design Decision Guidance are outlined including a detailed discussion on the application of RSAP to work zone scenarios. The data collection and development efforts associated with Work Zone Speed Prediction Model are also summarized. Chapter 5 reports on Conclusions and Recommendations. Several conclusions identify information gaps that, if filled, could be used to develop work zone design guidance with more direct safety linkages. A key recommendation is for agencies to adopt the Design Decision Guidance. Other recommendations provide specific suggestions on how to improve the research products and work zone safety in the future.

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CHAPTER **1**

INTRODUCTION

1.1 BACKGROUND

Each year, state transportation departments reconstruct and rehabilitate thousands of miles of high-speed highways. To varying degrees, the associated construction activities require alteration of traffic patterns and the introduction of new features to the driving environment. Whereas permanent roads are designed solely to facilitate safe and efficient traffic movement, roadways in work zones must also accommodate mechanized and labor-intensive construction activity. The transportation and construction functions are often at cross-purposes; research indicates that crash rates in work zones are generally higher than those for the same site during normal operations (*1, 2*). As the portion of the capital funds committed to rehabilitation of roads increases, road user and road worker exposure to work zones will also increase.

The public and transportation agencies are increasingly aware of the potential disruption that construction work zones can inflict on mobility and safety. Survey results published in 2001 indicate that work zones are the second leading cause of public dissatisfaction with highways (*3*). In 2004, the Federal Highway Administration (FHWA) promulgated an updated Work Zone Safety and Mobility regulation in response to a congressional directive. However, some of the technical resources needed to effectively manage the transportation system while providing for continual renewal and enhancement of the supporting infrastructure have not been widely available.

Until recently, work zone design generally consisted of developing temporary traffic control plans. Temporary traffic control plans are critical to work zone safety and operational efficiency. However, the work zone challenge cannot be met with temporary traffic control alone. Transportation management and the design of supporting infrastructure for work zones are also necessary to mitigate the potential negative impacts of work zones. Up to this point, no guidance has been published with an intended use as national guidance for construction work zone design. The FHWA *Manual on Uniform Traffic Control Devices* (*MUTCD*) (*4*) is a national standard applicable to development of temporary traffic control plans. The AASHTO 2001 *Policy on Geometric Design of Highways and Streets* (*Green Book*) (*5*) is available and recognized nationally as the benchmark guidance publication for permanent roads. Many state DOTs have work zone design guidance and publications that guide design of construction work zones. These DOT publications vary in the scope and depth. Taking the various DOT publications together, there are areas of agreement and disparity on matters of substance. This research was undertaken to develop design decision guidance for any transportation agency involved in designing construction work zones on high-speed highways.

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1.2 RESEARCH SCOPE AND PRIORITIES

The overall objective of the research was to develop a design decision methodology for construction work zones on high-speed highways. In delineating the project scope, a distinction was made between temporary traffic control and work zone design features. The principal work zone design decisions include work zone type, horizontal and vertical alignment, cross sectional elements and dimensions, roadside design and access points.

All of the common work zone design features are covered by the design decision guidance. However, some aspects of work zone design are considered especially important or problematic and worthy of more intensive effort. During the preliminary phase of the research, detailed research plans were developed for the following topics:

1. Statistical Studies of Lane Shifts With and Without Lane Width Reductions;
2. Development of Roadside Safety and Roadside Barrier Placement Guidance;
3. Development of a Speed Profile Model in Construction Work Zone Using Artificial Neural Networks;
4. Performance of Heavy Trucks in Construction Work Zones;
5. Influence of Design Features on Driver Performance;
6. Analyzing Work Zones Using Simulation.

Based on the priorities expressed by state DOTs through the survey, available resources, and other considerations, the panel directed that studies 2 and 3 be conducted.

Further refinement of the research and scope of the design decision guidance was accomplished through a literature review and survey of state departments of transportation (DOTs). A review of published research indicated a limited number of established relationships between work zone design decisions and the probable safety and operational consequences. DOTs were surveyed on their work zone criteria, practices and design guidance needs. Collectively, these information sources indicated that work zone speeds are an ongoing concern for transportation agencies. The concerns cover the gamut of potential inconsistencies between speeds in the work zone and the approaches, speeds used in the design process and observed speeds, and posted and observed speeds. However, the highest priority expressed through the survey of state DOTs was for improved barrier placement guidance.

Based on the preliminary assessment, it was concluded that the comprehensive design guidance should cover work zone design decisions not fully addressed by other publications, specifically the *MUTCD* and the AASHTO *Roadside Design Guide* (*6*). Developing new guidance for use in conjunction with other publications was determined to be a more appropriate use of resources than supplanting or duplicating existing, accepted publications. To address the identified gaps and priorities, emphasis was placed

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on development of a speed prediction model for common freeway construction work zone types and design guidance for barrier placement.

1.3 ORGANIZATION OF THIS REPORT

This report provides an overview of work zone issues for high-speed highways and in-depth review of subjects related to work zone design and safety. Previously completed work zone safety and operations research was reviewed, assessed and summarized in Chapter 2. Construction work zone design guidance applicable to high-speed highways was identified, reviewed and summarized in Chapter 3. This includes publications with national applicability, state DOT design guidance publications, and information gleaned from responses to the state DOT surveys. Chapter 4 explains and documents how the research products were developed. Chapter 5 provides conclusions and recommendations.

This research resulted in two products intended for use by agencies in establishing work zone design policies and criteria and by practitioners in making project-level work zone design decisions. Appendix A is the comprehensive design decision guidance for construction work zones on high-speed highways. It consists of six chapters and is self-standing. The rationale for the guidance is included in the body of the research report, primarily in Chapter 4. The second research product is the speed prediction model, which is in Appendix B and is presented on a compact disc (CD). The model will run on Microsoft Windows-equipped computers and has a Microsoft Excel user interface. Predicted speeds are graphically plotted in the form of speed profiles. A user’s manual is also included.

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CHAPTER 2

REVIEW OF WORK ZONE SAFETY LITERATURE

The research studies reviewed were published from 1978 to 2004, and specific articles were selected based on their conformance to the scope of this project or for any original contribution to the state of knowledge on work zone crashes. They are summarized in the following sections.

2.1 DATA AND METHODOLOGIES

Seventeen of the reviewed studies included a range of data, observational designs, and analysis methodologies used in work zone safety studies. Usually, data were obtained in one of two ways: 1) by using an electronic database or police accident report with work zone tags (*7,8,9,16,17,18,19,20*) or 2) by matching the date and location of accidents, either in electronic or hard copy form, with the dates and locations of work zones on certain roadways (*1,10,11,12,13,14,15,21*). A weakness of the former is that, in most cases, the work zone tag was marked only if the reporting officer considered the crash to be related to the presence of the work zone. A similar weakness is associated with the latter option if the researcher selects/de-selects accidents based on a perceived relationship to work zone presence, as in (*21*). As one research team pointed out, "one cannot ever be sure that an accident was or was not attributable to the presence of construction" (*1*). Nonetheless, the subjective identification of work zone-related crashes was a common technique in the safety literature.

In addition to whether the crash occurred in a work zone, the databases or crash records usually included variables such as crash severity, crash type, date, time of day or light condition (day/night), vehicle types, major contributing factors (opinion of reporting officer), weather condition, roadway surface condition, and location within the work zone. Some databases, including the Fatality Analysis Reporting System (FARS) (*22*), have a generic variable for roadway alignment (presence of curve or presence of grade); however, specific work zone design features (e.g., lane width, shoulder width, radius of curve, etc.) at the location of the crash were not included in any of the data sets reviewed. This has been pointed to as a major cause of the wide range and sometimes conflicting results in the safety literature and as a significant weakness in most work zone safety research (*20*).

The observational designs were also of two predominant types: 1) frequency observations of work zone crashes (*7,8,9,16,17,18,19,20,21*) or 2) before-during observational studies (*1,10,11,12,13,14,15*). Analyses of the former included simple observations of frequencies and proportions of different types of work zone crashes with no statistical testing; observations of frequencies and proportions of different types of work zone crashes with statistical testing (usually χ^2 tests of proportions); or comparisons of frequencies and proportions of work zone crashes with crashes outside of work zones, with and without statistical testing. Analyses of the latter included straight before-during

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comparisons of frequencies, proportions, or rates without statistical testing; before-during comparisons of frequencies, proportions, or rates with statistical testing; or before-during comparisons of frequencies, proportions, or rates with statistical testing and use of control/comparison sites. This final type of analysis is recommended for before-during studies (*23*) and was conducted by (*1,13,15*).

The accuracy and scope of the data sets and the different analysis types led to a wide range of conclusions regarding the magnitudes and characteristics of work zone crashes. As stated earlier, a major contributor to these different, sometimes conflicting, conclusions was the lack of data on specific work zone design features.

2.2 QUANTITATIVE SAFETY EFFECTS OF WORK ZONE DESIGN FEATURES

Six studies addressed the safety effects of different design features in a controlled fashion (*10,13,14,15,16,17*). The features evaluated included work zone length, traffic diversion strategies (e.g., lane closures, median crossovers), and entrance ramps. The results are the focus of this section.

2.2.1 Work Zone Length

Three studies developed negative binomial regression models to predict expected accident frequencies on work zone segments (*13,14,16*). Length as an independent variable was included in the final models of two (*14,16*). In one model (*16*), increasing the length of a work zone by 1 percent while keeping all other factors constant led to a 0.85 percent increase in the expected number of injury/fatality crashes and a 1 percent increase in the expected number of property-damage-only (PDO) accidents. The respective increases for the other model (*14*) were 0.75 and 0.61 percent. A model to predict expected accident frequencies on work zone approaches was also developed (*16*). A crash was assigned to a work zone approach if its location fell within the estimated congested segment upstream of the beginning of the work zone and the time of the crash coincided with the work zone presence. The model indicates that increasing work zone length will cause a decrease in the expected number of injury and PDO crashes on work zone approaches. The relationship is exponential, meaning that a 1 percent increase in the length of a long work zone results in a greater decrease in expected crashes than a 1 percent increase in the length of a shorter work zone.

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2.2.2 Traffic Diversion Strategies

Four studies quantified the safety effects of different traffic diversion strategies (*10,13,17,24*). In an analysis of 79 construction projects on mostly high-speed roadways in one of the studies (*9*), mean accident rates ranged from 0.77 accidents per million vehicle miles (MVM) for a crossover and detour to 5.29 accidents per MVM for a lane closure and temporary bypass. Table 1 provides a summary of these accident rates. It should be noted that the sample sizes for some lane closure strategies were quite small, which probably resulted in very large confidence intervals in predicting the population means.

Table 1 Mean crash rates for different traffic diversion strategies (8)

Traffic Diversion Strategy	Number of Projects	Mean Accident Rate (Accidents per MVM[1])
Lane closure	48	2.13
Crossover	4	2.24
Temporary bypass	0	--
Detour	0	--
Lane closure and crossover	5	1.50
Lane closure and temporary bypass	4	5.29
Lane closure and detour	10	2.99
Crossover and detour	3	0.77
Temporary bypass and detour	1	4.37

[1] million vehicle miles.

Another of the studies (*24*) reported on accident rates at 49 construction work zones on four-lane divided highways. The researchers compared long-term single lane closures installed in one direction to a crossover strategy, in which traffic in both directions of travel was reduced to one lane and a crossover provided two-lane, two-way operations on one set of travel lanes while work was completed on the other set of lanes. Overall, researchers found no statistically significant differences in the accident rates at both types of projects. Accident rates at the two types of projects averaged 1.96 and 2.62 accidents per MVM, respectively, before construction, as compared to 2.86 and 2.78 accidents per MVM during construction. Although the rate for the single lane closures did appear to increase more significantly than did the rate at the crossover sites, the high degree of variability in rates from site to site kept these differences in accident rates from being detected as statistically significant.

An investigation of Indiana interstate highway work zone crashes also looked at before-during crash rates for lane closures and crossovers (*13*). The results are summarized in Table 2. Although the mean crash rates during the work zone period and the change in total and severe crash rates (during-before) are greater for crossover work zones, a comparison of the means showed no significant difference in both of these values (i.e., mean crash rate during work zone, mean change in crash rates from before to

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during). This result is similar to that in the study (*10*) where work zones with crossovers had a slightly higher, but not much higher, crash rate than work zones with lane closures.

Table 2 Mean crash rates for work zones with crossovers and lane closures (accidents per MVM[1])(*13*)

Sites	Rate without Work Zone	Rate with Work Zone	Change in Crash Rate
Sites using crossover (2 lanes in each direction)	0.62	0.83	0.21
Sites using partial lane closure (2 lanes in each direction)	0.58	0.77	0.19
Sites using crossover (3 lanes in each direction)	0.60	0.97	0.37
Sites using partial lane closure (3 lanes in each direction)	0.78	1.05	0.27

[1] million vehicle miles.

The same study (*10*) also looked at the effects on accident rates of degrading various road types. The results are shown in Table 3.

In the final study reviewed on the subject of safety effects associated with different traffic diversion strategies (*17*), data were obtained for North Carolina work zone crashes through the Highway Safety Information System. The effects of work zone characteristics on the most seriously injured occupant (no injury, minor, moderate, severe, fatal) and the total harm (measured in economic cost) in truck-involved and non-truck-involved collisions were studied. The ordinal probit model was used to investigate the former, and linear regression was used to investigate the latter. Table 4 presents model coefficients for multi-vehicle collisions. For all crash types, severity and harm were highest in work zones located on two-way, undivided roadways. For truck-involved, multi-vehicle collisions, severity and harm were overwhelmingly the highest in work zones classified as “roadway closed, detour opposing side.” It is unclear what this category includes. Possible scenarios are median crossovers and one-way alternating traffic.

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Table 3 Before-during accident rates by road degradation (accidents per MVM[1]) (*10*)

Roadway	Number of Projects	Before Construction	During Construction	Change (%)
6- or 8-lane interstate reduced to 2 lanes per direction	8	2.02	2.13	+5.3
6- or 8-lane interstate reduced to 1 lane per direction	3	2.37	5.10	+114.6
4-lane interstate reduced to 1 lane per direction	22	1.42	2.39	+68.6
4-lane interstate reduced to 2-lane, 2-way	2	0.42	1.05	+147.2
4-lane divided reduced to 1 lane per direction	5	3.28	3.77	+14.8
4-lane divided reduced to 2-lane, 2-way	5	1.84	2.14	+15.9
4-lane divided on new alignment	6	2.59	2.09	-19.5
4-lane undivided reduced to 2 lanes	3	8.35	7.94	-4.9
5-lane undivided with TWLTL[2] reduced to 2 lanes	3	5.09	8.08	+59.0
2-lane roadway reduced to 1 lane	7	3.79	4.96	+30.7
2-lane roadway on new alignment	11	6.63	5.68	-14.3

[1] million vehicle miles.
[2] two-way left turn lane.

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Table 4 Coefficients for injury severity and total harm models (*18*)

	Variable	Injury (Ordered Probit)			Harm (Semi-log)		
		All	Truck	Non-Truck	All	Truck	Non-Truck
Roadway configuration	One-way, not divided	0.192	0.305	0.168	0.108	0.211	0.076
	Two-way, not divided	0.428 [a]	0.510 [a]	0.398 [a]	0.266 [a]	0.313 [a]	0.247 [a]
	Two-way, divided, no median barrier	0.137 [c]	0.362 [b]	0.085	0.104 [b]	0.260 [b]	0.072
	Two-way, divided, median barrier [1]						
Construction effect on roadway	Lane closed		-0.166			-0.096	
	Shoulder/median closed		0.278			0.230	
	Roadway closed, detour opposing side		1.011 [a]			0.889 [a]	
	Lane shift/becomes narrow		-0.689			-0.381	
	Other/unknown		0.122			0.136	
	None [1]						

[a], [b], and [c]: the coefficient is significantly different from 0 at the 1 %, 5 %, and 10 % level of significance (two-tailed test), respectively.
[1] base category for coefficient comparison.

2.2.3 Ramps

One study (*15*) investigated changes in accident occurrence during construction at urban freeway entrance-ramp areas and non-entrance-ramp areas to determine if accidents increased disproportionately in the entrance-ramp areas compared with the non-entrance-ramp areas within the construction work zone. The data were from two long-term urban freeway reconstruction projects in Texas, I-35 W in Fort Worth and I-45 in Houston. Comparison sites were also chosen and were located either upstream or downstream of the construction sites. The analyses were done separately for each construction site with inclusion of a G^2 test for comparability of the work zone and comparison sites (*22*). The results are summarized in Table 5. A ratio greater than 1 indicated that accident frequencies increased more in entrance-ramp areas than non-

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entrance-ramp areas during construction. For I-35 W, all accident types increased more at entrance-ramp areas than at non-entrance-ramp areas. The increase at entrance-ramp areas was significantly greater for total accidents, PDO accidents, severe accidents, daytime accidents, and other multi-vehicle accidents. For I-45, five of eight accident categories increased more and three of eight accident categories increased less at entrance-ramp areas than at non-entrance-ramp areas. However, none of these differences was statistically significant. Looking at the difference in results between the two locations, it should be noted that the ramp geometrics on I-35W were greatly altered during construction. This included having very short acceleration lane lengths (approximately 50 feet). Conversely, ramp geometrics on I-45 in Houston were not as greatly affected during most of the construction efforts.

Table 5 Non-entrance-ramp areas versus entrance-ramp areas (*15*)

I-35W Entrance-Ramp vs. Non-Entrance-Ramp Areas		I-45 Entrance-Ramp vs. Non-Entrance-Ramp Areas	
Accident Category	**Percent Difference in Change in Accident Frequency**	**Accident Category**	**Percent Difference in Change in Accident Frequency**
Total accidents	+30.4[a]	Total accidents	+3.6[b]
Accident severity		Accident severity	
PDO[1]	+26.1[a]	PDO	-2.0[b]
Severe	+45.6[a]	Severe	+19.0[b]
Time-of-day		Time-of-day	
Daytime	+34.7[a]	Daytime	+10.7[b]
Nighttime	+22.5[b]	Nighttime	-7.3[b]
Collision type		Collision type	
Single vehicle	+4.4[b]	Single vehicle	+9.8[b]
Rear-end	+15.4[b]	Rear-end	+1.4[b]
Other multi- vehicle	+49.2[a]	Other multi-vehicle	-1.7[b]

[a] control and construction sections are comparable and differences are significant.
[b] control and construction sections are comparable and differences are not significant.
[1] property damage only.

2.2.4 Lane Widths

One quantitative assessment of lane width was reviewed (*10*). Accident rate comparisons were between projects that had reduced lane widths and projects that maintained normal lane widths. The level of lane width reduction was not given. Six projects with reduced lane widths during construction experienced a 17.6 percent increase in accident rates during construction, whereas the other 69 projects with normal lane widths experienced a 6.6 percent increase.

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2.3 WORK ZONE CRASH CHARACTERISTICS

Many of the reviewed studies investigated work zone crash characteristics in some way. The many tests and conclusions do not provide consistent findings as to the magnitude of certain effects. For example, when looking at overall magnitude of work zone crashes, one group (*10*) found a 7.5 percent increase in accident frequency during the work zone period, while another investigation (*11*) found a 119 percent increase. Similarly, work zone accident rates ranged from 0.89 (*12*) to 8.63 (*13*) crashes per MVM. These large differences can be attributed to lack of control or data regarding possibly important explanatory variables (e.g., cross section, alignment, roadside). This section will present general findings with illustrative numerical results. It is important to note that the studies of crash characteristics were only able to report magnitudes and are plagued by a lack of exposure data. Therefore, it is difficult to draw meaningful conclusions about the actual safety consequences of work zones. A first attempt at estimating true work zone exposure has recently been made (*25*).

2.3.1 Crash Magnitude and Severity

It was a common finding that the presence of a work zone on a specific roadway segment is likely to degrade its safety. Studies found crash frequencies and crash rates to be, on the average, higher during work zone periods than before (*1,10,11,12,13,14*). However, the results varied. Studies that used a sample of work zones often had a certain, sometimes significant, portion of the sample with lower crash rates during the work zone period (*10,13*). For example, in one study (*10*), 31 percent of the projects experienced decreases in accident rates during construction, 47 percent experienced increases between 0 and 50 percent (exclusive), and 24 percent experienced increases of 50 percent or more. There are probably factors, unaccounted for, that differentiate the sample sites. Similar variability was found in another study (*26*): 45 percent of the study sites experienced increases in accident rates of 40 percent or more, 8 percent experienced decreases in accident rates of 40 percent or more, and 47 percent of the study sites experienced less than 40 percent changes in accident rates.

Conclusions regarding the severity of crashes in work zones were mixed. Some studies found work zone crashes to be less severe than crashes outside of work zones (*6,9*), while others found work zone crashes to be more severe (*1,11*). These determinations were made by either comparing the percent increases in PDO crashes to the percent increases in fatal and injury crashes in before-during studies (*1,10,11*), or by comparing work zone accidents to statewide accidents outside of work zones (*7*). The higher severity in one study (*11*) was due to a 300 percent increase in fatalities (from 2 fatal accidents to 8). The most severe work zone crash type appeared to be multi-vehicle collisions involving a heavy vehicle (*17*).

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2.3.2 Crash Type and Location

The most common work zone crash type in six studies (*7,9,10,18,20,21*) was a rear-end collision, accounting for anywhere between 35 and 52 percent of all work zone crashes. One investigation (*11*) found that fixed object collisions were the most predominant type, and another (*12*) found run-off-road and fixed object collisions to be most common. Yet another (*8*) found the most common fatal collision type to be a single vehicle crash.

In a recent study (*9*), the predominant crash location was the work area, accounting for 70 percent of all work zone crashes. Although terminology is different, another team (*21*) found 39.1 percent of crashes to occur in the lane closure (perhaps equivalent to buffer area), 22.5 percent in the lane taper (transition area), and 16.6 percent in the construction area. Both of these studies also investigated crash type by location and are in pretty close agreement. One (*21*) found the most common location-type combination to be rear-end crashes in the lane closure, and the other (*9*) found it to be rear-end crashes in the activity area.

A higher proportion of crashes occurred during daylight, but in three of four before-during studies, night crashes increased more than day crashes (*1,10,11*). One team (*12*) found no difference in the percent increase of night and day accidents. Another team (*7*) compared statewide work zone accidents to accidents outside of work zones and found that similar percentages occurred during day and night hours. In an analysis of fatal accidents, a team (*8*) found that 42 percent occurred during night conditions.

The most common vehicle type involved in a work zone accident was a passenger car. However, in a comparison of work crashes to crashes outside work zones, a higher percentage of work zone crashes involved heavy vehicles than crashes outside work zones (*7*).

2.4 SUMMARY OF WORK ZONE RESEARCH

This section focused on safety effects of specific work zone design features as well as prevalent characteristics of work zone crashes. It presented the following findings:

- In most cases, work zones with crossovers appear to have slightly higher accident rates than work zones with lane closures. In addition, multi-vehicle accidents in which a truck is involved are much more severe in work zones with crossovers than work zones with other types of roadway configurations.
- It is inconclusive whether accident magnitudes and characteristics are different at entrance-ramp locations from what they are at other areas in the work zone. However, removing or significantly shortening the length of entrance-ramp acceleration lanes may be associated with significant increases in accident rates in some cases.

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- Work zones where lane widths are reduced from pre-work zone conditions experience a higher increase in accident rate than work zones with no lane width reductions.
- A wide, sometimes conflicting, range of results exists from work zone research investigating crash frequencies and characteristics. These large differences can be attributed to lack of control or data regarding possibly important explanatory variables (e.g., cross section, alignment, roadside).
- Many studies that have investigated crash frequencies and characteristics are plagued by a lack of exposure data. Therefore, it is difficult to draw meaningful conclusions about the actual safety consequences of work zones.
- In general, crash frequencies and crash rates appear to be, on the average, higher during work zone periods than before.
- Conclusions regarding the severity of crashes in work zones were mixed. Some studies found work zone crashes to be less severe than crashes outside work zones while others found work zone crashes to be more severe.
- The predominant crash type was a rear-end crash, and the predominant crash location was the activity area of the work zone.

Other information relevant to construction work zone design and traffic control exists in current national guidance publications such as the *MUTCD*, *Green Book*, and *Highway Capacity Manual*. A review of the information from these publications is provided in Chapter 3.

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CHAPTER **3**

CURRENT WORK ZONE DESIGN GUIDANCE

This chapter includes a review of current guidance related to construction work zone design. The reviewed references include the 2003 *MUTCD* (*4*), 2001 *Policy on Geometric Design of Highways and Streets* (*Green Book*) (*5*), 2002 *Roadside Design Guide* (*6*), 2000 *Highway Capacity Manual* (*27*), and the design guidance of state DOTs. (Because most readers will be familiar with the national manuals, reference notes will not be inserted at subsequent referrals to them in this report.) The DOT guidance was obtained through a search of Web-accessible guidance during the review of work zone research and through a survey of state DOTs conducted under this project.

3.1 NATIONAL GUIDANCE

Although nationally recognized design and analysis methods have been developed for many highway engineering disciplines (e.g., bridge, geometry, pavements), similar guidance for the design of work zones on high-speed highways does not exist. Several national publications provide useful guidance; however, a comprehensive process for the design and analysis of work zones has not been developed. The following review outlines the current guidance in these documents, as well as gaps in national guidance related to the design of construction work zones on high-speed highways.

3.1.1 Manual on Uniform Traffic Control Devices

The *MUTCD* is an authoritative publication with nationwide applicability. It provides information on traffic signals, signs, pavement markings and numerous other devices. Part 6 of the *MUTCD* focuses on temporary traffic control, and portions of it are directly applicable to stationary work zones on high-speed highways (e.g., lane reduction tapers). Part 6 also addresses a wide variety of topics that are not directly related to the scope of this research report, including mobile and short-term, stationary work zones. By definition, the *MUTCD* pertains to traffic control devices; therefore, Part 6 provides extensive guidance on the application of specific devices (e.g., drums, barricades and signs) to work zones. Its intended purpose is to "depict common applications of temporary traffic control devices" that "provide for the safe and efficient movement of vehicles, bicyclists, and pedestrians through or around temporary traffic control zones while reasonably protecting workers and equipment." Although traffic control devices are an important element, they are but a part of work zone design. As indicated by the following excerpt, Part 6 provides limited guidance in some aspects of work zone design:

> "The basic safety principles governing the design of permanent roadways should also govern the design of temporary traffic control zones. The goal should be to route road users through such zones using *roadway geometrics and roadside features* and temporary traffic control devices as *nearly as possible to normal highway situations"* (emphasis added).

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This passage, in effect, recommends that work zones be designed to approximate the geometric and roadside criteria applicable to permanent facilities. Although the *MUTCD* does not refer to a source for these criteria, the *Green Book* and *Roadside Design Guide* (reviewed below) are the logical references for information on normal roadway geometrics and roadside features. The *Green Book* is the pre-eminent guidance document for geometric design. It outlines fundamental design conventions and principles and provides horizontal and vertical alignment and cross section criteria for all facility types. *Green Book* criteria are generally applied to the permanent features of new construction and reconstruction projects. Given the temporary nature and physical constraints inherent in construction areas, using permanent roadway geometric criteria as a goal is unwarranted and impractical.

The *MUTCD* divides the typical temporary traffic control zone into four areas: the advance warning area, the transition area, the activity area, and the termination area. Many of the studies on work zone crashes have adopted these classifications. The advance warning area is the section of highway where road users are informed about the upcoming work zone. For stationary construction, it usually consists of a series of signs. The transition area is the section of highway where road users are directed out of their normal path to a new path. This usually involves the strategic use of tapers. The activity area is the section of the highway where the work activity takes place. It is comprised of the work space, the traffic space (i.e., the area of highway in which the road users are routed through the activity area), and the buffer space (the lateral or longitudinal area that separates road user flow from the work space or an unsafe area). Finally, the termination area is where the road users are returned to their normal path.

Other guidance given in Part 6 of the *MUTCD* that will have an effect on work zone design elements other than traffic control devices relates to:

- Reduced speed limits - “Reduced speed limits should be used only in the specific portion of the temporary traffic control zone where conditions or restrictive features are present. However, frequent changes in speed limit should be avoided. A temporary traffic control plan should be designed so that vehicles can safely travel through the temporary traffic control zone with a speed limit reduction of no more than 10 mph. . . . . Where restrictive features justify a speed reduction of more than 10 mph. . . the speed limit should be stepped down in advance of the location requiring the lowest speed. . . . Reduced speed zoning [lowering the regulatory speed limit] should be avoided as much as practical because drivers will reduce their speeds only if they clearly perceive a need to do so.”
- Tapers - The types of and criteria for tapers are given in Tables 6C-3 and 6C-4 of Part 6 of the *MUTCD* [see Figure 1]. Tapers are created by using a series of channelizing devices and/or pavement markings to move traffic out of or into the normal path. Tapers are used in the transition and termination areas.

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Table 6C-3. Taper Length Criteria for Temporary Traffic Control Zones

Type of Taper	Taper Length (L)*
Merging Taper	at least L
Shifting Taper	at least 0.5L
Shoulder Taper	at least 0.33L
One-Lane, Two-Way Traffic Taper	100 ft maximum
Downstream Taper	100 ft per lane

Table 6C-4. Formulas for Determining Taper Lengths

Speed Limit (S)	Taper Length (L) Feet
40 mph or less	$L = \frac{WS^2}{60}$
45 mph or more	$L = WS$

Where: L = taper length in feet

W = width of offset in feet

S = posted speed limit, or off-peak 85th-percentile speed prior to work starting, or the anticipated operating speed in mph

Figure 1. Tables 6C-3 and 6C-4 from the 2003 MUTCD.

- Traffic barriers - Traffic barriers should be used to protect workers. The barriers should be placed along the work space, depending on factors such as lateral clearance of workers from traffic, traffic speed, duration and type of operations, time of day, and volume of traffic. It is recommended that Chapter 9 of the *Roadside Design Guide* be used for barrier design and placement.

In summary, the *MUTCD* provides extensive information on the design and application of traffic control devices used in temporary traffic control zones, as well as typical traffic control zone set-ups based on duration, location, type of work, and highway type. The only information given that relates (directly or indirectly) to geometric design elements (i.e., cross section, horizontal alignment, etc.) deals with speed limit reduction and taper design. For the elements outside the scope of the *MUTCD,* it is recommended that the roadway geometrics and roadside features compare as nearly as possible to normal highway situations.

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3.1.2 A Policy on Geometric Design of Highways and Streets

The 2004 *Green Book* provides geometric design guidance for permanent roads. Work zones are addressed briefly in the *Green Book's* Chapter 3 under the section, Maintenance of Traffic through Construction Areas, and the guidance is limited to three pages. Where "traffic lanes are closed, shifted, or encroached upon in order that the construction be undertaken" the *Green Book* recommends that a traffic control plan should be developed to "minimize the effect on traffic operations by minimizing the frequency or duration of interference with normal traffic flow." It advises that "a well thought out and carefully developed plan for the movement of traffic through a work zone will contribute significantly to the safe and efficient movement of traffic as well as the safety of the construction forces." It also suggests that the traffic control plan have some built-in flexibility for unforeseen changes in work schedules, delays and traffic patterns.

The traffic control plan includes the layout of the construction area as well as the use and application of signs and other traffic control devices. The *Green Book* references the *MUTCD* for guidance in the selection of traffic control devices and stresses the importance of its use. The *Green Book* also gives the following very minimal guidance with respect to the roadway geometry through the construction area:

- The traffic control plan should use geometrics and traffic control devices as nearly comparable to those for normal operating situations as practical, while providing room for the contractor to work effectively;
- A clear zone should be provided between the work space and the passing traffic and under certain conditions, a positive barrier is justified;
- Adequate tapers should be provided for lane drops or where traffic is shifted laterally.

Other guidance relating to geometric issues, pavement, and traffic control include 1) increasing the capacity when using an existing road as a detour by eliminating troublesome turning movements and physically widening the travel way; 2) providing adequate delineation and warnings for geometric features and roadway environments on detours and temporary connections that require more guidance and alertness; 3) maintaining the surface of the traveled way so that it is in a condition to permit the safe movement of traffic at reasonable speeds; and 4) providing for all pedestrian flows. No dimensional guidance or quantitative methods are included.

3.1.3 Roadside Design Guide

The 2002 *Roadside Design Guide* devotes Chapter 9 to Traffic Barriers, Traffic Control Devices, and Other Safety Features for Work Zones. The chapter is intended to be used in conjunction with Part 6 of the *MUTCD* by adapting the criteria from *Roadside Design Guide* Chapters 1 through 8 and, where warranted, applying them to work zones. The chapter states, "The design and selection of work zone safety features should be based on expected operating speeds and proximity of vehicles to workers and pedestrians.

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Actual operating speeds may be considerably higher than posted speed limits and as much as 20 to 25 mph faster on freeways when temporary 40 mph zones are established."

The clear zone is a key element of roadside design for permanent roadways. Chapter 9 provides the following guidance on the application of the clear zone concept to work zones (paraphrased and quoted):

> The forgiving roadside concept should be applied to all work zones as appropriate for the type of work being done and to the extent that existing roadside conditions allow. This includes providing a clear recovery area for longer term projects and using traffic control devices and safety appurtenances that are crashworthy or shielded. The work zone clear zone is defined as "the unobstructed relatively flat area impacted by construction that extends outward from the edge of the traveled way." Because of the limited horizontal clearance and heightened awareness of drivers in work zones, the clear zone requirements are less, and "engineering judgment" must be used in applying the clear zone concept to work zones.
>
> Some designers determine clear zone widths on a project-by-project basis (based on speeds, geometrics, etc.) whereas others use a specified width. Where available, the widths of commonly used work zone clear zones are 12 to 18 feet, with collateral hazards such as equipment and stored materials calling for widths greater than 30 feet from the traveled way.
>
> The tabulated clear zone widths used by one (unspecified) state are provided as an example (reproduced from Chapter 9 as Figure 2).

TABLE 9.1 Example of clear zone widths for work zones

Speed [mph]	Widths [ft]
[60-70]	[30]
[55]	[23]
[45-50]	[16]
[30-40]	[13]

Figure 2. Table 9.1 of the 2002 Roadside Design Guide.

The Chapter 9 guidance on work zone clear zones appears to be a summary of current practice ("commonly used work zone clear zones are. . ."). The guidance also imparts flexibility and discretion in dealing with construction work zones ("to the extent that existing roadside conditions allow") ("where width is available").

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Other *Roadside Design Guide* Chapter 9 guidance addresses:

- Providing a safe environment for pedestrians, bicyclists, and highway workers - which may include providing safe pathways where pedestrians and bicyclists are allowed to traverse the work zone by shielding adjacent excavations or other unsafe areas;
- Use of temporary or permanent traffic barriers - to protect traffic from entering work areas such as excavations or material storage sites, provide positive protection for workers, separate two-way traffic, protect construction such as falsework for bridges and other exposed objects, and separate pedestrians from vehicular traffic.

Chapter 9 covers the physical properties (e.g., dimensions, weight, deflection, etc.) and mechanical installation (e.g., connections) of barriers. Some of the Chapter 9 barrier use guidance is quantitative, while other advice is primarily qualitative in nature. Examples are provided below (paraphrased):

- Use of temporary longitudinal barriers should be based on an engineering analysis;
- The portable, concrete, safety-shape barrier (PCB) is the option preferred by most state transportation agencies;
- No consensus on specific barrier warrants exists. Barriers are usually justified for bridge widening, shielding of roadside structures, roadway widening (especially with edge drop-offs), and separating two-lane, two-way traffic on one roadway of a normally divided facility;
- A minimum offset of 2 feet from the travel lane of a PCB is desirable;
- Benefit-cost analyses indicate that accident costs are minimized for flare rates of 4:1 to 8:1. A flare rate of 5:1 or 6:1 may be favorable for urban streets with higher volumes, lower speeds, and higher impact angles;
- In situations of restricted geometry (e.g., intersecting roadways near or within the work activity area) where expected impacts could be greater than 25 degrees, the designer should refer to *NCHRP Report 358, Traffic Barriers and Control Treatments for Restricted Work Zones;*
- Desirable end treatments and acceptable (for low speeds) end treatments are given in section 9.2.2;
- Adequate transitions should be made between temporary barriers of differing flexibility or between temporary and permanent barriers.

Several types of stationary and temporary crash cushions and their properties are identified in Chapter 9. Temporary crash cushions include truck mounted attenuators (TMAs). These TMAs may be used for moving operations or at long-term, stationary construction sites. Their suggested uses are given in Table 9.3 of the *Roadside Design Guide* (Figure 3). Quantitative guidelines for the recommended buffer distances and spacing of these vehicles are also given.

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The *Roadside Design Guide* Chapter 9 also contains information regarding the dimensions, crashworthiness, use and placement of traffic control devices for work zones. These include channelizing devices (e.g., cones and tubular markers, vertical panels, drums, barricades) and signs and supports. Traffic control devices should be designed and installed such that impact severity is minimized. In the *Roadside Design Guide*, work zone traffic control devices are grouped into four categories based on their crashworthiness (i.e., their relative safety when struck by a vehicle). These categories were first established in one of two FHWA memoranda on guidance for crash testing of work zone traffic control devices (*28*):

- Category I devices were those lightweight devices that could be self-certified by the vendor;
- Category II devices were other lightweight devices that needed individual crash testing;
- Category III devices were barriers and other fixed or massive devices also needing crash testing;
- Category IV devices were trailer-mounted lighted signs, arrow panels, etc.

The second memorandum listed devices that were acceptable under Categories I, II, and III (*29*). Some final guidance in *Roadside Design Guide* Chapter 9 addresses:

- Use of glare screens to reduce headlight glare and block the view of work zone activities that may distract the driver (here qualitative guidance is given on considerations when deciding whether to install glare screens);
- Avoiding large (greater than 2 inches) pavement edge drop-offs and providing mitigation depending on the extent of the drop-off.

In summary, the *Roadside Design Guide* contains significant information on the physical characteristics and crashworthiness of work zone traffic control devices and barriers. However, guidance is limited with respect to specific dimensions (i.e., clear zone width, slopes, horizontal clearance) and barrier placement guidance.

3.1.4 Highway Capacity Manual

The 2000 *Highway Capacity Manual* Chapter 22 contains guidance on how to investigate reduced capacity resulting from construction and maintenance freeway work zones. This guidance is important in that decisions about lane widths, the number of travel lanes, etc. that agencies will allow during construction are typically based on considerations of whether traffic volumes expected to use the work zone can be adequately accommodated through the work zone. The *Highway Capacity Manual* divides construction activities into short-term and long-term; however, its definitions differ from those used for this research. The *Highway Capacity Manual* suggests that the primary distinction between short-term and long-term work zones is the type of devices used to demarcate the work area, with long-term using portable concrete barriers and short-term using conventional channelizing devices (traffic cones, drums, etc.).

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Table 9.3 Suggested priorities for application of protective vehicles and truck mounted attenuators

		Ranking*			
			Non-Freeway		
Closure/Exposure Condition	Examples of Typical Construction Maintenance Activities	Freeway	50 mph	45 mph	40 mph
Mobile Activities:					
No Formal Lane Closure					
Shadow vehicle for operation involving exposed personnel	Crack pouring, patching, utility work, striping, coning	A-1	A-2	A-3	A-4
Shadow vehicle for operation not involving exposed personnel	Sweeping, chemical spraying	E-1	E-2	E-3	E-4
No Formal Shoulder Closure					
Shadow vehicle for operation involving exposed personnel	Pavement repair, pavement marking, delineator repair	B-2	B-3	C-3	C-3
Barrier vehicle for operation not involving exposed personnel	Open excavation, temporarily exposed bridge pier	E-2	E-3	E-4	E-5
Stationary Activities:					
Formal Lane Closure					
Barrier vehicle for operation involving exposed personnel	Pavement repair, pavement marking	B-2	B-3	C-4	D-5
Barrier vehicle for condition involving significant obstruction	Open excavation	E-2	E-3	E-4	E-5
Formal Shoulder Closure					
Barrier vehicle for operation involving exposed personnel	Pavement repair, pavement marking, guardrail repair	C-3	C-4	D-5	D-5
Barrier vehicle for condition involving significant obstruction	Open excavation	E-3	E-4	E-5	E-5

*The alphabetic ranking indicates the priority assigned to the use of a protective vehicle. The use of protective vehicles:

A – is very highly recommended
B – is highly recommended
C – is recommended
D – is desirable
E – may be justified on the basis of special conditions encountered on an individual project when an evaluation of the circumstances indicates that an impact with a protective vehicle is likely to result in less serious damage and injury than would impact with a working vehicle or the obstruction

*The numerical rank indicates the level of priority assigned to the used of a TMA on an assigned protective vehicle. The use of a TMA under the defined conditions:

1 – is very highly recommended
2 – is highly recommended
3 – is recommended
4 – is desirable
5 – may be justified on the basis of special conditions encountered on an individual project

Figure 3. Table 9.3 of the 2002 Roadside Design Guide.

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A methodology for calculating the capacity of short-term freeway work zones has been developed (*30*). The capacity is given by

$$c_a = (1600 + I - R) * f_{HV} * N \tag{1}$$

Where

$c_a =$ adjusted mainline capacity (vehicles per hour);
$1600 =$ the “base” capacity for short-term freeway work zones;
$I =$ adjustment factor for the intensity of work activity, referring to the numbers of workers on site, the number and size of work vehicles in use, and the proximity of the work to the travel lanes; the values for I range from -160 to +160 passenger cars per hour per lane (pc/hr/l) and “should be applied on the basis of personal judgment, recognizing that 1,600 pc/hr/l is an average over a variety of conditions”;
$R =$ adjustment factor for ramps resulting from the following *Highway Capacity Manual* narrative: entrance ramps should be located at least 1,500 feet upstream from the beginning of the full lane closure; if that cannot be done, then either the ramp volume should be added to the mainline volume, or the capacity of the work zone should be decreased by the ramp volume (up to half the capacity of one lane, assuming that at very high volumes mainline and ramp volumes will alternate);
$f_{HV} =$ the same heavy vehicle adjustment factor used elsewhere in the manual, here used to account for the effects of heavy vehicles in the work zone;
$N =$ number of lanes open through the short-term work zone.

$$f_{HV} = \frac{1}{1 + P_T\left(E_T - 1\right)} \tag{2}$$

Where

$P_T =$ proportion of heavy vehicles;
$E_T =$ passenger car equivalent for heavy vehicles.

For long-term construction work zones, the capacity values are based on research in (*31*) and shown in table 6.

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Table 6 Summary of capacity values for long-term construction zones (*32*)

Number of Normal Lanes	Lanes Open	Number of Studies	Range of Values (Vehicle/Hr/Lane)	Average Values (Vehicle/Hr/Lane)
3	2	7	1,780-2,060	1,860
2	1	3	—	1,550

The *Highway Capacity Manual* also gives the following research-based (*30,31*) guidance: “If traffic crosses over to lanes that are normally used by the opposite direction of travel, the capacity is close to the 1,550 vehicles/hour/lane value. . . . If no crossover is needed, but only a merge down to a single lane, the value is typically higher and may average about 1,750 vehicles/hour/lane.”

Finally, based on another research study (*32*), capacity reductions as a result of reductions of lane width in freeway work zones are given. “For traffic with passenger cars only, headways increase by about 10 percent in going from 11-foot widths to 10.5- or 10-foot widths and by an additional 6 percent in going to 9-foot widths.” These translate into 9 and 14 percent drops in capacity, respectively.

3.1.5 Summary

In summary, the *MUTCD, Green Book*, and *Roadside Design Guide*, which are frequently referenced by highway engineers, provide guidance on work zones but leave substantial voids related to geometrics, relationships among geometrics and appropriate traffic control, roadside design, and special features used exclusively or primarily in construction work zones. The underlying principles across all three documents are, for work zone elements that fall outside the realm of their guidance: “(use) the basic safety principles governing the design of permanent roadways. . .” and “route road users through such zones using roadway geometrics, roadside features and TTC (temporary traffic control) devices as nearly as possible comparable to those for normal highway situations” (from *MUTCD*). This advice, although perhaps desirable, is limited and impractical. In addition, guidance presented in the *Highway Capacity Manual* on determining capacity reductions as a result of construction or maintenance freeway work zones is quite limited.

FHWA recognized the benefits of greater standardization when it established the National Highway Work Zone Safety Program by stating, “Having appropriate national and state standards and guidelines would contribute to improved safety” (*35*). With national guidelines as a base, individual DOTs can adopt or adapt them to meet the unique needs and conditions of their jurisdictions.

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3.2 STATE TRANSPORTATION AGENCY GUIDANCE AND PRACTICE

The primary objective of this research is to develop a comprehensive design-decision methodology that, when properly applied, will result in the safe and efficient movement of traffic through construction work zones on high-speed highways. Therefore, a review of current work zone design guidance from state transportation agencies was conducted.

A significant amount of information was identified and reviewed regarding how state DOTs design work zones. As with other information sources on this topic, state DOT publications on work zones usually address the full array of categories (e.g., low-speed/high-speed, short-term/intermediate-term/long-term, mobile/stationary), not just construction work zones on high-speed highways. Information included in this summary was obtained from two sources:

- State DOT survey conducted during the research - States were asked to respond to specific questions and to provide their policy and guidance publications. In many cases the applicable state documents were Web-based, in which case the states provided URLs. Thirty-two states returned survey questionnaires. After the responses were reviewed, ten states were contacted for clarification and supplemental information. This generally resulted in useful information being included in the summary. In a few cases, the original response was not useful. In those instances where the DOT response did not yield reasonable or relevant interpretation, the original response was not reported. For example, one DOT’s responses consistently referred to their practice for “non construction” work zones. The research team received no response to follow-up requests for information regarding construction work zones and therefore the information will not be included in the review.
- Review of state DOT Web-accessible information - Every state DOT has a Web site. To varying degrees, these sites provide access to policies, criteria, and procedures. A search of these sites was conducted. Much of the material retrieved through the Web search duplicated that obtained through the survey. However, additional useful information was also found. Mostly, this consisted of information from the Web sites of state DOTs that did not return a completed questionnaire. In several cases, the information provided by a completed questionnaire was augmented by a search of the responding agency’s Web site.

Work zone design processes have been developed and documented to a fairly extensive degree within state DOTs. Of the 32 states responding to the survey questionnaire, 25 (78 percent) indicated having a publication that provides policy or guidance on the design of work zones and traffic control plans. However, in some cases the documents or publications were not made available.

The breadth and depth of guidance varies widely among states. In some cases, temporary traffic control is the primary or exclusive area of guidance, while other states

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address traffic management strategies, geometric design, drainage, roadside safety and traffic barriers, and interchange auxiliary lanes, in addition to traffic control. The construction work zone design information of some states is distributed among traffic control and design guidance and standard drawings. Several state DOTs have a document that is similar in scope to the Part 6 of the *MUTCD*. In some cases, topic-specific memoranda or reports were provided as the source of guidance. Three states submitted draft and interim guidance documents on a specific topic (e.g., use of temporary barriers). In narrative responses, several states also indicated an intention to revisit or revise a particular aspect of their current practice.

Overall, the collected information enabled development of a fairly comprehensive summary of state DOT construction work zone design practice for high-speed highways. While there are differences in the manner construction work zones and permanent roads are designed, there are also many process similarities. The ensuing paragraphs summarize what was learned about state DOT work zone design practices on a variety of topics.

3.2.1 Work Zone Design Strategies and Assessment

Several state DOTs have guidance on conceptual work zone design. The information from DOTs in California, Connecticut, and Indiana was found to be the most comprehensive. Information from the latter two is very similar, and information from all three shares common elements. These three DOTs also provide guidance related to development of traffic operations plans (e.g., supplemental transit, corridor capacity strategies), which is very useful but is separate from a traffic control plan and therefore not reported here. To varying degrees, DOTs with less comprehensive guidance publications also address some of the topics covered below. The following work zone types are identified and characterized in the guidance documents reviewed:

- Alternating one-way operation (one-lane, two-way operation);
- Crossover;
- Detour;
- Diversion (runaround);
- Lane constriction;
- Lane closure;
- Intermittent closure;
- Use of shoulder or median.

These work zone types are presented as options, or the menu from which a selection(s) is made.

3.2.1.1 Capacity Considerations

The capacity through construction work zones is typically less than prior to the project. No information was found in state DOT publications on methods to quantitatively determine the effect of construction work zones on capacity. However, Illinois DOT provides qualitative guidance on options to mitigate capacity reductions associated with construction work zones (e.g., temporary parking restrictions, contra-flow lanes). Several

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computer software packages have the capability to assess work zone traffic operations but no references to these tools were found in the DOT work zone design guides.

3.2.1.2 Construction Contract Options

Illinois DOT's work zone design guidance identifies several common construction strategies (e.g., reconstruction by halves, serial/segmental reconstruction) and phasing options. The advantages and disadvantages of each are discussed. Additionally, A+B bidding (also known as A+Bx) and incentive/disincentive contract options are identified and discussed.

3.2.1.3 Strategy/Type Selection

Several DOTs provide the same or a similar chart for use in identifying feasible work zone types for various facility characteristics (e.g., number of lanes, traffic) and construction activity. The chart from Connecticut DOT's guidance is included as Figure 4.

3.2.2 Principles of Design

Maintaining traffic through a construction work zone often requires providing a road on a location different from the permanent road for which it substitutes. This necessitates a series of design decisions similar to those associated with permanent roads. The temporary nature of work zones is a defining characteristic and one that distinguishes them from permanent roads. The attribute of limited service life is implicit to many decisions and explicitly reflected in several state DOT publications. The temporary nature of work zone roads and some roadside features are identified as a consideration in establishing criteria and as guidance for decision processes. Consequently, several state DOTs do not apply the same design criteria to a work zone road or roadside as are applied to permanent facilities. These variations are found in various design criteria and decision processes of state DOTs.

3.2.2.1 Speed

Speed and its relationship to design decisions is a complex subject for permanent roads. The relationships among design speed, regulatory speed, and operating speed are not consistent. An ongoing research project (NCHRP Project 15-25) was initiated to study these issues and evaluate alternatives to the design speed approach used for permanent roads. The situation for work zones can be further complicated when it is desirable to reduce speed at the work zone in relation to that of the approaching road and pre-project conditions. Further, there is a perception that lower speeds within work zones will improve safety, and considerable effort is often expended to induce speed reductions.

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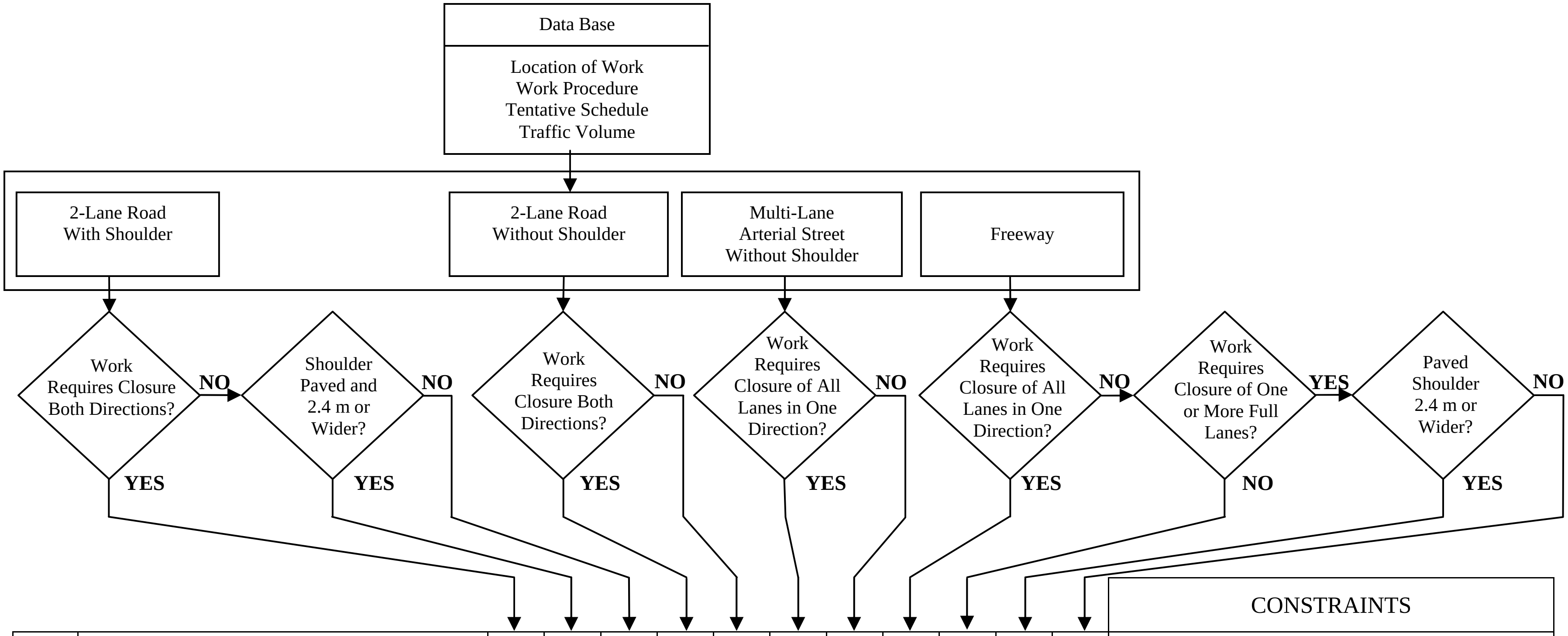

													CONSTRAINTS
Alternate Work Zone Types	LANE CONSTRICTION (Use part of the shoulder if		✓	✓						✓			Restripe lane lines; keep lanes 3.0 m or wider. For freeways and other divided highways, the minimum lane width is 3.3
	LANE CLOSURE							✓		✓	✓	✓	
	ONE-LANE, TWO-WAY OPERATION					✓							
	TEMPORARY ROADWAY	✓		✓					✓				Sufficient right-of-way
	INTERMITTENT CLOSURE	✓			✓				✓				Off-peak hours
	USE OF SHOULDER/MEDIAN (As a full lane)		✓								✓		May need to upgrade shoulder
	CROSSOVER						✓		✓				
	TWO-WAY TRAFFIC ON DIVIDED FACILITIES						✓		✓				
	DETOUR TO EXISTING ROAD	✓		✓	✓		✓	✓	✓		✓	✓	Reasonable detour route(s) available. Maintain local

✓ Feasible

CHART FOR IDENTIFICATION OF FEASIBLE WORK ZONE TYPES

1 meter (m) = 3.28 feet.

Figure 4. Sample work zone type feasibility chart (Connecticut DOT)

Unlike the design of permanent roads, for which a single speed parameter (i.e., design speed) is used for nearly all speed-dependent design decisions, an assortment of speed parameters is used in work zone design decisions. Numerous temporary traffic control decisions covered by *MUTCD* Part 6 (e.g., taper lengths, device spacing) are based on speed. In defining the “speed” term used in formulae, the *MUTCD* refers to “posted speed limit, or off-peak 85th percentile speed prior to work starting, or the anticipated operating speed.” This choice of speed values is applicable to the determination of sight distance. In the AASHTO design process, stopping sight distance and decision sight distance are computed using the design speed.

Hence, the always complex topic of speed is further complicated in work zones. With this background, the survey sought to determine if the design speed approach was being applied to work zones and, if so, on what basis design speeds were selected.

Establishing a design speed or another speed measure for construction work zones is a common but not universal practice among state DOTs. The survey indicated that 21 of the 32 DOTs responding to this question (66 percent) “often” establish a design speed or similar parameter for design of construction work zones. Another eight states (25 percent) “sometimes” establish a design speed or similar parameter for work zone design. Two responding states (6 percent) indicated they “never” establish a design speed for construction work zones. One state DOT did not respond to this question.

A review of survey responses indicates that different states use a variety of speed parameters for construction work zone design. Various state respondents indicated that posted/regulatory speed, operating/prevailing/85th percentile speed, or the design speed of the highway being reconstructed was used as the starting point to set work zone design speeds. In some cases, reductions from this base value were determined appropriate. Hence there appears to be no single speed parameter that is consistently applied to the design of construction work zones. Given the variety of speed parameters that may be applied to a single *MUTCD* formula, it is not unexpected that states use a variety of speed measures in their guidance. Despite this, there does appear to be a widely shared goal with regard to speed accommodation in construction work zones. Nearly all responding states indicated a preference to provide work zone features that accommodate the same or similar speeds (i.e., the base value) as the affected road and to avoid design features necessitating speed reductions. Most states indicated that it is not always practical to accommodate the approach roadway or pre-project speed through work zones. In these cases, respondents indicated that reductions should be minimized. Ten state responses identified the goal of not reducing work zone speeds by more than 10 mph. Several of the same states indicated exceptions (i.e., larger reductions) to this criterion were sometimes needed. One state’s design manual indicates that work zone design speeds should not be less than 15 mph below the approaching road design speed. The *MUTCD* guidance on speed through work zones states “[a] Temporary Traffic Control (TTC) plan should be designed so that vehicles can reasonably safely travel through the TTC zone with a speed limit reduction of no more than 10 mph.” The state DOT survey responses are in close alignment with this guidance.

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The specific laws and procedures under which state DOTs establish (i.e., reduce) regulatory speed limits in work zones vary. The procedures used to determine if a reduction is appropriate vary as well. North Dakota DOT has developed a flow chart based on seven types of work activity and a series of factors (e.g., worker presence, lane width reduction) to determine if a speed reduction is appropriate. Indiana DOT has a complex set of guidelines. The guidance provides a table of suggested "Work Zone Special Limit (official action)" and "Work Site Speed Limit (Indiana statutes)" values for freeways based on facility type and pre-project speed limit. The work zone speed limit is determined based on the construction zone design speed, traffic volumes, construction work type, geometrics, project length, etc. The work zone speed limit should not exceed the construction zone design speed through the construction area. Indiana statutes permit the DOT to establish work site speed limits without an "official action." The work site speed limit is the lesser of 45 mph or 10 mph below the original posted speed.

North Carolina DOT did not respond to the survey. However, its *Roadway Design Manual* is available on the Web and indicates that the design speed of horizontal and vertical curves for crossovers and diversions on interstates and freeways should be equal or greater than the posted speed limit. Design speeds for median crossovers on expressways and major arterials with partial or no control of access may be lowered to 10 mph below the posted speed limit. Detour design speeds for facilities (arterials other than those indicated, collectors, local roads) should not be more than 10 mph below the posted speed of the existing roadway.

Several states also commented that the work zone design speed was most pertinent to diversions and crossovers. South Dakota DOT has standard details for median crossovers that allow 45-mph, 55-mph, or 65-mph traffic to be maintained. The design manual indicates speed of traffic is usually reduced through and sometimes between the crossovers.

Under the current *Green Book* design procedure, the selected design speed has a direct and indirect influence on numerous design features. (See the research at [*37*].) Criteria for sight distances, horizontal curvature, superelevation, vertical curves and clear zone width are directly related to the selected design speed.

3.2.2.2 Sight Distance

The survey sought information on the stopping sight distance (SSD) criteria state DOTs apply to the design of construction work zones. States are divided on providing guidance for stopping sight distance in construction work zones. In response to the question, "Does your agency have stopping sight distance criteria for construction work zones?", 14 states responded "no," 16 states indicated "yes," 1 indicated "yes/no," and 1 did not respond. For those that do, there is substantial consistency in the approach, which is to select a speed parameter and use that as the basis for determining stopping sight distance in the same manner used for permanent roads. In most cases, this involves selecting the speed parameter (discussed previously) and applying Exhibit 3-1 from the

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Green Book or *MUTCD* Table 6C-2, Stopping Sight Distance as a Function of Speed. Some state DOTs have not adopted the approach and values associated with the *Green Book*. This may reflect a deliberate decision not to change or the lag associated with revising guidance. For example, Virginia DOT uses the conventions (eye, driver height, range) and values associated with the pre-2001 AASHTO SSD policy, except that posted speed is used in lieu of design speed.

Although, information specifically on SSD was solicited, several states provided additional information related to sight distance. Two states indicated the desirability of providing adequate visibility in advance of work zones, particularly tapers. One state commented, “The beginning of tapers should not be hidden behind curves.” New Jersey DOT traffic control details provide a table of Recommended Sight Distances to Beginning of Channeling Tapers for various regulatory speeds and settings (i.e., urban and rural). The values correspond to the decision sight distance values in the pre-2001 *Green Book*. The minimum and desirable *Green Book* values correspond to the New Jersey DOT urban and rural values.

3.2.2.3 Superelevation

States were asked if they had guidance regarding superelevation of horizontal curves through construction work zones. Fifteen of the 32 states (47 percent) responded in the affirmative. Additionally, 4 of the 13 state DOTs that answered “no” provided insightful comments on their practice. Collectively, these responses indicate a variety of approaches to superelevation design and horizontal curve design for construction work zones on high-speed highways. These different techniques are grouped in the following summary.

The most common reported practice is to use the same superelevation design practice for construction work zones as is used for permanent roads, based either on the *Green Book* or state DOT design manual. This requires further elaboration since the superelevation design practices for permanent roads vary among states. For high-speed facilities, the *Green Book* recommends that superelevation be distributed in accordance with Method 5. While this is the dominant practice among states for permanent roads, it is not universal. California DOT (Caltrans) uses a different superelevation design approach; the design values rely more heavily on friction than AASHTO Method 5. Responses such as “use AASHTO guidelines” and “follow AASHTO *Green Book*” were considered to mean the use of Method 5. In summary, the responses of seven states were interpreted to indicate that superelevation on horizontal curves for construction work zone roads is determined in the same way as it is for reconstruction and construction of permanent roads.

Eight states were identified that use an approach different from the one they use to determine superelevation rates for new or reconstructed, permanent, high-speed roads. Three states explicitly indicated the use of AASHTO Method 2. Florida DOT has developed a table of minimum radii for a range of design speeds and normal crown. The radii values are based on limiting values of friction found in the *Green Book*. If a radius

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less than the tabulated value is provided, the curve is superelevated. Montana DOT uses a similar method. The DOTs for Illinois and Indiana use Method 2 distribution for construction work zone roads. Colorado DOT also uses Method 2 distribution but with a different set of friction values. Two states were identified that use radii sufficiently large so as not to require superelevation. The minimum work zone road radius used by Mississippi DOT is one that can be provided without superelevation. Method 2 superelevation distribution is used to determine curvature-speed-superelevation relationships. Connecticut DOT uses the same approach. North Carolina DOT does not provide superelevation commensurate with the speed parameter and permanent road criteria. The North Carolina DOT *Roadway Design Manual* indicates that superelevation of interstate highway and freeway median crossovers cannot meet design speed standards due to existing restraints and it is more desirable to have lower superelevation rates that smoothly transition vehicles through the alignment than higher rates that have short lengths of change and that may create abrupt vehicle behavior. The South Dakota standard median crossover includes reverse curves with slope/superelevation of 2 percent (i.e., reverse crown).

3.2.3 Alignment

Some work zone types rely exclusively on existing roads and do not involve the design of horizontal and vertical alignments. Other work zone types, such as diversions and median crossovers, involve temporary roadways that must be designed. The guidance obtained relates primarily to these work zone types.

3.2.3.1 Vertical Alignment

Information from 17 state DOTs was obtained on some aspect of vertical alignment design for construction work zones. Five of the responses indicated that permanent road design criteria, using either AASHTO or their state design manual, were applied to work zones. Several state DOTs (e.g., Connecticut, Indiana) use 3R maximum grade criteria for work zones. North Carolina DOT has tabulated maximum grade value for detours based on speed. The two speed categories classified as high speed (46 to 55 mph and more than 55 mph) have maximums of 8 percent and 7 percent, respectively. Illinois and Indiana indicated that sag vertical curves are designed to meet the comfort criterion. One state indicated that vertical curves are designed to provide stopping sight distance based on the adopted design speed. The Vermont Agency of Transportation indicated that it attempts to provide vertical curves that correspond to the speed parameter’s criteria; but if this is not practical, it provides warning signs indicating the safe speed. Many state DOT work zone design publications do not address this topic directly.

3.2.3.2 Horizontal Alignment

Horizontal alignment and, specifically, radius of curvature are closely associated with superelevation design. In several cases, the guidance and criteria for horizontal curvature are directly related to cross slope considerations (i.e., normal crown and

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superelevation). Connecticut and Mississippi use the same general approach of limiting horizontal curvature to radii that may be normally crowned, including the provision of “negative” superelevation. Both states compute the minimum curvature that can be normally crowned using state-developed 3R criteria which, in both cases, involve Method 2 distribution. Florida and Montana DOTs use the same approach (but different from Connecticut and Mississippi). They tabulate values for the minimum radii for a specific design speed that may be normally crowned, based on Method 2 superelevation distribution. Radii may be less than those corresponding to normal crown, in which case superelevation is required. Three state DOTs have established maximum degrees of curvature for crossovers. Okalahoma and Oregon have established the maximum degree of curvature for median crossovers as 2 degrees, 30 minutes, and 2 degrees, respectively. Mississippi DOT uses a maximum of 1 degree, 30 minutes, for mainline crossovers on tangent sections. The South Dakota DOT standard median crossover uses 4-degree curves.

3.2.4 Roadway Cross Section Elements

Construction work zones are often confined spaces. High speeds increase the potential for high-severity crashes as the separation between traffic and construction operations is compressed. Because of these conditions and the temporary nature of construction work zones, many states apply roadway cross section criteria to the design of construction work zone roadways that are different from what they apply to permanent roads.

3.2.4.1 Travel Lane Width

The *Green Book* states, “Lane width of a roadway greatly influences the safety and comfort of driving.” Previous research conclusions (*37,38*) have established relationships between lane width and safety for two-lane rural roadways. Lane width determination is a decision that, implicitly or explicitly, must be made for virtually every construction work zone. Although lane width is often discussed as an isolated design feature, it should be considered in its complete context. The review found that state DOTs often consider a series of factors (e.g., number of lanes, single- or bi-directional travel, existence of a barrier) in determining appropriate width(s) for a particular application (e.g., crossover, detour, existing roadway). To form an accurate understanding of DOT practices, without posing excessively complex queries in the survey, two questions were prepared to garner information about travel lane and traveled way widths. In some cases, the responses to these two questions might appear incongruous. However, the context of the questionnaire was considered. One question invited numerical responses for a range of specific conditions. The other elicited narrative on how difficult and exceptional cases were addressed. The results reported below are an interpretation of the collective responses to the two questions.

Guidance on numerical values for work zone travel lane width was obtained from 22 state DOTs, either from survey responses or guidance materials. As was stated in several responses and implied in nearly all others, DOTs prefer that construction work

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zone travel lane widths meet the permanent road criteria for the affected facility. Several cases identified 12 feet as the desirable lane width. With varying degrees of stated reluctance, 14 states indicated using lanes as narrow as 10 feet under some circumstances. The following information elaborates on the responses from several of the 14 states that use 10-foot lanes under some conditions.

Arizona DOT permits 10-foot lanes only "without lateral constraint"; the minimum with lateral constraint is 11 feet. Colorado DOT permits a 10-foot lane when the truck average daily traffic (ADT) is less than 50, the design speed is 45 mph or less, and there are no curves greater than 7 degrees (all criteria must be met). Colorado DOT also identifies specific criteria requiring a 12-foot lane. Florida DOT permits 10-foot lanes only on non-freeways; freeways require 11-foot lanes, and interstate highway lanes must be a minimum of 11 feet and at least one 12-foot lane per direction. Indiana DOT uses 10-foot lanes only on undivided highways; divided highways should be 11 feet; multi-way and multi-lane roadway widths should be 12 feet, and temporary crossovers should be 16.5 feet. Maryland State Highway Agency (SHA) generally uses an 11-foot minimum lane width for high-speed highways but may use as little as 10 feet. Nevada DOT has used 10-foot lanes for short distances and short durations without defining explicitly these distances and durations. Virginia has used 10-foot lane widths infrequently.

Mississippi reported using lane widths as narrow as 10.5 feet. Alabama and Connecticut indicate 11 feet as their minimum lane width. Vermont uses 12-foot lanes for truck routes and narrower lanes on local roads, selectively. Most other states, in their responses or guidance, indicated hierarchies of preference (e.g., desirable, 12-foot; preferred minimum, 11-foot; absolute minimum, 10-foot); others make decisions based on specific project conditions. Some state DOTs have guidance that is dependent on the type of facility (e.g., existing road, temporary detour). The South Dakota standard median crossover provides for a 12-foot driving lane.

3.2.4.2 Traveled Way Surface Type

The information indicated that travel lanes through construction work zones are nearly always paved. However, five state DOTs indicated using unpaved traveled ways to some extent. Connecticut DOT stated that unpaved travel surfaces are allowed only on non-limited-access facilities with ADT less than 15,000. Area type, truck traffic and operating speeds are also decision factors. These surfaces are used for a maximum of five days. Montana DOT has guidance on the type of surface to be provided on detour roads constructed specifically for the project. The guidance is reproduced here as Figure 5. Wisconsin DOT uses unpaved driving surfaces in construction work zones on low-volume roads when the duration of use is limited to several days. Texas DOT uses unpaved traveled way surfaces but did not elaborate on decision factors and limiting conditions. North Carolina DOT's Web-accessible guidance indicated that temporary detours carrying an ADT of less than 750 should have unpaved surfaces and may be unpaved up to an ADT of 2,000.

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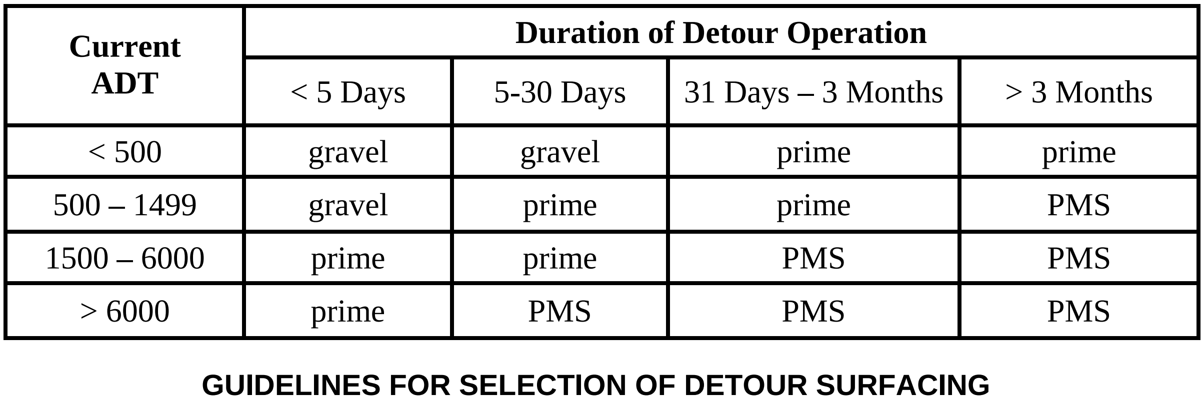
Missouri DOT uses structurally designed pavements for most work zone driving surfaces. However, for temporary bypasses that will be in place for only one season, a pavement consisting of a bituminous base mix material placed directly on the subgrade is used.



Current ADT	Duration of Detour Operation			
	< 5 Days	5-30 Days	31 Days – 3 Months	> 3 Months
< 500	gravel	gravel	prime	prime
500 – 1499	gravel	prime	prime	PMS
1500 – 6000	prime	prime	PMS	PMS
> 6000	prime	PMS	PMS	PMS

GUIDELINES FOR SELECTION OF DETOUR SURFACING

Figure 5. Montana guidance on surface type for detour roads constructed for project.

3.2.4.3 Shoulder Width

Eleven state DOTs reported having guidance related to construction work zone shoulder width. Six respondents indicated that their agencies do not have guidance, and numerous others did not respond to this question, probably because no agency guidance on the subject exists. Additionally, guidance from two non-responding state DOTs (North Carolina, South Dakota) was found on the respective DOT Web sites. Shoulder width was highly dependent on the type of facility (e.g., existing roadway of divided highway; two-lane, two-way road; temporary road). The responses are summarized in Table 7.

3.2.4.4 Shoulder Surface Type

Most state DOTs responding to the survey either indicated that their guidance did not address work zone shoulder type or did not respond to question. Mississippi DOT indicated construction work zone road shoulders are “usually gravel.” It is reasonable to conclude that when non-paved driving surfaces are provided (as indicated by five responding DOTs), shoulders are constructed of the same material. North Carolina provides minimum shoulder widths of 4 feet, 2 feet of which are paved.

3.2.4.5 Barrier Offset

It is not uncommon for a barrier system to be placed adjacent to construction work zone roadways. The “shy distance” is the limit of where a roadside object will be perceived as an obstacle by the typical driver to the extent the driver will change the vehicle’s placement or speed. It is measured from the edge of the traveled way. The *Green Book* recommends that a 2-foot offset be provided where a roadside barrier, wall or other vertical element adjoins shoulders. As reported in section 3.1.3, the *Roadside Design Guide* Chapter 9 also recommends a 2-foot offset to portable concrete barrier. In

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construction work zones, shoulders may be narrow or non-existent. Some state DOTs address barrier offsets in their construction work zone design practices. For certain types of lane closures on divided multi-lane highways, Arizona DOT's minimum travel lane width is 10 feet if unconstrained and 11 feet if constrained. The DOTs of Alabama, Missouri and Nevada strive to offset barriers 2 feet from the traveled way. Virginia DOT reported that barriers are normally placed from 0.5 to 1 foot from the traveled way edgelines.

Table 7 Summary of construction work zone shoulder width guidance

State DOT	Shoulder Width (ft)				
	Divided Highway		Undivided Highway	Unspecified	
	Right	Left			
Alabama				4	
Arkansas				2	
California	10	5			
Connecticut	2	2	1		
Illinois	2	2	1		
Indiana	2	2	1	[a]	
Iowa				3[b]	
Mississippi				DHV	Minimum
				< 200	3[c]
				> 200	5[c]
North Carolina	4[d]	4[d]	4[d]	DHV	Desired
				< 100	4[e]
				100-400	6[e]
				> 400	8[e]
Oregon				2	
Virginia	10		<10		
South Dakota	4[f]				
Wisconsin	2 – 3	2 - 3	5[g]		
West Virginia				10	

DHV = design hour volume.

[a] runarounds: 6 feet, left and right; one-lane temporary crossovers: 5 feet, left and right; multi-way and multi-way operations: 5 feet, left and right.

[b] information in table is for detours and based on review of Web-accessible design manual; survey response indicated no guidance on subject.

[c] applies to two-lane, two-way diversions and detours.

[d] minimum for crossover and detours associated with all functional classes.

[e] graded width for detours carrying local roads, collectors and minor arterials.

[f] applies to median crossovers.

[g] applies to left and right shoulders of single-lane crossovers.

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3.2.4.6 Shoulder Rollover

The algebraic difference between the slopes of a traveled way and adjoining shoulder can affect vehicle operations. For permanent roads, the *Green Book* recommends that this “rollover” (also know as “breakover”) be limited to 8 percent. The crown between adjoining cross slopes can be limited by rounding between the opposing-direction slopes. The survey sought information on state DOT practices regarding maximum rollover values in construction work zones. The majority of survey respondents either did not respond or stated they have no guidance on the subject; 13 states did provide a response. Colorado DOT indicated it was practice to extend the superelevation across shoulders, thereby eliminating the rollover. West Virginia DOT uses its “standard” rollover. Vermont stated that construction shoulders are too narrow to be a concern. Five state DOTs reported using AASHTO guidelines, presumably an 8 percent maximum. Oregon DOT uses a 4 percent maximum rollover. Two states reported using a 5 percent maximum. New Hampshire DOT uses a maximum of 6 percent, while Alabama and Mississippi indicated a 7 percent maximum. Arkansas was the only respondent specifically citing a maximum value of 8 percent.

3.2.5 Roadside and Barrier Placement

Adoption of the roadside safety principles and the implementing procedures outlined in the *Roadside Design Guide* has significantly enhanced highway safety. The concepts of forgiving roadside, clear zone, prioritized treatment of hazards, and crashworthiness are applicable to work zones as well as permanent roads. There are also very significant differences between permanent roads and construction work zones. First, more people (i.e., workers) are proximate to high-speed facilities while the facilities are under construction/reconstruction. Roadside design of permanent roads does not address protection of people from vehicular traffic. Additionally, roadside hazards in the form of construction equipment and work site features (e.g., slopes, drop-offs, unshielded structures) are subject to frequent change. Consequently, construction work zones involve some unique roadside design considerations, which are recognized in a chapter of the *Roadside Design Guide* devoted to work zones. State DOT policy and guidance documents and survey responses generally reflect this expanded range of factors.

The order of preference in the *Roadside Design Guide* for addressing roadside obstacles (i.e., removal, redesign) is based on safety efficacy and does not address practicality or cost-effectiveness, both of which must be considered. Hence, several conventions and terms that are applied to roadside design for permanent roads, such as clear zone distances and barrier warrants, may be interpreted differently for permanent roads and work zones. The unique context of construction work zones and its influence on design decisions is generally recognized by state DOTs. Several states have established very specific guidance, and others rely on more general advice and principles. The review of state DOT documents on this subject produced conclusions that are consistent with those reported in the *Roadside Design Guide* and summarized in section 3.1 of this chapter. The summary of state DOT practice is outlined in three categories.

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3.2.5.1 Clear Zone

Caltrans uses the same roadside guidance for work zones and permanent roads. This guidance addresses, but does not explicitly define clear zone distances. A clear recovery area 20 feet wide "on conventional highways is advised." Designers are further advised to consider a variety of site-specific factors in determining the clear zone distance. Work zones are not specifically mentioned. Colorado DOT establishes detour clear zone distance on the basis of speed, geometry and traffic. Connecticut DOT determines clear zone width by applying the design speed adopted for the work zone to its clear zone guidance for permanent roads. The guidance relies on the set of variables presented in the *Roadside Design Guide* Table 3-1. Virginia DOT determines work zone clear zone distance on the basis of speed. Illinois DOT identifies specific features (e.g., drop-offs) that require consideration of positive protection; its guide to determine clear zone distance is included as Figure 6. The processes for determining clear zone distance of the state DOT of Illinois is based on speed, traffic, and slope.

3.2.5.2 Barrier Placement Guidance

Two general conditions were identified for which barriers are routinely placed. One is part of the roadside design strategy to shield errant vehicles from roadside hazards (i.e., fixed objects, critical slopes and drop-offs) and people, particularly construction workers. The other general category of barrier use is to separate vehicle paths.

The *Roadside Design Guide* defines "warrants" as "the criteria by which the need for a safety treatment or improvement can be determined." This term will be avoided here only because some people may infer a rigid relationship between a condition and barrier placement. Instead a summary will be presented of guidance used by state DOTs as to where longitudinal barriers or other shielding devices should be provided. Some DOTs have guidance that is very specific, but most have more general information. No state DOT has guidance that addresses every situation; varying degrees of judgment are necessary to implement all the guidance documents reviewed. The most deterministic policies are those based on definitive clear zone distances, identification of hazards, and declarative guidance for treatment of hazards within the clear zones. For example, the section of the North Carolina DOT *Design Manual* addressing the use of detours and crossovers for maintenance and protection of traffic states, "The clear zone and recovery area should be maintained in accordance with the *Roadside Design Guide* or protected by guardrail or concrete median barrier." This is the most deterministic guidance found.

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Approach posted speed limit	ADT	Front slopes			Back slopes		
		1:6 or flatter	1:5 to 1:4	1:3	1:3	1:5 to 1:4	1:6 or flatter
		Work zone clear zone distances (ft)					
35 mph or less	Under 750	4-6	4-6	**	4-6	4-6	4-6
	750-1500	6-8	8-10		6-8	6-8	6-8
	1500-6000	6-8	10		8-10	8-10	8-10
	Over 6000	10	10-12		10	10	10
35-50 mph	Under 750	6-8	6-10		4-6	4-6	6-8
	750-1500	10	10-14		6-8	8-10	10
	1500-6000	10-12	12-16		8-10	10	10-12
	Over 6000	12-14	16-18		10	12	12-14
55 mph	Under 750	6-8	10-12		6	6-8	6-8
	750-1500	10-12	12-16		6-8	10	10-12
	1500-6000	12-14	16-18		10	10-12	12-14
	Over 6000	14-16	16-20*		10-12	12-14	14-16
60 mph	Under 750	10-12	12-16		6-8	8-10	10
	750-1500	12-16	16-20*		8-10	10-12	12-14
	1500-6000	16-18	20-24*		10-12	12-14	16
	Over 6000	18-20*	22-28*		12-14	16	16-18
65 mph	Under 750	12	12-16		6-8	10	10
	750-1500	16	18-22*		8-10	12	12-14
	1500-6000	18-20*	22-26*		10-12	14-16	16-18
	Over 6000	18-22*	24-28*		14-16	16-18	18

* Clear zones may be limited to 18 feet for practicality.
** Use guidance for permanent roadways.

Notes:

- All distances measured from edge of traveled way.
- For clear zones, the ADT will be the total ADT on two-way roadways and the directional ADT on one-way roadways. Traffic volumes will be expected traffic volumes through the work zone.
- The values for back slopes apply only to a section where the toe of the back slope is adjacent to the shoulder. For roadside ditches, use permanent roadway guidance.
- Approach posted speed is approach posted speed prior to the work zone.

CLEAR ZONE DISTANCES (ft)

(Construction Projects)

Figure 6. Excerpt from Illinois DOT design guidance.

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Colorado DOT provides barriers when any hazards exist within the clear zone of a detour. Under Connecticut DOT design guidance, if the recommended clear zone cannot be achieved, the safest treatment should be provided consistent with cost-effectiveness and geometric considerations. The traffic barrier placement guidance of Indiana and Montana DOTs are similar. Both DOTs have a procedure for establishing clear zones. They also indicate that due to the limited time exposure, it may not always be cost effective to meet the permanent installation criteria. Both DOTs also indicate that the designer must use considerable judgment when applying the clear zone distances, due to the hazardous conditions that typically exist in construction zones. Indiana DOT identifies 9 location types where the provision of positive protection should be considered and 13 factors that should be considered in the placement decision. Virginia DOT uses a process to address hazards within the clear zone that considers the hazard type (i.e., fixed object, slope), speed and exposure (length and duration).

Florida DOT guidance indicates that barriers serve four specific functions: 1) protect traffic from entering work areas, such as excavations or material storage sites; 2) provide positive protection for workers; 3) separate two-way traffic; and 4) protect construction such as falsework for bridges and other exposed objects. However, specific placement guidance is not provided. Designers are charged with anticipating “when and where barriers will be needed.” The Missouri DOT’s draft guidance calls for barrier placement in conjunction with bridge rail replacement and full-depth deck repair activities. Oregon DOT identifies other specific conditions for which barrier placement should be considered if the conditions will be exposed to traffic for more than five days.

A number of state DOTs have general guidance that either augments more specific guidance or stands alone. Some DOTs indicated, without further elaboration, that barrier placement decisions are determined on a case-by-case basis. Other DOTs identified factors (e.g., speed, volumes, duration of exposure, distance from traveled way) that should be considered in decisions. Although several state DOTs, such as Florida DOT, identified worker safety as a consideration in barrier placement decisions, no specific guidance on this subject was found.

The practice of installing barriers to separate two-way traffic on a single roadway of a normally divided highway was found to be widespread. For some responding state DOTs (e.g., Michigan, New York), this was the only reported situation for which barrier placement was routinely provided.

3.2.5.3 *Traffic Barriers*

Information on traffic barrier types and installation details is available in the design guidance, construction details, and standard drawings of many states. Temporary (portable) concrete barrier is the dominant type, for which there are many dimensional and structural variations. When DOT publications referred to “positive” separation, it was interpreted to mean rigid concrete barrier. Other longitudinal roadside systems, such as the semi-rigid W-beam, are also used but far less frequently. Many details of taper ratios,

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anchorage systems, and end treatments are available and were reviewed. The *Roadside Design Guide* Chapter 9 and other resources provide detailed information on crashworthiness requirements and the performance of individual systems. Therefore, these details are not considered appropriate for this report, and a summary is omitted here.

A number of state DOTs are actively developing or revising their roadside design policies and guidance. Illinois DOT indicated that it is developing a policy to determine where temporary concrete barriers should be placed. As described earlier, Missouri DOT has developed draft guidance that identifies recurring conditions for which barriers should be provided. Virginia DOT has a roadside design policy specifically for work zones. The policy is being revisited. Wisconsin DOT is presently using interim guidance and information from research reports for roadside design and traffic barrier placement decisions.

3.2.6 Ancillary Design Information

3.2.6.1 Drainage

There are several basic purposes of highway drainage, including the rapid evacuation of moisture from the driving surface, prevention of pavement structure saturation and maintenance of the hydrologic systems traversed by the roadway. Drainage design for construction work zones has similar purposes, although draining the subsurface of temporary pavements is not emphasized. Erosion and sediment control, bank protection, and storm water management are important design considerations for construction work zones. However, these issues are generally regarded as part of project permitting and environmental management. The requirements and guidance vary substantially by jurisdiction. As such, no information was sought on these subjects.

Less information on drainage practices was elicited through the survey than other topics; 9 of the 32 responding DOTs (28 percent) indicated having guidance on design practice for construction work zone drainage. However, the responses and guidance publications provide information on significant points associated with this topic.

Maintaining a well-drained driving surface during and after construction is an important consideration for any project. Many of the same factors associated with designing a drainage system for a permanent road are considered. However, the abbreviated service life of the roadway has direct implications for the specific criteria applied to drainage structures. State DOT guidance was found on the following topics:

Drainage of temporary roads. For projects that include detours, crossovers and other supplemental driving surface, drainage schemes and structures are usually required. The preponderance of survey responses provided information on the design criteria for temporary roads and attendant drainage works. A basic decision in designing a hydraulic structure is the selection of a design frequency or recurrence interval. This selection is based on cost and risk considerations, and design frequencies for various types of

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structures are generally included in state DOT drainage manuals. Major structures (e.g., bridges and culverts associated with arterial highways) are designed for infrequent events (i.e., 25 to 100 years). When the capacity of these structures is exceeded, significant disruption and losses result. Therefore, it is cost-effective to design these structures for events that are exceeded very rarely. On the other hand, less important crossings and roads (e.g., median drain of a collector) are designed with the recognition that the hydraulic capacity will be exceeded with greater frequency but less dire consequences. The results of the survey indicate a mix of practices regarding the selection of design frequencies for temporary drainage structures. Several states indicated using the same criteria as permanent facilities; several others indicated using two-year frequencies. The AASHTO *Model Drainage Manual* (*39)* suggests that drainage systems for detours and temporary roads be designed for a two-year frequency, if the roadway is required for a year or less, and a five-year frequency, if it is required for more than a year.

The differing practices of state DOTs may not be a matter of great practical significance. Often, DOTs establish minimum diameter pipes and culverts based on other-than-hydraulic considerations (e.g., debris, maintenance). The design of many structures is controlled by minimum size rather than hydraulic capacity.

Extension and continuation of existing drainage systems. The Florida DOT publication, *Temporary Drainage Design Handbook,* was the only state DOT guidance found that addresses temporary base drains, extending culverts, and exercising care to avoid drainage diversions.

Construction staging considerations. When maintaining traffic on existing driving surfaces and reconstructing facilities in place, the goals of drainage design may be achieved through thoughtful sequencing and near replication of the existing drainage structures. While no unique hydrologic or fluid mechanics techniques are needed, careful review and application of drainage principles can avoid the accumulation of water on a driving surface. Florida DOT has published guidance to address several potentially problematic situations. Guidance is provided on milling pavements to prevent runoff from the closed/milled lane onto the traffic lane. If not properly sloped, turnouts can result in ponding adjacent to the travel lane. Sandbags used as temporary curbing and temporary inlets for positive drainage are suggested remedies. An equation and implementing guidance are also provided for computing spread (the lateral limit of flowing water) adjacent to temporary concrete barriers. These can be used to assess travel lane encroachment, and, if excessive, provide additional relief.

3.2.6.2 Turnouts

Turnouts or pull-offs are refuge areas within construction work zones that have narrow or non-existent shoulders. Information on agency practices regarding provision, spacing and configuration of these refuge areas was solicited through a survey question. Eleven of the 32 responding DOTs (34 percent) indicated their agencies “never” provide turnouts in construction work zones. Thirteen state DOTs (41 percent) “sometimes” use turnouts, and six others (19 percent) do so “often.” One state DOT reported

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"often/sometimes" use. One state did not answer this question. In terms of design guidance, most of the 20 DOTs that provide turnouts with some frequency (often or sometimes) did not indicate specific criteria (e.g., traffic volumes, facility types) where turnouts are provided. There were numerous references to case-by-case determinations. Maryland generally provides turnouts when a shoulder is closed for a half mile or longer. Oregon DOT uses the passing and climbing lanes that are part of their sometimes long and winding permanent roads to provide turnouts. Pennsylvania and Vermont space pull-offs at approximately half-mile intervals. Wisconsin DOT uses a spacing of half to three quarters of a mile. The length of Wisconsin DOT pull-offs is approximately 150 feet plus tapers. Virginia DOT provides turnouts infrequently and primarily on high-trafficked interstate projects. It is investigating expanded use of these features and development of a policy. New York DOT provides pull-offs on the median side of facilities carrying two-lane, two-way traffic on a single roadway of a normally divided highway; typical spacing is 1 mile.

3.2.6.3 Visual Barriers

The use of devices to improve visibility and focus within construction work zones is common. Glare screens are longitudinal systems intended to prevent or reduce the adverse effect of headlights on opposite-direction-driver vision. There are several types of designs, including vertically extended concrete traffic barriers and manufactured products that are installed on top of temporary precast concrete barriers. A separate type of visual screen is sometimes used to inhibit driver visibility of work zones, and thereby reduce potentially detrimental distraction from the driving task. These installations are sometimes referred to as "gawk screens." Responses to the survey indicate that 5 of 31 states responding to this question (17 percent) use visual barriers "often"; 20 states (60 percent) reported using them "sometimes," and six responding DOTs (23 percent) indicated "never" using visual barriers.

Most of the narrative comments referred to considerations associated with glare screens. Several states indicated that glare screens are used most frequently at locations susceptible to unusual headlight glare (e.g., horizontal and vertical curves, crossovers). Another common application is between opposing-direction traffic lanes, often when two-way traffic is on a single roadway of a normally divided highway. Pennsylvania DOT uses temporary concrete barrier with a height of 52 inches, except at locations where a barrier of less height is used to improve stopping sight distance. Nevada DOT decides on use/non-use based on location, traffic volumes, etc. It has found that temporary screens are effective in some cases and a problem in others.

Two responding DOTs addressed the use of barriers that inhibit driver visibility of the construction area. Maryland installs these systems if construction activity is expected to result in significant distraction of road users, especially on high-speed roadways. Oregon attaches plywood atop temporary concrete barriers "to keep drivers focused on the road ahead and not on the roadside construction." Guidance on when this system is installed was not provided.

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3.2.6.4 Interchange Speed Change Lanes

Construction work zones that encompass interchanges involve considerations and decisions beyond those associated only with segments. Interchanges are locations of potential conflicting movement and place high demands on driver performance. In addition to directional and/or lane changes, significant speed changes and speed variance occur within interchange areas. Acceleration and deceleration lanes facilitate the transition from crossroads to the mainline and vice versa. A design objective is to minimize the speed disparity between mainline and entering/exiting traffic streams. However, providing speed change lanes in work zones is often difficult. The survey sought information on state DOT practices regarding the design of temporary interchange arrangements on three specific features: acceleration lane length, deceleration lane length, and yield verses stop control, including signing practices.

The responses required some interpretation, since several made general references to use of the *Green Book, MUTCD* and standard drawings. A reference to the *Green Book* was considered to mean that the respondent applied the acceleration and deceleration lane length criteria found in Chapter 10 (i.e., Exhibits 10-70 and 10-73). The *MUTCD* Part 6 provides typical applications that illustrate general configurations and traffic control devices. Some of these address work zones that include and involve ramps and speed change lanes and associated signing. The *MUTCD* illustrates entrance and exit configurations but does not provide acceleration and deceleration lane lengths. With this background, four state DOTs indicated using the *Green Book* and/or *MUTCD* to determine speed change lane length and signing. In general, only a few state DOT publications (e.g., policy, drawings, written guidance) were identified that address speed change lane geometry within construction work zones. The *MUTCD* and several state DOT manuals provide information on traffic control policy and practice.

Arkansas DOT reported that it does not provide acceleration lanes to maintain traffic. Caltrans referred to its standard drawings, which illustrate options for closing exit and entrance ramps and temporary provision. Figure 7 illustrates two examples; the lengths of acceleration and deceleration lanes are not provided. Connecticut DOT attempts to provide acceleration lane lengths that meet the permanent highway criteria for the work zone design speed. Maryland traffic control details include a figure to determine acceleration lane length on the basis on mainline design speed and ramp speed, with adjustments for ramp grades over 2 percent. Michigan DOT’s informal guidance is to provide a minimum length of 300 feet. New Jersey DOT’s guidance is to provide the same length acceleration lane as existed without the work zone. Oregon DOT strives to provide 70 percent of the length that would apply to a permanent facility/condition. Virginia DOT attempts to provide the pre-project acceleration lane length.

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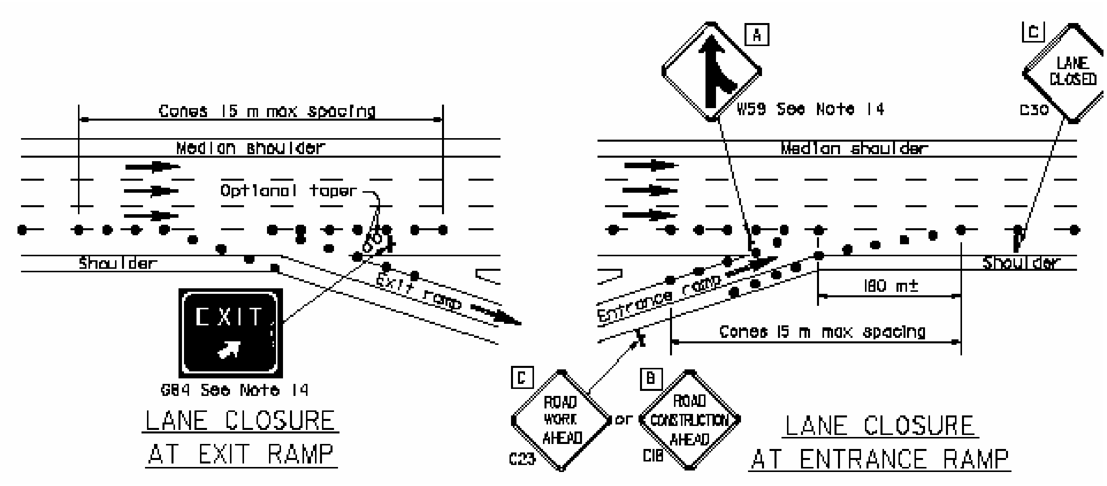

Figure 7. Examples of temporary interchange access points (Caltrans).

Some DOTs relate the use of YIELD and STOP signs at interchange entrance ramps to acceleration lane length. Alabama DOT installs YIELD signs on acceleration lanes that do not meet the minimum criteria; STOP signs are provided when there is no acceleration lane. Arkansas provides a YIELD or STOP sign when the acceleration lane length is less than the *Green Book* value. Indiana DOT employs additional traffic control devices on acceleration lanes if the length is less than indicated by its guidance. Maryland SHA uses a Yield Sign Warrant Checklist. If the acceleration lane length is less than the value criteria (described in previous paragraph), a YIELD sign is provided. New Jersey DOT installs YIELD signs in conjunction with acceleration lanes. If no acceleration lane is provided, the decision to place either a YIELD or STOP sign is made on a case-by-case basis. Wisconsin DOT does not install YIELD signs at locations where the mainline has more than one lane open to traffic and the taper is as long as that of the pre-project condition. West Virginia DOT's *Traffic Control Manual* provides conditions for the use of YIELD and STOP signs for entering normally divided highways under different work zone conditions. Examples of both entry and signing conditions associated with yield and stop control are included as Figures 8 and 9. The *MUTCD* Part 6 includes a set of typical applications (TA-40 to TA-44) illustrating signing and other traffic control associated with temporary interchange ramp connection arrangements.

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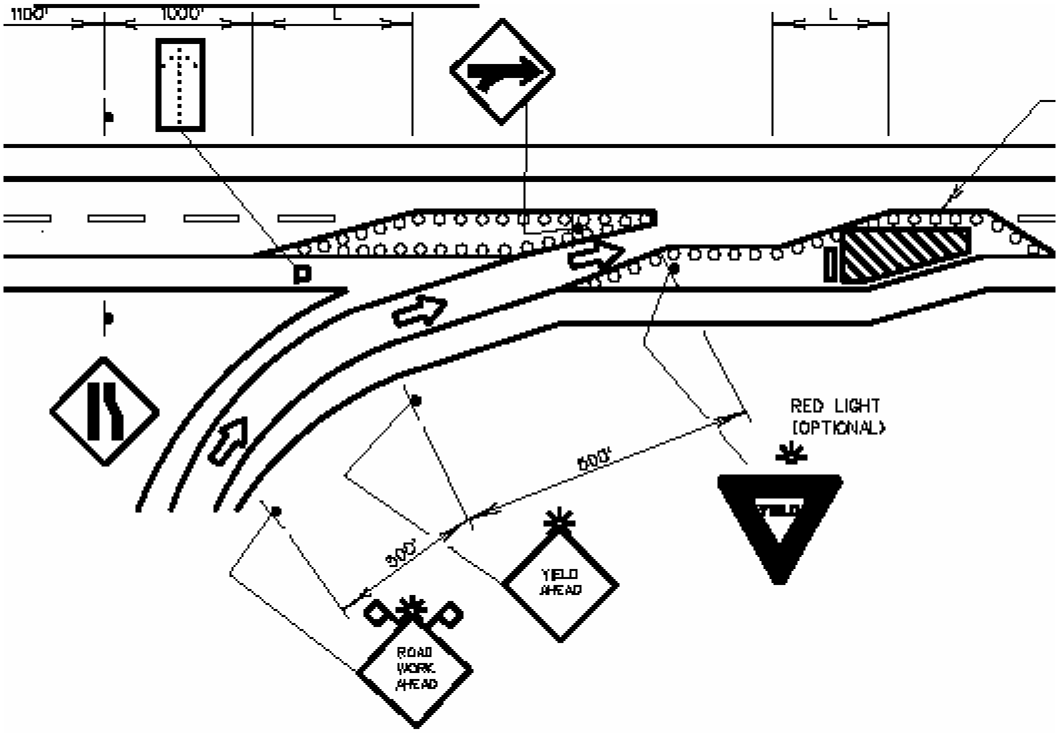

Figure 8. Example of entrance ramp with YIELD sign (*West Virginia DOT*).

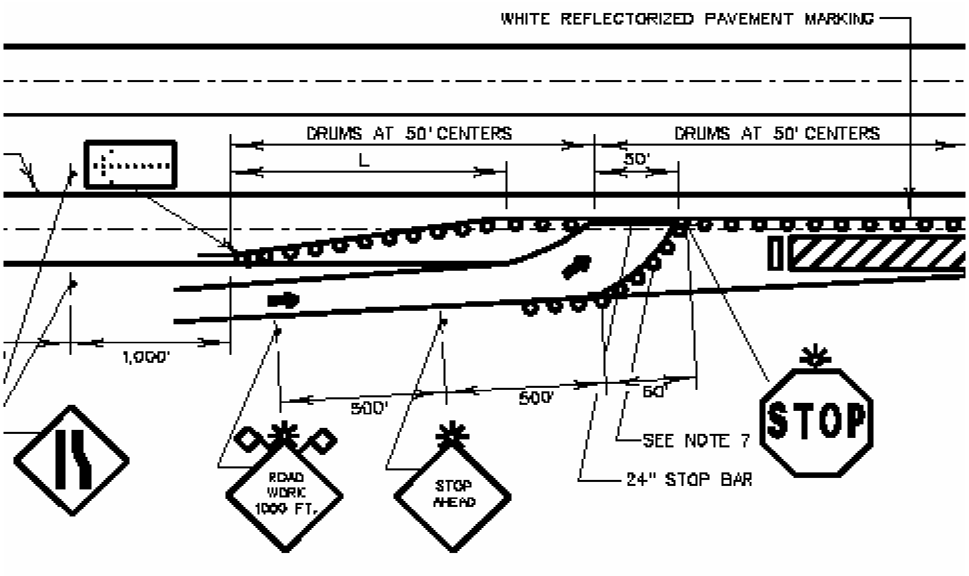

Figure 9. Example of entrance ramp with STOP sign (*West Virginia DOT*).

The New Jersey DOT traffic control details indicate a combined length of 500 feet for the taper and deceleration lane on divided highway interchanges. Wisconsin DOT

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uses 200-foot exit tapers and 200-foot deceleration lane lengths when necessary within construction work zones.

3.2.6.5 Large Vehicle Accommodation

Most state DOTs responding to the survey consider oversize vehicles in designing construction work zones on high-speed highways, with 23 (72 percent) responding “yes” to this question and 9 (28 percent) indicating “no.” Most of the efforts associated with oversize vehicle accommodation are related to intra-agency coordination. Numerous DOTs reported having procedures in place to coordinate between affected organizational units (e.g., construction, design and permits). In some cases, DOTs will refrain from issuing permits for oversize vehicles to traverse a particular route segment if the available clear width is at or below some value. States have different threshold width values (e.g., 14.5, 15, 16 feet) for permit issuance restrictions. The Wisconsin DOT procedure is unique and summarized here. Permits for oversize vehicles are not route specific. Vehicles wider than 8.5 feet require permits; the maximum vehicle width permitted is 14 feet. The design function of the DOT attempts to provide a minimum travel width of 15 feet to accommodate all vehicles. If the 15-foot width is not provided, advance warning signs are posted prior to the last interchange exit before the start of the width restriction, and they direct vehicles to exit.

Six respondents indicated that signs were placed to indicate restricted road conditions and alternate routing. One respondent (Alabama DOT) provides wider pavements for abnormal volumes of oversize vehicles.

3.2.6.6 Review of Contractor Traffic Control Plans

There is a very high degree of consistency in the general approach of state DOTs to consideration of contractor-developed traffic control plans. The DOTs of Illinois and Iowa are exceptions to the general pattern; they do not permit contractors to submit alternative traffic control plans. All other responding states do. The dominant model is that a DOT-developed traffic control plan is included in the contract drawings. The contractor may submit an alternative plan, which may only be implemented following its approval by the DOT. Oregon DOT has a unique contracting requirement. The contractor for every project must submit a traffic control plan, even if it is a letter indicating the intention to implement the DOT plan. The procedures for reviewing alternative, contractor-developed traffic control plans vary among states in terms of submission time frame and internal DOT review/approval roles. Two states (Alabama and Indiana) indicated that the cost of the contractor’s alternative plan is limited to that of the original plan. The Michigan and New York State DOTs review contractor traffic control plans as value engineering proposals.

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CHAPTER 4

METHODOLOGY AND FINDINGS

4.1 DEVELOPMENT OF ROADSIDE DESIGN AND TEMPORARY BARRIER PLACEMENT GUIDANCE FOR CONSTRUCTION WORK ZONES

Task 3 of NCHRP Project 3-69 called for “a survey of the states to collect guidance related to construction work zones and traffic control.” At the time that the survey was created, it appeared that previous research and the associated literature would not provide direction as to which design features are high risk factors in work zones and should be prioritized for selected research during phase II of the project. This indeed was the case (see Chapter 2 of this report). Therefore, an additional objective of the survey became: determine priority topics associated with the design of construction work zones using state DOT input.

Of the 32 states that responded to the survey, 24 ranked having or improving guidance on *traffic barriers and roadside design* as “most important/critical.” This was the highest ranking topic of those included in the survey or added by DOT responses. Therefore, a specific study to address this issue was proposed in the first interim report, and the NCHRP project panel approved the study for execution during phase II of this project. This section documents the methodology and results of that effort. In addition, the results are also incorporated into Chapter 5 of the design guidance (Appendix A), Roadside Design and Barrier Placement.

4.1.1 Research Methodology

Information for completion of this study and development of guidance would come from four sources:

- Roadside principles and practices for permanent roadways;
- Completed and ongoing research related to roadside safety in construction work zones;
- State DOT roadside design guidance for construction work zones;
- Incremental benefit-cost analysis of work zone scenarios.

Each of these sources and their pertinence to this study are reviewed below. Section 4.1.6, Integration and Fusion to Develop Roadside Design Guidance, discusses the background and source of all relevant information used to develop practical guidance for roadside design and placement of temporary traffic barriers for construction work zones on high-speed highways.

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4.1.2 Roadside Principles and Practices for Permanent Roadways

Adoption of the roadside safety principles and the implementing procedures outlined in the *Roadside Design Guide* has significantly enhanced highway safety. The forgiving roadside concept, clear zone, prioritized treatment of hazards, and crashworthiness are applicable to work zones as well as permanent roads. The forgiving roadside concept is based on the premise that “Regardless of the reason for a vehicle leaving the roadway, a roadside environment free of fixed objects with stable, flattened slopes enhances the opportunity for reducing crash severity.”

An integral part of the forgiving roadside concept was the establishment of a clear zone, a traversable and unobstructed roadside area. When this concept was introduced in the AASHTO Yellow Book (*40*) in 1974, the dimension of the desired clear zone, 30 feet, was based on studies that indicated that 80 percent of the vehicles leaving the roadway could recover within this distance. Because of the perceived impracticality and sometimes inadequacy of this dimension for variable volumes and speeds and for different roadside slopes, variable desired clear zones were introduced in 1977 by AASHTO’s *Guide for Selecting, Locating and Designing Traffic Barriers* (*41*). Variable clear zones, based on design speed, volume, and roadside slopes, with adjustments based on the horizontal alignment, can still be found in the 2002 edition of the *Roadside Design Guide*.

Where objects are located in the roadside, and especially within the desired clear zone, a series of alternative actions should be considered to reduce the risk to errant vehicles. The order of preference for addressing roadside obstacles follows:

1. Remove the obstacle;
2. Redesign the obstacle so it can be safely traversed;
3. Relocate the obstacle to a point where it is less likely to be struck;
4. Reduce impact severity by using an appropriate breakaway device;
5. Shield the obstacle with a longitudinal barrier designed for redirection, or use a crash cushion;
6. Delineate the obstacle if the above alternatives are not appropriate.

Alternatives 4 and 5 introduce the concept of crashworthiness. Where conditions require the presence of an obstacle or barrier near the traveled way, it should be designed to perform appropriately (i.e., minimize probable motorist harm) if struck. Signs, signals, luminaire supports, and utility poles should be breakaway devices. Guidance for these objects is contained in AASHTO’s *Standard Specifications for Structural Supports for Highway Signs, Luminaires, and Traffic Signals (42), A Policy on the Accommodation of Utilities within Highway Right-of-Way (43),* and *A Policy on the Accommodation of Utilities within Freeway Right-of-Way (44)*. Roadside barriers are deemed crashworthy by passing the crash test criteria of *NCHRP Report 350,* “Recommended Procedures for Safety Performance Evaluation of Highway Features” (*45*).

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The clear zone concept has been widely accepted because of its perceived simplicity. In general, the idea has been to observe the clear zone of a roadway segment. If there are objects that present a potential safety hazard to a motorist when struck, analyze and treat the hazard with one of the prioritized treatments. However, the current edition of the *Roadside Design Guide* gives the following instruction:

> *A basic understanding of the clear zone concept is critical to its proper application. The numbers obtained…imply a degree of accuracy that does not exist… In some cases, it is reasonable to leave a fixed object within the clear zone; in other instances, an object beyond the clear zone distance may require removal or shielding.*

Similar discussion complements the above instruction:

> *…to include every recommendation or design value in this chapter (Chapter 3) on every future highway project is neither feasible nor possible. Engineering judgment will have to play a part in determining the extent to which improvements can reasonably be made with the limited resources available.*

These excerpts indicate that application of the clear zone approach often involves subjective roadside safety decisions. The use of incremental benefit-cost analysis to roadside conditions is one means of reducing the level of subjective judgment.

4.1.2.1 Benefit-Cost Analysis for Permanent Roadways

Benefit-cost analysis is "a method by which the estimated benefits to be derived from a specific course of action are compared to the costs of implementing that action (*6*)." The benefits usually refer to reduced crash or societal costs as a result of decreases in the number and/or severity of crashes. The costs of implementing the action are the direct costs to the highway agency for initial installation, maintenance, and repair costs. If the ratio of benefits to costs (equation 3) exceeds 1, then the benefits derived will be equal to the investment over the analysis period. The benefit-cost ratio can be used to compare several different actions against each other and against the no action alternative.

$$\text{B/C Ratio}_{\text{j-i}} = \frac{CC_i - CC_j}{DC_j - DC_i} \qquad (3)$$

Where

$\text{B/C Ratio}_{\text{j-i}}$ = Incremental benefit-cost ratio of alternative j to alternative i;
CC_i, CC_j = Crash or societal costs resulting from crashes under alternatives i and j (annualized over the analysis period);
DC_i, DC_j = Direct costs for alternatives 1 and 2 (annualized over the analysis period).

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A benefit-cost ratio greater than 1 does not alone justify the implementation of a particular alternative. However, observing the ratios provides designers or other decision makers with quantitative information to help in making the best investment for safety and mobility needs.

To perform a benefit-cost analysis based on safety, several tools need to be available for the analyst:

- Method to predict crash frequencies under all proposed alternatives.
- Method to predict crash severities under all proposed alternatives.
- Crash cost estimates by severity;
- Repair cost estimates;
- Installation and maintenance costs for specified safety treatments;
- Discount rate over the analysis period.

Expected crash frequencies are difficult to predict because of the infrequency and randomness of the event. Different methods to do so include (1) crash prediction models, which are usually regression models used to predict crashes given the roadway geometry, segment length, and traffic, (2) historical data on the roadway of interest or similar roadways, and (3) simulation. The last is the most common method for predicting roadside crashes. The simulations are usually based on an encroachment model that predicts the frequency of encroachments as well as the encroachment speed, angle, and lateral extent of the encroachment. Knowing these variables as well as the layout of the roadside, it can be predicted whether or not a crash would occur. The weaknesses of these simulations are that the results are only as good as the underlying encroachment models, the state of which has not been advanced much since the 1970s.

Crash severities can also be predicted in several ways. As in predicting frequencies, these include (1) logistic regression, used to predict crash severity given a series of predictor variables including roadway geometry, (2) historical data on the roadway of interest or similar roadways, and (3) simulation. As with predicting frequencies, the accuracy of simulating crash severities is dependent on the reliability of the underlying algorithms. These algorithms are sometimes based on historical data of crashes with different objects for a range of impact conditions. However, data of this detail for a range of objects are not widely available, and experience and judgment are sometimes used.

Crash costs for varying crash severity levels are calculated by estimating the results of a motor vehicle crash and the effects of a specified injury on the involved persons' entire lives. The most useful measure of crash cost is a comprehensive cost, which includes 11 different cost components: property damage; lost earnings; lost household production; medical costs; emergency services; travel delay; vocational rehabilitation; workplace costs; administrative, legal, and pain costs; and lost quality of life. Estimates of crash costs are usually published by several public and private organizations, all using different bases and assumptions. Therefore, a range of cost estimates exist.

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Repair costs consider the cost of repair of a safety treatment or other roadside object that has functional value after a crash has occurred with that object. Repair costs can be estimated from historical data, full scale crash testing, or simulation. For example, crash testing and simulation can be used to determine the length of damage to a guardrail or other safety treatment given a certain vehicle size and impact speed. The repair cost would then be the product of the length (or other unit) of the damaged safety treatment and the unit cost for repair.

Installation and maintenance costs can usually be determined by a state DOT through historical records. For example, some states publish this type of price information based on contractors' bid prices for standard bid items.

Finally, discount rates are interest rates used to determine the current value of costs that will be incurred over the entire period of a benefit-cost analysis. It is the current value of the benefits and costs that are used in equation 3. Discount rates can be determined by observing the interest rate charged to commercial banks and other depository institutions on loans they receive from their regional Federal Reserve Bank's lending facility.

Observational before-after studies are a more controlled type of study to determine the benefits of a safety treatment; however, the treatment must be applied and several years of before-and-after data accumulated before the benefit is determined. The planned *Highway Safety Manual* will include procedures to help state DOTs determine the benefits of safety countermeasures using these types of procedures. After years of implementation, historical data as a result of these analyses will exist to assist DOTs in predicting the benefits of future countermeasure applications. For a variety of reasons, conducting observational before-after studies to determine the effects of different safety treatments is often not viable. Therefore, the techniques used as part of benefit-cost analysis discussed above (e.g., crash frequency/severity prediction) will need to be continually updated and refined as data become available.

The adaptation and application of the benefit-cost analysis procedures discussed above to construction work zones is discussed in Section 4.1.5.

4.1.2.2 Use of Roadside and Median Barriers for Permanent Roadways

A roadside barrier "is a longitudinal barrier used to shield motorists from natural or man-made obstacles located on either side of a traveled way. It may also be used to protect bystanders, pedestrians, and bicyclists from vehicular traffic under special conditions (*6*)." Similarly, median barriers are longitudinal barriers used to separate opposing traffic on a divided highway. In either case, the purpose of a longitudinal barrier is to contain or redirect a vehicle that leaves the roadway and strikes it, with less severe consequences than if the barrier had not been there. Both roadside and median barriers must meet the performance criteria set forth in *NCHRP Report 350,* "Recommended Procedures for the Safety Performance Evaluation of Highway Features."

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Roadside and median barriers should only be installed where crashes with the barrier are likely to be less severe than crashes without the barrier. In addition, the roadside hazard being shielded should be exposed to a significant level of traffic over the performance period to justify the cost of providing and maintaining the barrier. Subjective analysis or benefit-cost procedures are the two methods discussed in the *Roadside Design Guide* for making these determinations.

Roadside barriers are used to shield errant vehicles from two basic categories of roadside conditions: embankments and roadside obstacles. Embankment height and side slope are the basic factors considered in determining potential harm to errant vehicles. *Roadside Design Guide* Figure 5.1 was developed based on the relative severity of encroachments on embankments versus impacts with roadside barriers. Figure 5.1 does not take into account the probability of an encroachment or the cost of leaving the slope unshielded versus the cost of barrier installation, maintenance, and repair. Therefore, from a benefit-cost standpoint, the figure most likely overestimates the need for barrier for lower-volume roads. Figures 5.2 and 5.3 of the *Roadside Design Guide* are modifications of the criteria in Figure 5.1 that do consider these additional factors. The charts are not included for application, but states are encouraged to develop similar criteria based on their own evaluations. An example is shown in Figure 10 below.

Median barriers are used to separate opposing traffic on divided highways, through traffic from local traffic, or high occupancy vehicle (HOV) lanes from general purpose lanes. Median barriers are similar to roadside barriers except that they are designed to redirect vehicles striking either side of the barrier. Figure 6.1 of the *Roadside Design Guide* (Figure 11 below) provides suggested guidelines for median barriers on high-speed, controlled access roadways that have relatively flat, traversable medians. The criteria are based on a limited analysis of median crossover crashes and should be used in the absence of more current or site-specific data. For ADTs above 20,000 vehicles per day, Figure 11 suggests that the use of median barrier would provide some benefit. More recent studies may suggest that benefits exist for median widths of 70 feet or less.

When a roadside hazard is present in a construction work zone, a decision must be made on whether it would be cost effective to shield the hazard. A temporary concrete barrier is the option most preferred by state transportation agencies for this purpose. One objective of this research was to develop design aids for commonly occurring construction work zone scenarios that are easy to use, similar to Figures 5.1 and 6.1 of the *Roadside Design Guide.* The results of a series of benefit-cost analyses would be the primary criteria for development of the design aids. The scenarios and resulting design aids are presented in Chapter 5 of Appendix A.

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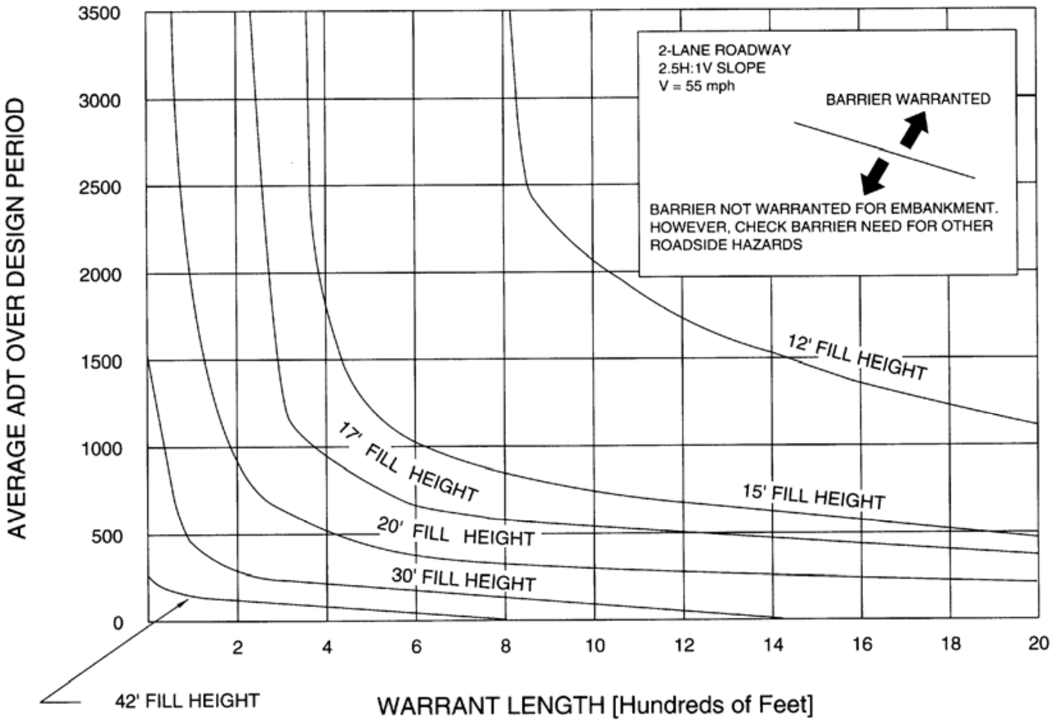

Figure 10. Example design chart for cost-effective embankment warrants based on traffic speeds and volumes, slope geometry, and length of slope (Figure 5.3b from Roadside Design Guide*) (*6*).*

4.1.3 Existing and Ongoing Research on Construction Work Zone Roadside Design and Safety

The two most relevant studies to the development of roadside design and barrier placement guidance were conducted by Sicking and Ross (*46*) and Michie (*47*). Sicking and Ross used a benefit-cost procedure to assess the need for positive traffic barriers in work zones. The procedure was applied to develop general guidelines for four typical activities: bridge widening, roadway widening, major structural work near a traveled way, and two-lane, two-way operation on a normally divided highway. The benefit-cost procedure was also used to evaluate end treatments for barriers, including flaring the barrier away from the traveled way and the use of crash cushions.

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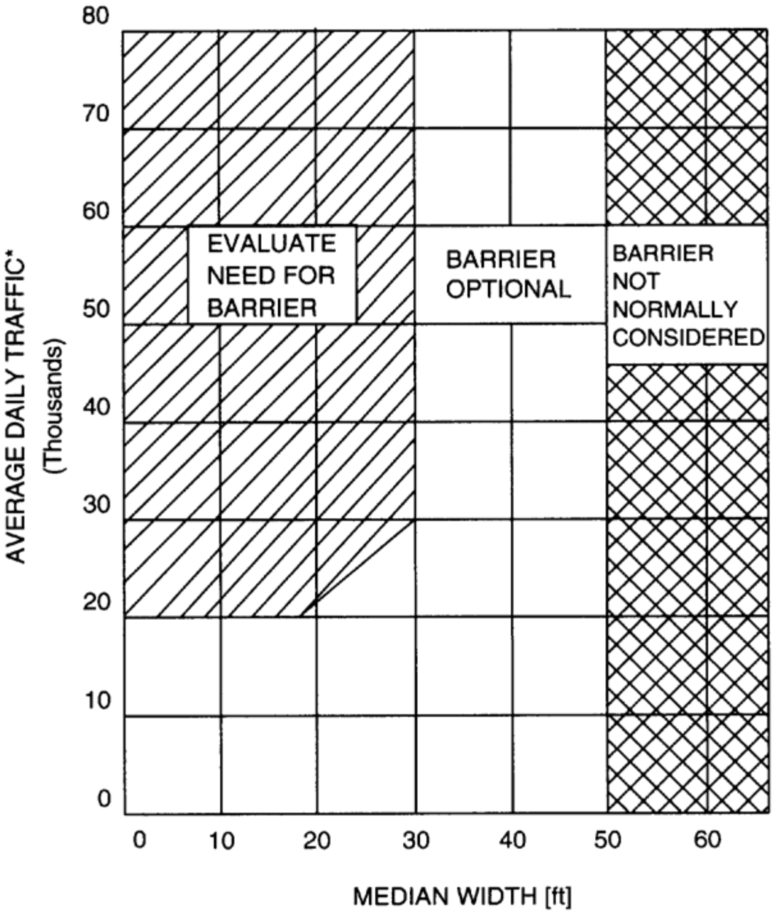

Figure 11. Suggested guidelines for median barriers on high-speed roadways (Figure 6.1 from Roadside Design Guide*) (*6*).*

Michie also used benefit-cost procedures to define typical construction zone activities where positive barriers are needed. His methodology utilized the AASHTO ROADSIDE computer program (available with the 1996 *Roadside Design Guide*) to generate estimates for the number of collisions in a work zone with and without placement of positive barrier. Michie based the severity indices of work-zone-specific features (i.e., equipment, workers) on the work of Sicking and Ross. The result of Michie's work was a series of design charts for different traffic speeds (43.5 mph to 68.3 mph) and hazard types (edge drop-off, structures, workers, heavy equipment, light equipment). Given the number, length, and offset of a hazard, Michie's charts will provide the threshold effective traffic volume (ETV) at the construction site required to justify temporary concrete barrier. The primary advantage of Michie's charts is that a variety of hazard combinations can be analyzed for cost-effectiveness of shielding with a barrier. The primary disadvantage is the complexity of use when compared to design charts in the *Roadside Design Guide*.

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The research reported in Section 4.1.5 attempts to build on the work of Sicking and Ross, and Michie. Primary differences were (1) the use of the Roadside Safety Analysis Program (*48*), which is the most recent computerized procedure that performs cost-effective analyses of roadside safety treatments and (2) the final form of the design guidance in Appendix A of this report, which illustrate four different benefit-cost regions given the input parameters of exposure and speed.

4.1.4 Existing State DOT Construction Work Zone Roadside Design Guidance

A review of state DOT guidance on roadside design and traffic barrier placement is provided in Chapter 3, section 3.2.5. In this section, gaps and needs in state DOT roadside design practices are identified. Additionally, current practice related to application of the clear zone concept in work zones is summarized.

State DOTs that completed this research project's Task 3 survey indicated that improved guidance on *traffic barriers and roadside design* was "most important/critical" and should be prioritized. Although results from the studies discussed in section 4.1.3 of this chapter have been published and available for some time, they have not been incorporated into work zone practice for determining barrier need. Instead, there is still considerable reliance on designer judgment and experience. Although judgment and experience will always be important factors in the provision of temporary concrete barrier to shield different work zone roadside hazards, this research should aim to fill the gaps in current state DOT guidance and provide more quantitative design tools.

As discussed in section 4.1.2 of this chapter, although the clear zone concept has been prevalent in roadside design since the 1960s, it does not clearly provide a solution to whether it would be cost effective to treat a roadside hazard with one of the prioritized safety treatments. However, the clear zone concept has been widely accepted because of its perceived simplicity (e.g., if an object is within the clear zone, provide one of the prioritized treatments; if it is outside the clear zone, it does not present a significant hazard to drivers). Because of its acceptance, designers may wish to use the clear zone concept instead of, or in combination with, the benefit-cost procedure discussed in section 4.1.5 below. Therefore, the state of practice for work zone clear zones was reviewed, and representative dimensions were provided in the design guidance. The representative guidance was based on that of Illinois DOT.

4.1.5 Incremental Benefit-Cost Analysis for Work Zone Scenarios

A major objective of this research was to develop easy-to-use barrier placement design aids for commonly occurring construction work zone scenarios. The results of a series of benefit-cost analyses would be the primary basis for development of the design aids. The design aids based on benefit-cost analysis are combined with information from various other sources to provide roadside design and temporary barrier placement guidance for construction work zones on high-speed highways.

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The Roadside Safety Analysis Program (RSAP) was considered by the research team to be the best available tool for developing work zone barrier placement guidance based on benefit-cost analysis. Available RSAP documentation does not include work zone analysis as a potential application of the program and inherent differences between work zones and permanent roadway situations were recognized. Selective departures from the RSAP default procedures were made to more closely represent the distinctive characteristics of work zones. A detailed review of these departures is provided in section 4.1.5.2. Section 4.1.5.1 provides a brief overview of the general RSAP algorithm. For a more detailed discussion, see *NCHRP Report 492*, "Roadside Safety Analysis Program (RSAP) – Engineer's Manual" (*48*).

4.1.5.1 RSAP

As discussed in section 4.1.2.1, to perform a benefit-cost analysis based on safety, several tools need to be available to the analyst:

- Method to predict crash frequencies under all proposed alternatives;
- Method to predict crash severities under all proposed alternatives;
- Crash cost estimates by severity;
- Repair cost estimates;
- Installation and maintenance costs for specified safety treatments;
- Discount rate over the analysis period.

The objective of NCHRP Project 22-9, *Improved Procedures for Cost-Effectiveness Analysis of Roadside Safety Features*, was to develop a computerized cost-effectiveness analysis procedure that (1) would incorporate these tools into a program that was capable of assessing roadside safety improvements at spot locations over sections of roadway and (2) could be used for development of warrants and guidelines of safety features with different performance levels. The product of this research was RSAP. The following discussion briefly summarizes the RSAP algorithm. It is not meant to supersede any of the detailed descriptions and information in the project report (*48*).

Crash Frequency. To predict crashes, RSAP uses an encroachment based model with a hazard envelope described in (*49*). The assumption behind estimating roadside crashes from the number of encroachments is that crash frequency is proportional to encroachment frequency. The link occurs by simulating encroachments, then (1) determining whether each encroachment is inside or outside the hazard envelope of a roadside object and (2) determining if the lateral extent of the encroachment is greater than or less than the lateral offset of the object.

To determine a base encroachment frequency, RSAP uses data collected in the 1970s (*50*). The data were based on observations of tire tracks in the median and roadside. Therefore, vehicles that encroached onto a concrete shoulder were not represented. To account for this under-representation, the frequencies are adjusted by different factors for undivided and divided highways. Adjustments are also made to account for controlled encroachments, the presence of horizontal curves, and the presence

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of vertical grades. The user can also input a User Defined Adjustment Factor to account for unusual situations that could affect encroachment frequencies beyond the parameters incorporated into the program.

The path of the encroaching vehicle is a function of encroachment angle, vehicle size, and vehicle orientation (*49*). A straight path with no steering or braking is assumed in the current version of RSAP. The lateral extent of each encroachment is determined through cumulative distribution functions of lateral extent for undivided and divided highways. These functions were developed from re-analysis of the data in (*50*).

The vehicle path is checked against the coordinates of the roadside features to determine if a crash would occur. If the encroachment would result in a crash, then the impact conditions are estimated. This includes speed, angle, and vehicle orientation. For each predicted impact with a roadside safety device such as a barrier or crash cushion, RSAP will check for penetration of the feature and subsequent impacts. Speed adjustments are made after each penetration, and if multiple crashes occur, the most severe will be used to calculate crash costs.

Crash Severity. After a crash is predicted to occur, RSAP estimates the severity of the impact. Crash severity estimation is perhaps the most important and most difficult step in the cost effectiveness analysis procedure. The initial intent of the RSAP developers was to use a new methodology for estimating crash severity that would involve a combination of police level crash data and kinematics analysis. However, development was too extensive and time consuming to be completed under the project. Instead, the severity indices listed in the 1996 *Roadside Design Guide* are used in the current version of RSAP.

The severity index (SI) scale is associated with fixed levels or percentages of fatality, injury, and property damage only (PDO) as shown in Table 8.

Severity indices are intended to be representative of average crashes and are usually developed through engineering judgment and expert opinion. Before implementation into RSAP, modifications were made to the severity indices in the 1996 *Roadside Design Guide*. These included relating SI to impact speed rather than design speed and developing a linear regression line to relate SI and impact speed for different object types.

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Table 8 Relationship of severity index to crash severity (*48*)

	Injury Level (%)						
SI	**None**	**PDO1**	**PDO2**	**C**	**B**	**A**	**K**
0	100.0	--	--	--	--	--	--
0.5	--	100.0	--	--	--	--	--
1	--	66.7	23.7	7.3	2.3	--	--
2	--	--	71.0	22.0	7.0	--	--
3	--	--	43.0	34.0	21.0	1.0	1.0
4	--	--	30.0	30.0	32.0	5.0	3.0
5	--	--	15.0	22.0	45.0	10.0	8.0
6	--	--	7.0	16.0	39.0	20.0	18.0
7	--	--	2.0	10.0	28.0	30.0	30.0
8	--	--	--	4.0	19.0	27.0	50.0
9	--	--	--	--	7.0	18.0	75.0
10	--	--	--	--	--	--	100.0

C = minor or possible injury.
B = moderate or non-incapacitating injury.
A = severe or incapacitating injury.
K = fatal injury.

Crash Cost. After the severity index of a crash is estimated, the crash or societal costs associated with the crash are calculated by multiplying the probability of each level of injury by the cost associated with that injury. RSAP provides the alternatives of four different sets of crash cost figures that can be used for the analysis:

- Cost figures from the *Roadside Design Guide;*
- FHWA comprehensive crash cost figures;
- User-defined crash cost figures categorized as fatal, severe injury, moderate injury, minor injury, and PDO;
- User-defined crash cost figures categorized as fatal, injury, and PDO.

Because of a scaling procedure used in RSAP to ensure that low probability, high cost events have adequate representation in a series of runs, the initial crash costs must be adjusted by a weighting factor. This procedure is discussed in Chapters 4 and 8 of (*48*).

Repair Cost. The cost of repairing roadside safety hardware in RSAP is determined by correlating repair costs to impact energy terms. Depending on the impact conditions, the amount (e.g., length) of a roadside safety hardware device that would need repair is determined and multiplied by the unit cost for the repair. Because the repair costs are based on probabilistic events (i.e., the impact conditions), they are weighted in the same manner as the crash costs. Repair costs represent average repair costs and can

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often introduce inaccuracies. However, these inaccuracies in repair costs are insignificant when compared to crash and installation costs and do not affect the overall benefit-cost analysis.

Installation Costs, Maintenance Costs, and Discount Rate. Installation and maintenance costs for each safety treatment in an alternative are user inputs. Installation cost is entered as a lump sum cost, and maintenance costs are entered as an annual value. This information can usually be determined by a state DOT through historical records. For example, some states publish this type of price information based on contractors' bid prices for standard bid items. Finally, a discount rate can be entered by the user that represents the real cost of borrowing money, measured by the difference between interest rates and annual inflation rate. RSAP uses a 4 percent discount rate as a default value; however, a different rate may be used if deemed appropriate by the analyst.

4.1.5.2 Adaptation of RSAP for Work Zone Analysis

The intended use of RSAP is to evaluate roadside safety alternatives for permanent roadways. Compared to permanent roadside situations, there are many factors that are inherently different in construction work zones; the most important of these factors are the number and types of safety hazards and the level of exposure to particular hazards. For example, barrier placement decisions for permanent roadside hazards may be evaluated over a 25-year analysis period, whereas construction work zone hazards may exist only for a few days to 24 months. In addition, common construction work zone hazards (e.g., clusters of equipment) are not normally considered for permanent roadway analysis.

To address the difference in exposure, each work zone scenario was run with a one-year analysis period (the minimum possible with RSAP), then multiplied by the ratio of the work zone duration to one year. For example, if the work zone scenario being analyzed lasted four months, then the one-year benefit-cost ratio would be multiplied by 0.333. An advantage for this approach was that for a one-year run, the benefit-cost ratio for an infinite number of exposure levels could be determined. This calculation is simplified in that it does not multiply the repair costs (in the denominator) by the respective duration. However, since the repair costs were small compared to crash and installation costs, the benefit cost ratios were not affected.

To address the different features that would be important for work zone analysis, but were not available in the RSAP object menus, the research team attempted to use the User Defined Feature capability of RSAP. However, it was discovered and later confirmed through communications with the RSAP development team that this capability was not operating correctly in the most recent version of the program. As an alternative, the characteristics of objects available on the RSAP object menus (but not otherwise used) were manipulated and used as surrogates. This approach was successful.

RSAP includes a series of files with #.dat extensions, which store information about different roadside features, including name, severity index at a 0 mph impact speed,

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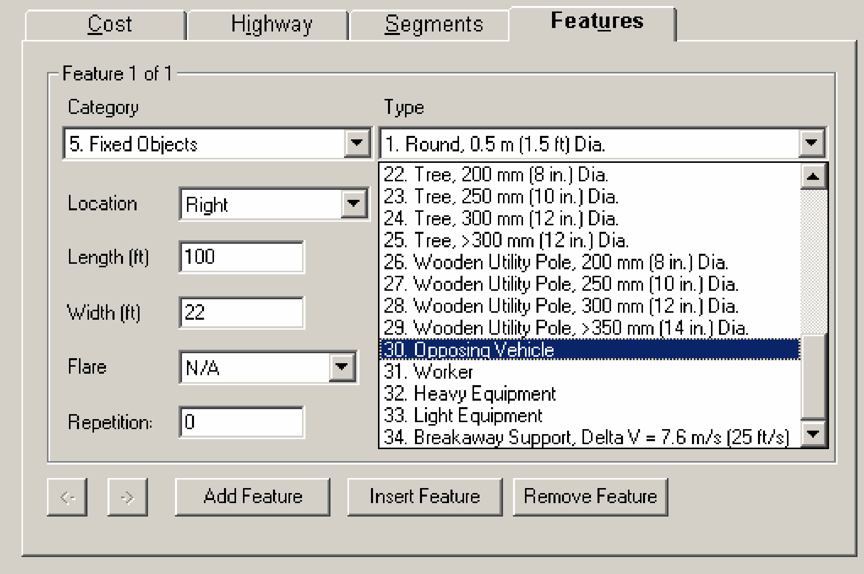
change in severity index with impact speed, and average repair cost per crash. This information was modified in the si5.dat file for fixed objects. Four types of breakaway sign supports, not otherwise used for the work zone analysis, were changed to opposing vehicles, workers, heavy equipment, and light equipment (see Figure 12). Attempts to model head-on collisions with opposing vehicles using RSAP were unsuccessful. The latter three objects were common to most work zone scenarios and will be discussed here.



Category: 5. Fixed Objects

Type: 1. Round, 0.5 m (1.5 ft) Dia.

Location: Right

Length (ft): 100

Width (ft): 22

Flare: N/A

Repetition: 0

Figure 12. Manipulated RSAP fixed objects pull-down menu.

The worker object was defined as an area occupied by workers. Heavy equipment represented construction zone hazards that are rigid and heavy and that would not deflect or move from impact by a motor vehicle (e.g., cranes, paving machines, milling machines, compactors). Light equipment includes less massive items such as welding machines, compressors and pick-up trucks. The severities of impacts associated with these objects as well as the average repair costs per crash are summarized in Figures 13, 14, and 15.

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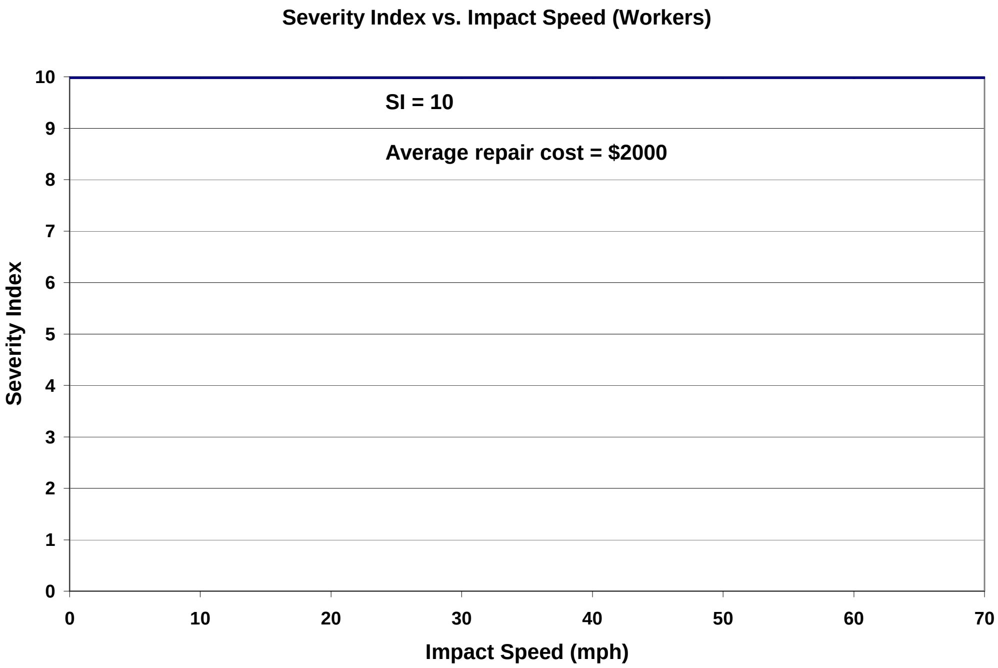

Figure 13. Severity index and repair costs for motor vehicle-worker crashes.

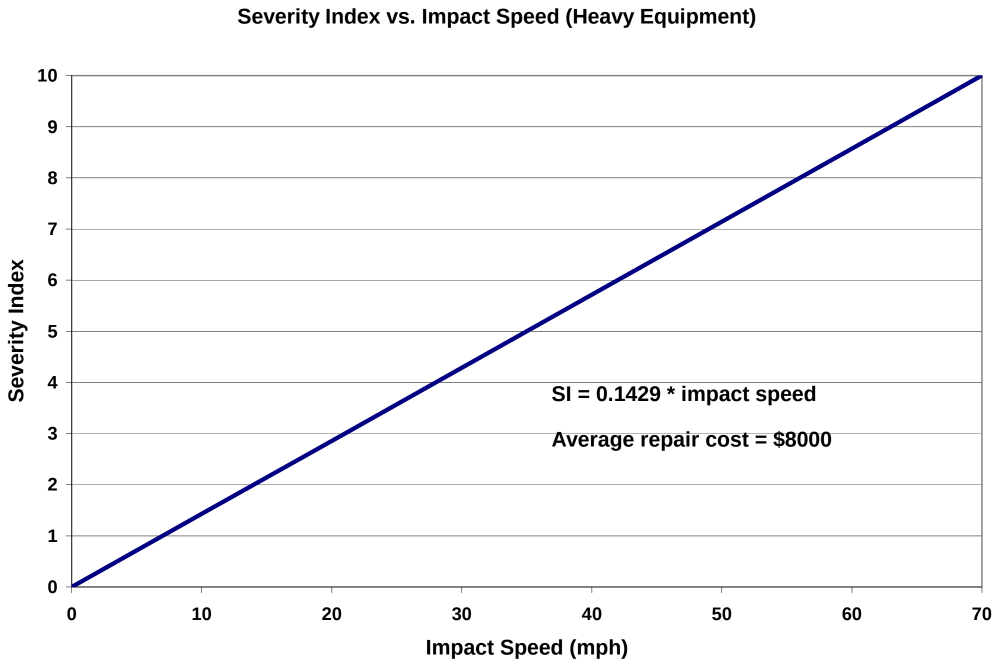

Figure 14. Severity index and repair costs for motor vehicle-heavy equipment crashes.

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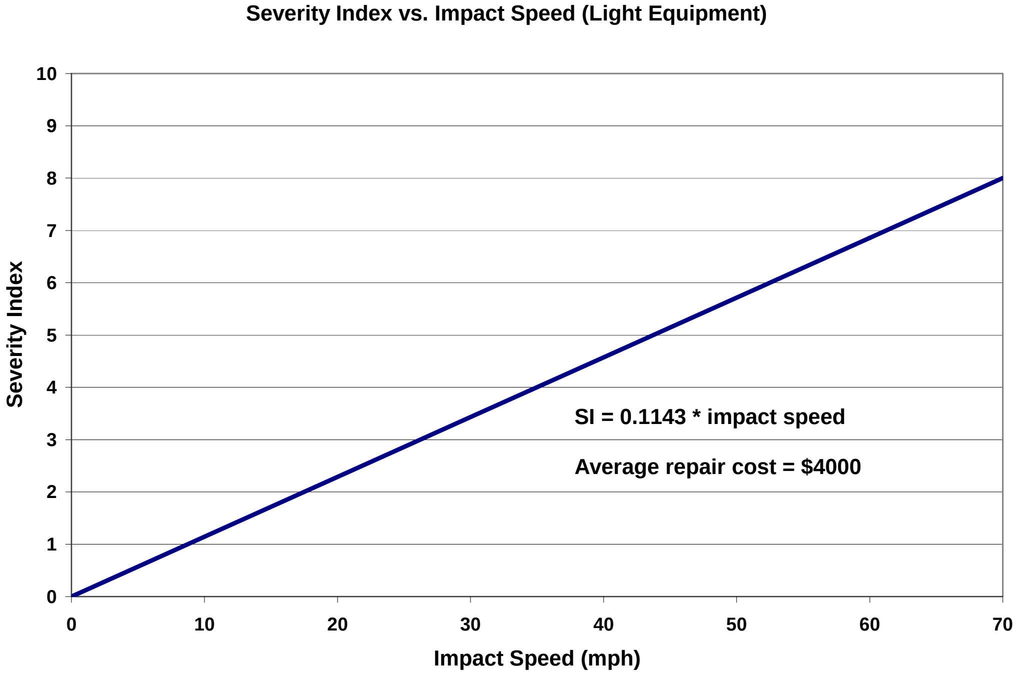

Figure 15. Severity index and repair costs for motor vehicle-light equipment crashes.

The RSAP base encroachment rate was also adjusted to reflect differences between permanent roads and work zones. As discussed earlier, the RSAP encroachment frequency was developed using data collected in the 1970s (*50*) and with several adjustments. A User Defined Adjustment Factor is available to account for factors affecting encroachment frequencies beyond the parameters incorporated into the program. In general, previous studies have shown that crash risk in work zones is higher than on permanent roadways. Increases in the number of crashes in a work zone compared to pre-work zone conditions generally ranged from 7 to 99 percent (see section 2.3.1). The results of several studies showed a crash increase between 20 and 40 percent. In addition, one study showed that work zones with lane widths less than 12 feet experienced a higher number of crashes than work zones with 12-foot lane widths (see section 2.2.4). Given those findings, the assumption that crashes are proportional to encroachments, and that RSAP makes no adjustment to encroachment rates depending on lane width, the following user-defined encroachment adjustment factors were used:

- 1.4 for 12-foot lane widths in work zones;
- 1.5 for 11-foot lane widths in work zones;
- 1.6 for 10-foot lane widths in work zones.

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The other assumptions inherent in all scenarios were the crash costs and direct costs for the safety treatments. FHWA KABCO crash costs from technical advisory *T 7570.2, Motor Vehicle Accident Costs* (*51*), were escalated to 2004 values using the Gross Domestic Product (GDP) implicit price deflator. The final values are shown below:

- Fatal, $2,938,000;
- Severe injury, $203,400;
- Moderate injury, $40,680;
- Minor injury, $21,470;
- PDO, $2,260.

A primary source for the safety treatment costs was Pennsylvania Department of Transportation's *Publication 287, Construction Costs Catalog for Standard Construction Items* (*52*). When the information was available, results of internet searches were also used to find a nationwide representative cost. Costs that were used for the commonly modeled items were:

- TL-3 portable concrete barrier, $27 per linear foot;
- TL-3 strong post guardrail, $9.00 per linear foot;
- TL-3 temporary impact attenuating device, $4000 each;
- Guardrail end treatment, $600 each.

For each common work zone scenario, a series of RSAP runs were made using various combinations of average daily traffic, project duration and posted speed. Average daily traffic directly influences encroachment rate and when combined with project duration influences encroachment frequency. Posted speed influences encroachment speeds, impact speeds and crash severity. Therefore, given a work zone roadside scenario, benefit cost ratios will change as these three variables (average daily traffic, project duration, posted speed) change. In general, the following relationships can be expected:

- As average daily traffic increases, the encroachment rate and benefit-cost ratio will increase;
- As project duration increases, the encroachment frequency and benefit-cost ratio will increase;
- As posted speed increases, crash severity and benefit-cost ratio will increase.

The results of the RSAP runs were plotted in two-dimensional space capturing the three variables discussed above. The x-axis represented exposure (total number of vehicles entering the study section). It is calculated by multiplying the two-way ADT (in vehicles per day) by the project duration (in days). The RSAP analysis assumes a 50/50 split of the two-way ADT. The y-axis represents posted speed and influences the probability of encroachment and impact speeds (higher posted speeds result in higher encroachment and impact speeds). Figure 16 shows an example plot of benefit cost ratios for an outside lane and shoulder closure with minor encroachment into an adjacent open (to traffic) lane.

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It is apparent that in some cases benefit-cost ratios for equal values of exposure and speed are different. The encroachment rate versus ADT function is not a linear for certain ranges of ADT. Therefore, different combinations of ADT and project duration, which when multiplied together result in equal levels of exposure, will result in different encroachment frequencies and benefit cost ratios. In addition, the random component of the RSAP Monte Carlo algorithm results in differences in crash frequencies, severities and benefit-cost ratios. However, given RSAP's convergence algorithm, differences resulting from this randomness are usually small.

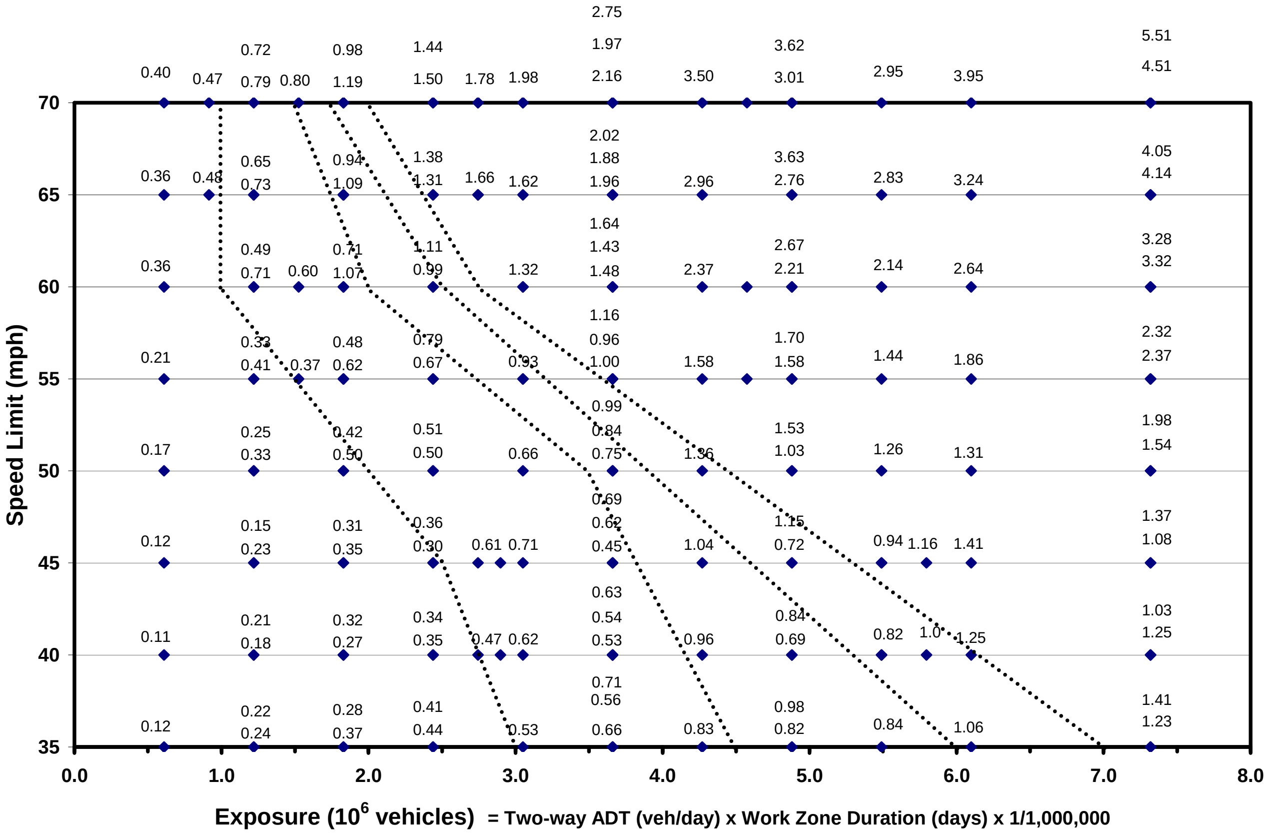

Figure 16. Example plot of benefit-cost ratios for an outside lane and shoulder closure with minor encroachment into an open lane.

The benefit-cost plots were divided into four regions representing the following ranges of B/C ratios:

- (B/C ratio > 1.25);
- (0.75 < B/C ratio ≤ 1.25);
- (0.5 < B/C ratio ≤ 0.75);
- (B/C ratio ≤ 0.5).

These regions are illustrated in Figure 16. In cases where different B/C ratios were computed for equal levels of speed and exposure, the conservative estimate (i.e.

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higher ratio) was used. An attempt was made to have breaks lines separating the boundaries at round increments of speed (5 mph) and exposure (500,000 vehicles). The regions were then shaded and labeled for inclusion into Chapter 5 of the work zone design guidance (Appendix A). An example is illustrated in Figure 17.

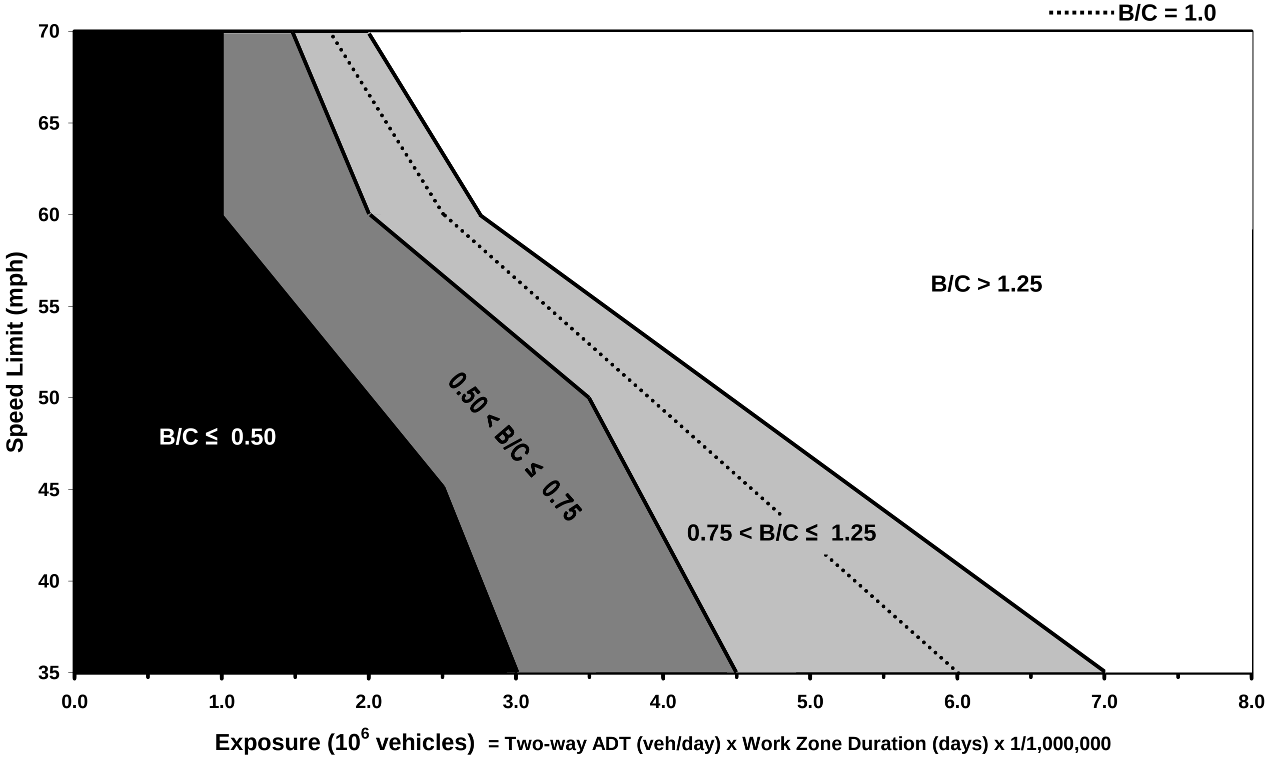

Figure 17. Example of benefit-cost chart included in work zone roadside design guidance.

The advantage of this approach is that it provides agencies and designers greater flexibility to establish policy or project level decisions. The disadvantage is that some agencies and individual designers may not find the guidance definitive enough. Consideration was given to labeling the regions with more definitive design-decision language. For example, the inclusion of notes such as “Barrier Study Optional” or “Barrier Not Normally Considered” were considered for the region with B/C ratios less than or equal to 0.5. However, such language would involve value judgments and might also mask the actual research results (which are estimated B/C ratios). Policy- and project-level decisions often (and properly) reflect numerous considerations, one of which may be cost-benefit analysis.

The scenarios presented in Chapter 5, section 5.5, of Appendix A represent commonly occurring conditions for which a designer would have to choose whether or not to provide temporary concrete barrier. The scenarios were developed using *MUTCD* Part 6H Typical Applications, as well as input from NCHRP Project 3-69 panel members and other practitioners. Each scenario contains a short description, an illustration of the work zone layout and cross sections, and the design guidance resulting from the RSAP

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runs. It should be noted here that in situations where there is a lane or shoulder closure with some encroachment on the remaining travel lanes, a design decision that must be made is how to distribute the remaining paved roadway for temporary lanes and shoulders. A number of combinations can often exist. For the tools used to develop barrier placement guidance, different combinations of lane and shoulder widths did not affect the resulting guidance in the referenced sections. Six scenarios and the resulting benefit-cost design aids are included in Appendix A:

- Scenario 1, outside lane and shoulder closure for part-width construction on a four-lane divided highway;
- Scenario 2, outside shoulder closure on a four-lane divided highway with minor encroachment;
- Scenario 3, median shoulder closure on a four-lane divided highway with minor encroachment;
- Scenario 4, bridge reconstruction with a temporary diversion/runaround on a two-lane, two way highway;
- Scenario 5, separation of two-lane, two-way traffic on a normally divided facility;
- Scenario 6, protection of a normally downstream barrier end for two-lane, two-way traffic on a normally divided facility.

Scenarios 1 through 3 have several roadside condition similarities. For a specific ADT, duration and speed, one might expect:

- For Scenario 1 to have the highest benefit-cost ratio for a barrier (compared to Scenarios 2 and 3) because all traffic is closer to the roadside hazards;
- For Scenario 3 to have the lowest benefit-cost ratio for a barrier (compared to Scenarios 1 and 2) because 67 percent of traffic is located further away from roadside hazards than scenarios 1 and 2;
- For Scenario 2 to have a benefit-cost ratio for a barrier somewhere between Scenarios 1 and 3 because 67 percent of traffic is located the same distance from roadside hazards as all Scenario 1 traffic and 33 percent of traffic is located further away.

RSAP runs did not produce these results. For equal ADT and speed, benefit-cost ratios for Scenarios 2 and 3 were practically equal to each other and significantly greater than those for Scenario 1. Through subsequent testing and conversations with the RSAP development team, potential programming errors were detected. For purposes of this project, conservative estimates of benefit-cost ratios (resulting from the analysis of Scenario 2) were used to represent all three scenarios.

Because it is a two-lane, undivided highway, Scenario 4 uses a different encroachment model than the other scenarios. Using this two-lane, undivided highway encroachment model leads to lower benefit-cost ratios at higher levels of exposure for many of the ADT and speed combinations that were run. This result is difficult to accept as valid and a modification of the encroachment model was made. The highest

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encroachment rate for this facility type occurs for an ADT of approximately 5000 vehicles per day. Therefore, this ADT was used for all runs, and different levels of exposure were computed by only varying project durations.

Scenario 5 posed a unique challenge. Attempts to model potential head-on collisions associated with this scenario were unsuccessful. Therefore, earlier work by Sicking and Ross (referenced in section 4.1.3) was used for the design aid related to this scenario.

Several concluding points will be noted about the method used to develop the estimated benefit-cost ratios. RSAP is based on a probabilistic approach to roadside safety. Further, as outlined previously, there are numerous assumptions associated with RSAP's development and its application to work zone scenarios. Consequently, the results it produces (including benefit-cost ratios) should be regarded as estimates of what would occur over many repetitions of the same conditions. Further, real world scenarios rarely conform to the exact conditions modeled. Therefore, the results shown should not be regarded as precise or always-accurate indication of the cost-effectiveness of a specific barrier placement.

4.1.6 Integration and Fusion to Develop Roadside Design Guidance

The guidance in Chapter 5, Roadside Design and Barrier Placement, of Appendix A is divided into 6 sections. Section 5.1 is an introduction to roadside safety in construction work zones. It is based on Chapters 1 and 3 of the *Roadside Design Guide* and presents the underlying principles of roadside safety and design. These include the forgiving roadside concept and the prioritized treatment of hazards. It also contains some important distinctions between permanent roadway segments and construction work zones.

Section 5.2 of Appendix A discusses the clear zone concept and its applicability to construction work zones. Several disadvantages and shortcomings of the clear zone concept are provided. These observations are based on statements from the *Roadside Design Guide* and from some state DOTs that provide work zone clear zone guidance. Nonetheless, the simplicity and practicality of the clear zone concept is recognized, and suggested dimensions are provided. The basis for these dimensions is guidance from Illinois DOT, which seemed to provide representative ranges of suggested clear zones (i.e., similar to guidance from other states, such as Indiana, Montana, and Oklahoma, that provided work zone clear zone dimensions).

Section 5.3 contains a discussion on the identification of work zone roadside hazards that may require treatment or shielding. For the most part, designer experience and judgment are relied upon for identification of hazards. However, a list of hazards often present in work zones is provided, compiled from guidance of several states: Illinois, Indiana, Mississippi, Montana, and Oklahoma.

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Section 5.4 of Appendix A discusses roadside safety and economics and is largely based on Chapter 2 of the *Roadside Design Guide* and on *NCHRP Report 492*. The main discussion item is the use of benefit-cost analysis for roadside safety treatment decisions. Section 5.5 presents the results of benefit-cost analysis to develop barrier placement guidance for a series of construction work zone scenarios. Study methodology detail is provided in section 4.1.5, some of which is repeated in the Appendix A to provide sufficient background detail for a designer using the aids.

Section 5.6 of the Appendix A presents a variety of other topics associated with traffic barriers and other roadside safety features in construction work zones. A number of the sections cross reference the *Roadside Design Guide*, primarily Chapter 9, which “describes the safety, functional, and structural aspects of traffic barriers; traffic control devices; and safety features used in work zones; and provides guidance on their application.” Information contained in the *Roadside Design Guide* is not repeated or summarized.

4.2 SPEED MODEL

4.2.1 Introduction to Artificial Neural Networks

Artificial neural networks (ANNs) have successfully been employed by researchers over the past 25 years in solving a wide variety of engineering problems. However, it has only been recently that ANNs have found their way into the area of transportation safety and operations. ANN structure and methodology are loosely based on the biological nervous system, which consists of many interconnected neurons similar to the two displayed in Figure 18. Each neuron consists of a cell body, dendrites and axon. Signals are passed from the axon of one neuron to the dendrite of another through a connection point called the synapse. Memories are stored by changing the connection strength of the synapse. The cell body then sums and thresholds all incoming signals to produce a new signal that is sent out the axon (*53*).

ANNs operate on a much smaller scale but use the same basic principles. As with the biological nervous system, ANNs consist of many interconnected but “artificial” neurons that weight, sum and threshold incoming signals to produce an output. Information is also stored within the strengths of the interconnections or weights. Figure 19 depicts a typical ANN architecture.

The neurons, sometimes referred to as nodes, are usually arranged into what are known as layers. The network shown in Figure 19 has one input layer (not always referred to as an actual layer), a hidden layer, and an output layer. Neurons in a layer are typically connected to every neuron in adjacent layers through a connection weight. These weights determine the function of the network. Each node sums its weighted inputs and then applies an activation function, typically a sigmoidal activation function, to produce an output.

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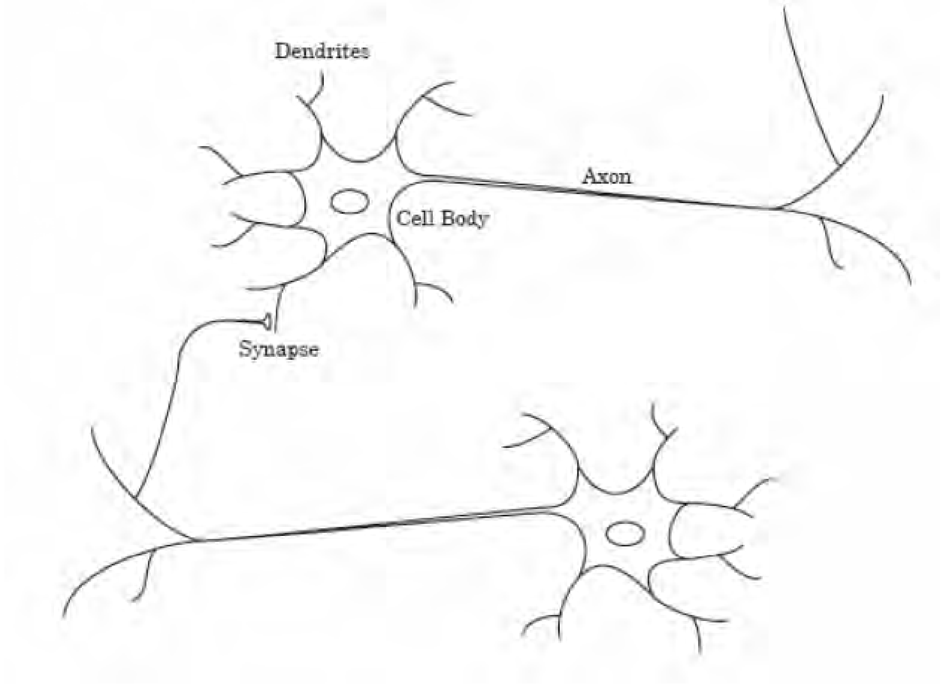

Figure 18. Schematic drawing of biological neurons.

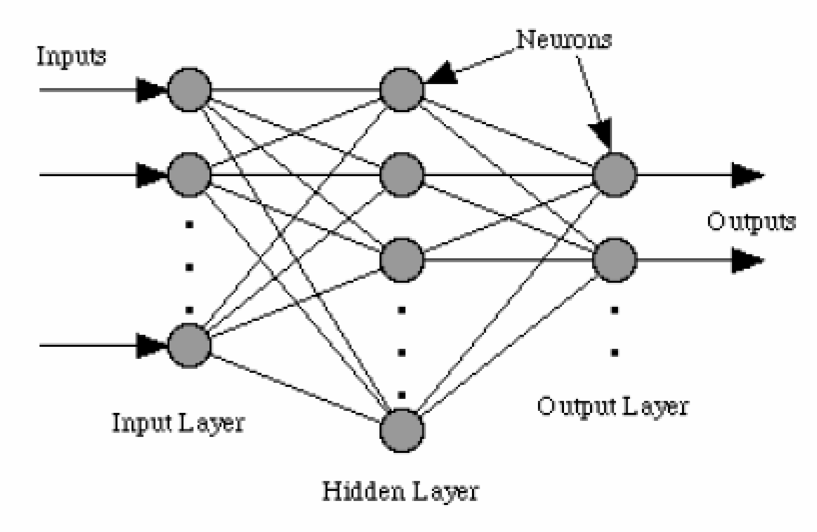

Figure 19. General structure of a feed-forward ANN.

Just as new memories are formed in biological neural systems through adjustments in the synaptic connection strengths, new memories are formed in ANNs by adjusting the weighted connections between neurons. This is typically done through some well established training procedures where the network is presented pairs of input/output data and an attempt is made to search for a global minimum on the error surface over the space of the network parameters or weight values. Figure 20 demonstrates the basic training process.

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Some of the advantages of using an ANN are:

- No assumptions need to be made as to the form of the model;
- It is capable of extracting non-linear variable interactions;
- It is able to generalize from small training data sets.

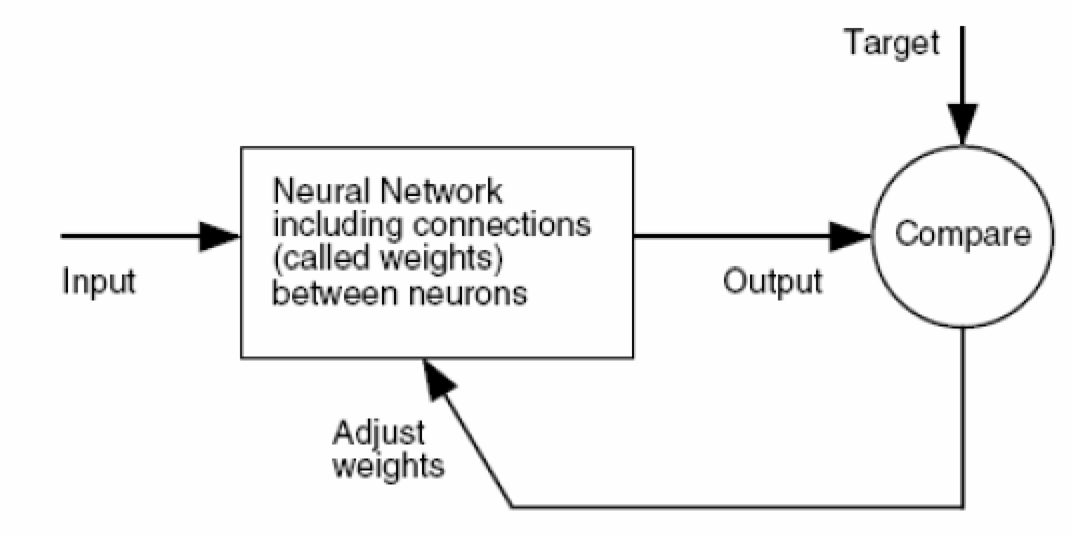

*Figure 20. Network training (*53*).*

4.2.2 Selection of Input Variables

The first step in developing the speed profile model was identifying variables that may affect vehicle speed and can serve as candidate model inputs. Although a large number of predictor variables were considered, selection was based on model goals and measurement feasibility. Since the scope of this study was to determine how road geometry and work zone traffic control affects vehicle speeds for passenger vehicles and large trucks, vehicle interaction/car following variables were not considered. The variable list went through several iterations and involved inputs from both transportation and dynamic system researchers on the NCHRP Project 3-69 team. Both continuous and categorical variables were included. It included geometric and traffic control features as well as upstream speeds and distances between speed data collection locations. Variables not included would be controlled for as much as possible during the data collection process. The final set of model inputs are discussed in section 4.2.4.

4.2.3 Data Collection and Descriptive Statistics

High-speed highways are defined as “roads and highways with free-flow operating speeds of 50 mph and higher.” Since this research involves construction work zones on high-speed highways, data was collected only for high-speed facilities.

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Furthermore, the scope of the speed model was limited to single lane closures (with traffic using the travel lane adjacent to the closed lane) and lane closures with median crossovers on four lane divided facilities. The following definitions apply.

Median crossover: a construction work zone type used on expressways (including freeways) wherein:

- The number of lanes in both directions are reduced;
- At both ends, traffic in one direction is routed across the median to the opposite-direction roadway on a temporary roadway constructed for that purpose;
- Bi-directional traffic is maintained on one roadway while the opposite direction roadway is closed.

Single lane closure: a construction work zone type where one travel lane and any adjacent shoulders are closed to traffic.

Data were collected in a total of 17 construction work zones; 11 single lane closures and 6 median crossovers in Pennsylvania and Texas. For crossovers, data were only collected in the travel direction containing the crossover. The work zone set-ups were “standard” lane closures and median crossovers. Anomalies that were designed to accommodate an uncommon situation were avoided. Data were collected during the times of day where lengthy queues did not form at any point throughout the work zone.

The speed profile of a traveling vehicle is continuous in nature; therefore, an ideal model should use a continuous representation of this profile. Such an approach would require tracking the speed of many vehicles through the entire length of a work zone, with each vehicle having its own unique profile for the particular site. Available methods of data collection, however, make it difficult to capture this profile as a continuous function. Therefore, measured speeds were captured only at particular locations or “points” throughout a work zone site. At each work zone, 2 to 19 locations were selected for speed data collection. One location was upstream of the work zone, prior to the influence of any temporary traffic control. The remaining locations were located in the lane taper and the activity area. The lane taper was defined as the transition between the normal cross section and the work zone cross section where one lane and the adjacent shoulder were closed. Tapers were typically created by a series of channelizing devices such as vertical panels or drums. The work area comprised the remainder of the work zone from the lane taper to the termination point.

Locations were selected to provide a range of conditions for roadway cross sections, roadside features and horizontal and vertical alignment. Locations where vehicle speeds appeared to be affected by the presence of entrance or exit ramps were avoided. At each location, approximately 200 free-flow speeds (defined as speeds of a vehicle with a headway greater than 4 seconds) were collected during dry, daylight conditions. In addition, traffic control plans combined with field observations were used to gather information on the following features:

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- Travel lane width;
- Right and left shoulder width;
- Right and left shoulder type;
- Presence of and offset to roadside objects (e.g. temporary or permanent barrier, work zone channelizing devices, other roadside conditions);
- Radius of horizontal curve;
- Vertical grade;
- Rate of vertical curvature;
- Posted speed limit;
- Distance from the lane taper;
- Cross slope.

The final data set consists of 26,902 free-flow observations from 136 locations. The breakdown by state, work zone configuration, and location type (i.e. upstream, taper, activity area) is summarized in Table 9. Tables 10 through 15 summarize the descriptive statistics of the categorical and continuous variables collected at the upstream, lane taper and activity area locations.

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Table 9 Breakdown of speed data by location and work zone configuration for passenger cars (PC) and heavy vehicles (HV)

State	Lane Closure								
	Upstream			Taper			Work Area		
	No. of Locations	No. of PC Observations	No. of HV Observations	No. of Locations	No. of PC Observations	No. of HV Observations	No. of Locations	No. of PC Observations	No. of HV Observations
PA	7	1096	328	6	824	399	23	2991	1593
TX	4	636	164	11	1598	577	11	1609	591
Total	11	1732	492	17	2422	976	34	4600	2184

State	Median Crossover								
	Upstream			Taper			Work Area		
	No. of Locations	No. of PC Observations	No. of HV Observations	No. of Locations	No. of PC Observations	No. of HV Observations	No. of Locations	No. of PC Observations	No. of HV Observations
PA	3	377	168	2	215	185	21	2290	1715
TX	3	398	202	4	475	325	41	4812	3334
Total	6	775	370	6	690	510	62	7102	5049

State	Total								
	Upstream			Taper			Work Area		
	No. of Locations	No. of PC Observations	No. of HV Observations	No. of Locations	No. of PC Observations	No. of HV Observations	No. of Locations	No. of PC Observations	No. of HV Observations
PA	10	1473	496	8	1039	584	44	5281	3308
TX	7	1034	366	15	2073	902	52	6421	3925
Total	17	2507	862	23	3112	1486	96	11702	7233

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Table 10 Descriptive statistics of candidate categorical predictor variables

		Lane Taper (23 locations)		Work Area (96 locations)	
Variable	**Categories**	**Frequency**	**Percent**	**Frequency**	**Percent**
Lane closed	Left	7	30.4%	9	9.4%
	Right	16	69.6%	87	90.6%
Posted speed	50	4	17.4%	25	26.0%
	55	2	8.7%	8	8.3%
	60	4	17.4%	31	32.3%
	65	7	30.4%	16	16.7%
	70	6	26.1%	16	16.7%
Police presence	no	6	26.1%	40	41.7%
	yes	2	8.7%	4	4.2%
	missing	15	65.2%	52	54.2%
Roadway type	Permanent	23	100.0%	66	68.8%
	Temporary	0	0.0%	30	31.3%
Horizontal alignment	Tangent	19	82.6%	52	54.2%
	Curve to the left	2	8.7%	27	28.1%
	Curve to the right	2	8.7%	17	17.7%
Vertical alignment	Flat (-1 to 1)	12	52.2%	41	42.7%
	Upgrade	2	8.7%	21	21.9%
	Downgrade	1	4.3%	25	26.0%
	Crest curve	7	30.4%	4	4.2%
	Sag curve	1	4.3%	5	5.2%
Location in vertical curve	Incoming grade	2	8.7%	0	0.0%
	Middle	1	4.3%	5	5.2%
	Outgoing grade	1	4.3%	2	2.1%
	N/A	15	65.2%	87	90.6%
	Missing	4	17.4%	2	2.1%
Traffic control device (TCD) to the left	None	15	65.2%	31	32.3%
	Drum	7	30.4%	7	7.3%
	Panel	0	0.0%	2	2.1%
	Guardrail	0	0.0%	4	4.2%
	Concrete barrier	1	4.3%	50	52.1%
	Opposing traffic	0	0.0%	2	2.1%
Traffic control device (TCD) to the right	None	7	30.4%	36	37.5%
	Drum	8	34.8%	17	17.7%
	Panel	1	4.3%	9	9.4%
	Guardrail	0	0.0%	9	9.4%
	Concrete barrier	4	17.4%	20	20.8%
	Other	3	13.0%	5	5.2%

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Table 11 Descriptive statistics of candidate continuous predictor variables

	Lane Taper (23 locations)					Work Area (96 locations)				
Variable	**N**	**Minimum**	**Maximum**	**Mean**	**Std. Deviation**	**N**	**Minimum**	**Maximum**	**Mean**	**Std. Deviation**
Length from taper (miles)	23	0	0.2	0.06	0.08	96	0.2	10.6	3.03	3.03
Radius of curve (ft)	4	2292	7640	4018	2448	44	1911	11480	5743	3198
Superelevation (%)	22	2	7.5	2.46	1.48	81	2.0	7.5	2.56	1.43
Incoming grade (%)	22	-3.22	3	0.39	1.35	96	-4.0	3.0	-0.33	1.77
Outgoing grade (%)	5	-3.5	-2	-2.96	0.61	7	-2.7	3.0	-0.18	2.41
Rate of vertical curvature (K) (ft/%)	7	247	615	364	127	9	150	500	258	128
Traveled way width (TWW) (ft)	23	12	24	17	4.6	96	11	16	12.44	1.29
Right shoulder width (RSW) (ft)	23	0	10	3	4.6	96	0	16	4.17	4.10
Left shoulder width (LSW) (ft)	23	0	8	3.7	3	96	0	36	3.23	4.40
Total paved width (TPW) (ft)	23	16	34	23	5.3	96	12	48	19.14	4.89
Left offset to TCD (ft)	8	0	5	1.1	1.8	65	0	48	3.91	9.44
Right offset to TCD (ft)	16	0	4	1.3	1.4	60	0	24	2.78	3.79

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Table 12 Descriptive statistics of 15th percentile speed (aggregated by location) for each vehicle type

	Aggregated 15th Percentile Speed for All Vehicles (mph)				
Location Type	**N**	**Minimum**	**Maximum**	**Mean**	**Std. Deviation**
Upstream	17	49	68	63.53	4.30
Lane Taper	23	44	63	54.70	5.45
Work Area	96	29	60	51.69	4.95

	Aggregated 15th Percentile Passenger Car Speed (mph)				
Location Type	**N**	**Minimum**	**Maximum**	**Mean**	**Std. Deviation**
Upstream	17	49	70	64.15	4.62
Lane Taper	23	45	66	55.66	5.94
Work Area	96	29	61	52.10	5.68

	Aggregated 15th Percentile Truck Speed (mph)				
Location Type	**N**	**Minimum**	**Maximum**	**Mean**	**Std. Deviation**
Upstream	17	44	66	62.18	5.00
Lane Taper	23	44	61	53.18	5.04
Work Area	96	29	61	51.27	5.58

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Table 13 Descriptive statistics of mean speed (aggregated by location) for each vehicle type

	Aggregated Mean Speed for All Vehicles (mph)				
Location Type	**N**	**Minimum**	**Maximum**	**Mean**	**Std. Deviation**
Upstream	17	54	73	68.29	4.16
Lane Taper	23	51	69	60.35	5.56
Work Area	96	37	66	56.42	5.30

	Aggregated Mean Passenger Car Speed (mph)				
Location Type	**N**	**Minimum**	**Maximum**	**Mean**	**Std. Deviation**
Upstream	17	54	74	68.90	4.53
Lane Taper	23	51	71	61.36	5.91
Work Area	96	37	68	56.89	5.39

	Aggregated Mean Truck Speed (mph)				
Location Type	**N**	**Minimum**	**Maximum**	**Mean**	**Std. Deviation**
Upstream	17	53	71	66.53	4.02
Lane Taper	23	49	66	58.21	5.11
Work Area	96	36	64	55.69	5.25

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Table 14 Descriptive statistics of 85th percentile speed (aggregated by location) for each vehicle type

	Aggregated 85th Percentile Speed for All Vehicles (mph)				
Location Type	**N**	**Minimum**	**Maximum**	**Mean**	**Std. Deviation**
Upstream	17	59	78	73.00	4.20
Lane Taper	23	57	74	66.00	5.70
Work Area	96	44	72	61.11	5.11

	Aggregated 85th Percentile Passenger Car Speed (mph)				
Location Type	**N**	**Minimum**	**Maximum**	**Mean**	**Std. Deviation**
Upstream	17	59	79	73.63	4.38
Lane Taper	23	57	76	66.81	5.85
Work Area	96	43	73	61.71	5.24

	Aggregated 85th Percentile Truck Speed (mph)				
Location Type	**N**	**Minimum**	**Maximum**	**Mean**	**Std. Deviation**
Upstream	17	60	75	70.88	3.41
Lane Taper	23	55	70	63.16	5.06
Work Area	96	44	68	60.10	4.95

Table 15 Descriptive statistics of standard deviation of speed (aggregated by location) for each vehicle type

	Aggregated Standard Deviation of Speed for All Vehicles (mph)				
Location Type	**N**	**Minimum**	**Maximum**	**Mean**	**Std. Deviation**
Upstream	17	3.58	6.13	4.98	0.705
Lane Taper	23	4.17	6.60	5.49	0.552
Work Area	96	2.79	8.33	4.70	0.940

	Aggregated Standard Deviation of Passenger Car Speed (mph)				
Location Type	**N**	**Minimum**	**Maximum**	**Mean**	**Std. Deviation**
Upstream	17	3.14	6.36	5.04	0.833
Lane Taper	23	4.45	6.68	5.46	0.648
Work Area	96	2.81	8.61	4.83	0.959

	Aggregated Standard Deviation of Truck Speed (mph)				
Location Type	**N**	**Minimum**	**Maximum**	**Mean**	**Std. Deviation**
Upstream	17	3.31	6.48	4.18	0.731
Lane Taper	23	3.49	6.40	4.89	0.866
Work Area	96	2.18	7.82	4.27	0.972

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After an initial analysis of the dataset, several geometric variables were eliminated from the model based on missing data and lack of variation. The following variables were eliminated due to missing data: superelevation (e), grade (G), and rate of vertical curvature (K). Several other variable categories (Other Soft Roadside Device Left and Right and Opposing Traffic for Roadside Device Right) were eliminated due to lack of observations.

4.2.4 Methodology for Development of ANN model

The most common network architecture is a two-layer feed-forward network with sigmoid transfer functions in the hidden layer and linear transfer functions in the output layer as shown in Figure 21. The reason that this network is so often used is because it has been shown that it is capable of approximating any function to any degree of accuracy, depending on the number of hidden neurons (*53*).

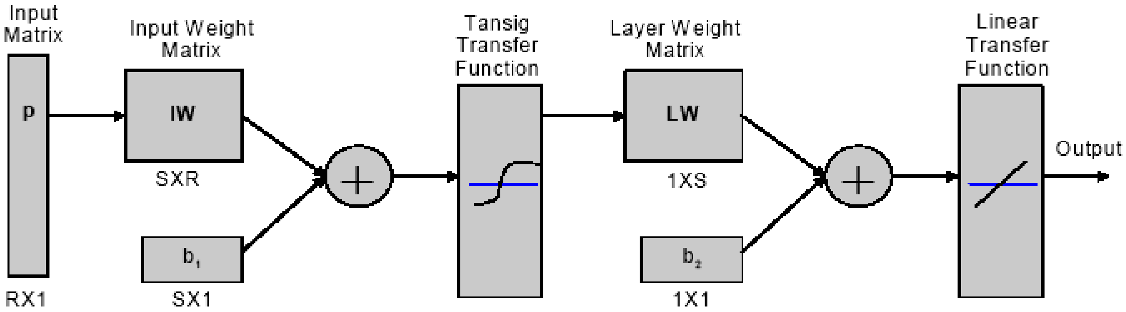

Figure 21. Two-layer feed-forward artificial neural network.

The network output in this case is given by equation 4**.**

$$\text{Output} = \text{LW} \times \Phi(\text{IW} \times \text{p} + \text{b}_1) + \text{b}_2 \quad (4)$$

Where

$$\Phi = \frac{2}{1 + e^{-2x}} - 1 \quad (5)$$

A block diagram of the ANN model implemented in this study is given in Figure 22. A two-layer feed-forward network with two hidden neurons and one output neuron was used in this study. The output of the model is the speed of a vehicle, v, as a function of distance, x, measured from the beginning of the work zone or lane taper. The model predicts speeds only for locations of "x" for which an input vector is defined. The ANN model predicts vehicle speed based on three inputs.

The first input, $\underline{\mathbf{u}}_{WZ}(x)$, is a vector containing the geometric variables at the particular location. Some of these variables, like work zone type, are constant for a

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particular site, while most variables change depending on the particular point within the site. The second input, $v(0)$, is upstream speed. This is the estimated speed of a vehicle prior to entering the work zone and is typically 2 to 3 miles upstream from the lane taper. The upstream speed is used in predicting all other speeds within the work zone. The final input is the previous predicted speed, which is fed back from the model output through a distance delay block. For the first speed predicted in a work zone, the previous predicted speed is the upstream speed, $v(0)$. It is important to note that distance to the previous predicted speed is included in $\underline{\mathbf{u}}_{WZ}(x)$. It is necessary to include this variable since data collection points were not equally spaced.

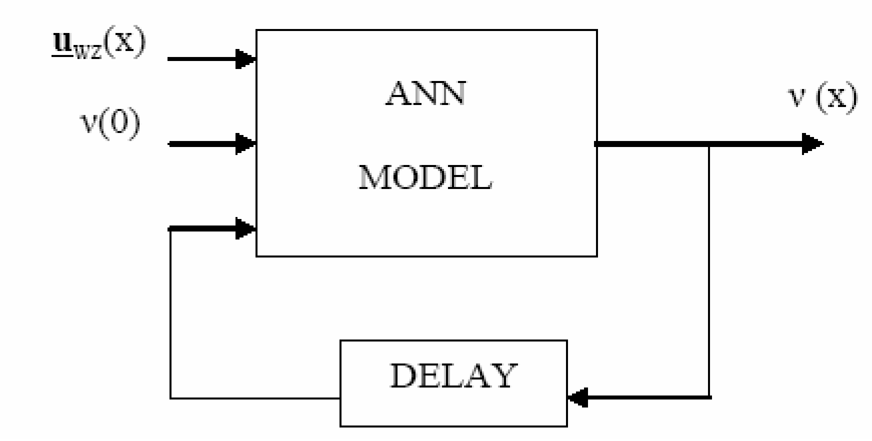

Figure 22. Block diagram of the speed profile model.

Before developing an ANN model, it is first necessary to transform the input vectors into a form that will be conducive to network learning. This was accomplished through a variable encoding process. A total of 31 network inputs were derived from the geometric database. The final list of model inputs is given in Table 16. Categorical variables were encoded using a binary representation which is typical in neural network implementation. For example, a variable containing N categories was represented using N separate binary inputs.

Radius of horizontal curvature was inverted in order to represent the quantity within a finite range. Since the inverse of radius contained similar, but more detailed, information to the categorical variable horizontal alignment, it was not necessary to include both variables as inputs. For this reason, horizontal alignment was eliminated as an input.

The Neural Network Toolbox in MATLAB (*54)* was used to develop the ANN model. Network inputs and targets were first normalized using the PRESTD command in MATLAB. The first step in training the network is separating the dataset into two groups: one for training the network and the other for testing the network. Because of the limited number of data points available, the testing dataset needed to be carefully selected such that it was a representative set. A total of five sample points was chosen for testing.

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Table 16 Final model inputs

Input variables (descriptions) choices and ranges
Work Zone Configuration; discrete choices: Lane Closure or Median Crossover
Upstream Speed (estimated or measured 85th percentile speeds upstream of work zone) any value between 48 and 72 mph
Location; discrete choices: Taper or Within Work Zone
Distance (location of analysis/prediction point measured from the taper) any value between 0 and 10.6 miles
Posted Speed (posted speed at prediction point) discrete choices: 50 to 70 mph, inclusive at 5 mph increments
Roadway Type; discrete choices: Permanent or Temporary
R (Radius of curvature) any value between 1,191 and 11,400 ft; 99999 is entered to signify a tangent
VA (Vertical alignment) discrete choices: Flat, Upgrade, Downgrade, Crest or Sag
TWW (Traveled way width) any value between 11 and 24 ft
RSW (Right shoulder width) any value between 0 and 16 ft
LSW (Left shoulder width) any value between 0 and 36 ft
TPW (Total paved width) any value between 12 and 48 ft
RSDL (Roadside device on left) discrete choices: None, Drum, Vertical Panel, Guardrail, Barrier, or Opposing Traffic w/ No Separation
Loffset (Left offset; the distance from the edge of the travel lane to the roadside device on the left side of the road) any value between 0 and 48 ft
RSDR (Roadside device on right) discrete choices: None, Drum, Vertical Panel, Guardrail, or Barrier
Roffset (Right offset; the distance from the edge of the travel lane to the roadside device on the right side of the road) any value between 0 and 24 ft

Predicted network outputs are compared to the actual measured speeds or target values. Network parameters or weight and bias values are adapted in the training process to minimize error. There are several different optimization algorithms that are capable of performing this operation. In this study, TRAINRP algorithm (resilient back-propagation) of MATLAB’s NN Toolbox was used.

4.2.5 Results

The ANN models were developed for six different datasets (two each for cars, trucks and all vehicles) as listed below:

- Mean of speed data for cars;
- Variance of speed data for cars;
- Mean of speed data for trucks;
- Variance of speed data for trucks;
- Mean of speed data for all vehicles combined;
- Variance of speed data for all vehicles combined.

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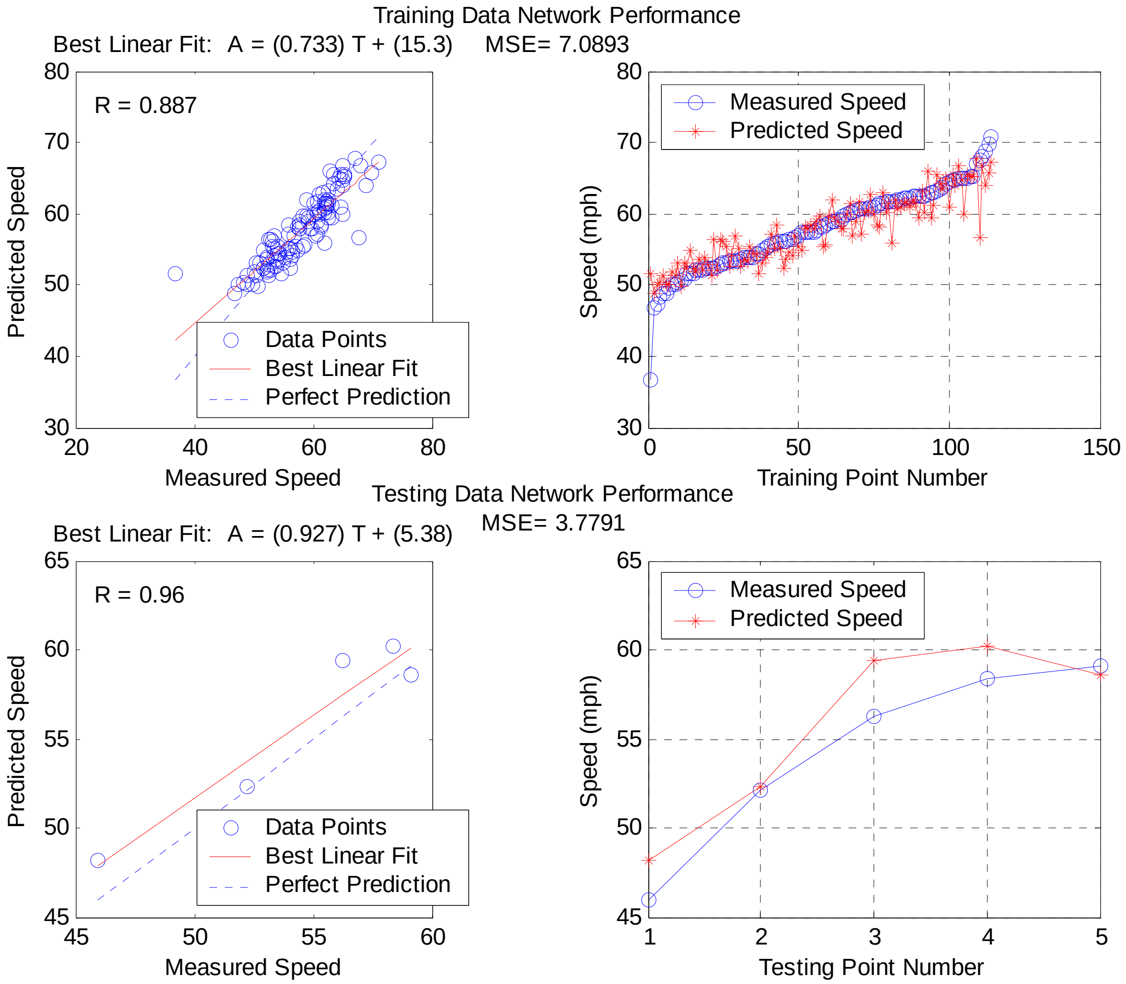
The results obtained using the mean speed datasets for cars, trucks and all vehicles are shown in Figures 23, 24, and 25. A summary of the mean square errors (MSE) obtained for all nine datasets is given in Table 17.



Training Data Network Performance

Best Linear Fit: A = (0.733) T + (15.3) MSE= 7.0893

Testing Data Network Performance

Best Linear Fit: A = (0.927) T + (5.38) MSE= 3.7791

Figure 23. ANN results for mean speed data for cars.

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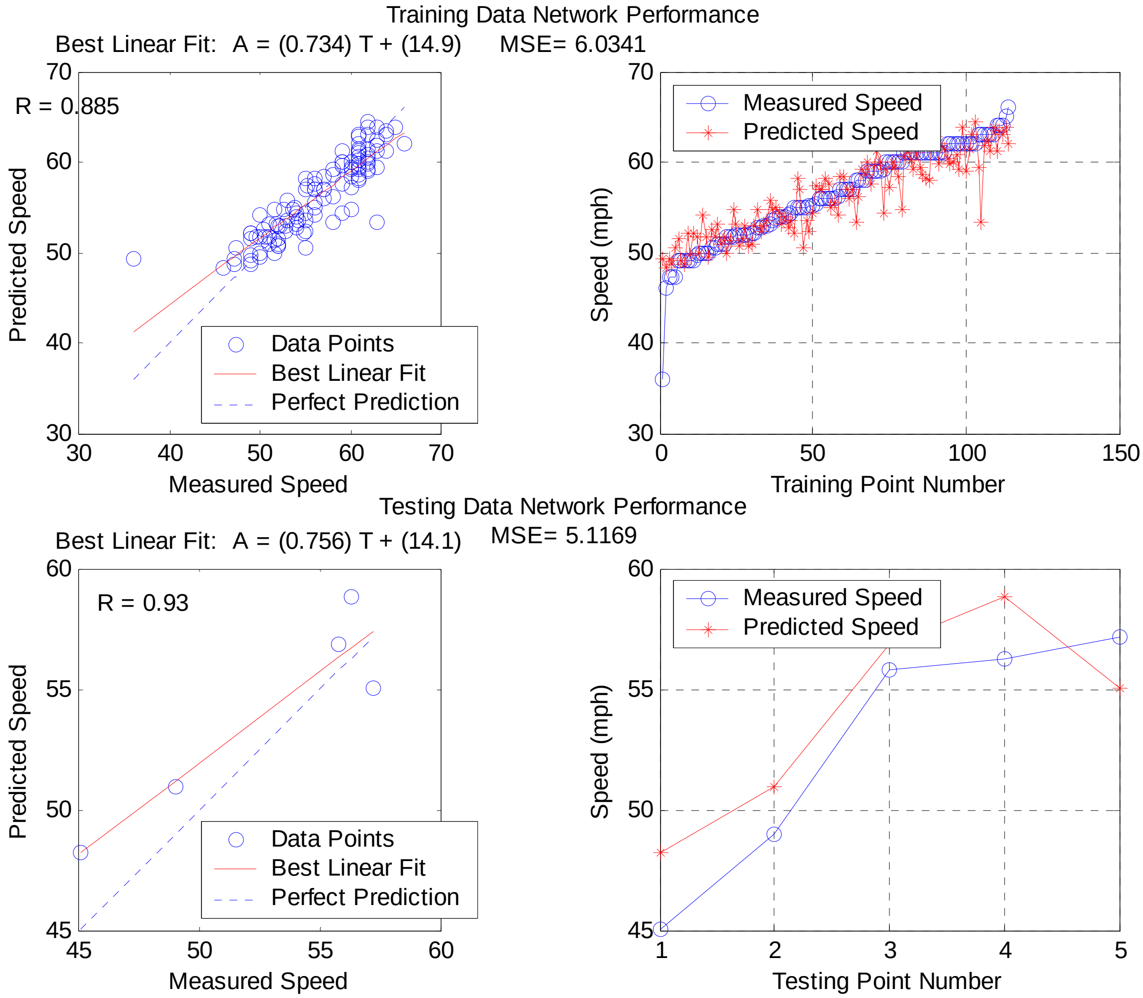

Figure 24. ANN results for mean speed data for trucks.

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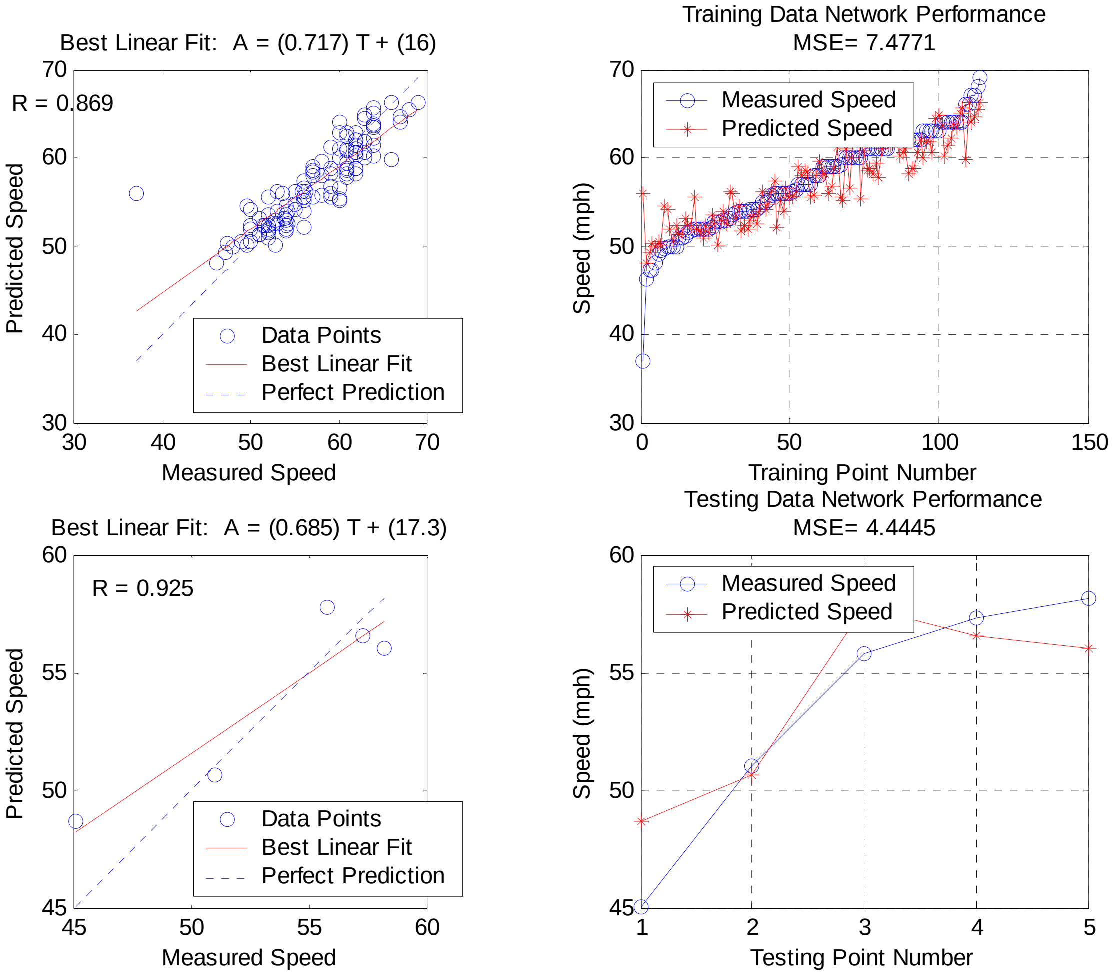

Figure 25. ANN results for mean speed data for all vehicles.

Table 17 Mean square errors (MSE) with different datasets

Model	MSE - Train Set	MSE - Test Set
Cars – Mean speed	7.0893	3.7791
Cars – Mean speed variance	24.6589	1.6753
Trucks – Mean speed	6.0341	5.1169
Trucks – Mean speed variance	25.7865	12.3127
All – Mean speed	7.4771	4.4445
All – Mean speed variance	19.9121	4.8804
Cars – Mean speed	7.0893	3.7791
Cars – Mean speed variance	24.6589	1.6753
Trucks – Mean speed	6.0341	5.1169

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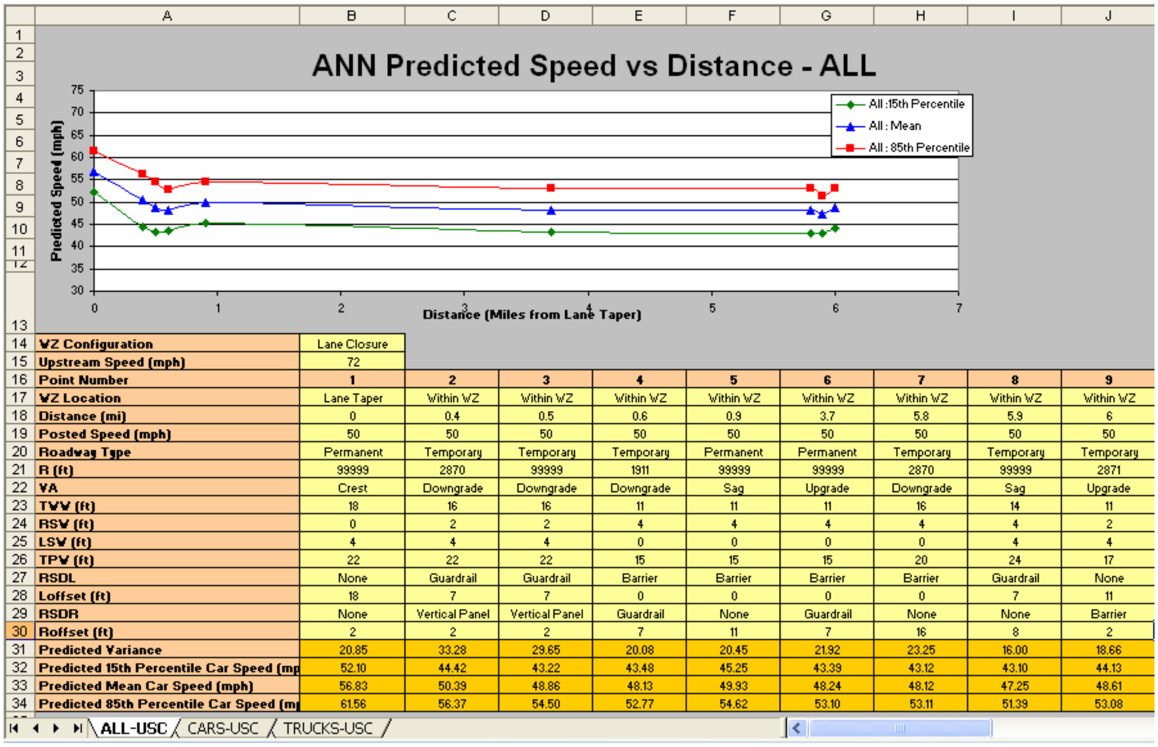
4.2.6 Excel Implementation

The spreadsheet then calculates the predicted speed profiles for 15th percentile speed, mean speed and 85th percentile speed and plots them on one graph. The 15th and 85th percentile speeds are calculated as follows:

- 15th Percentile speed = Mean speed – 1.036 S.D;
- 85th Percentile speed = Mean speed + 1.036 S.D.

S.D. refers to the standard deviation that is calculated as the positive square root of the variance predicted using ANN. The underlying assumption here is that the speed distribution is normal and is symmetrical about the mean speed. There are three separate spreadsheets: one each for cars, trucks and all vehicles. A screenshot of the program can be seen in Figure 26. A more detailed snapshot is given in Figure 27. The Excel sheet has a protected area wherein the weight and bias matrices obtained from the MATLAB ANN model are input. The user is advised against any alteration of the values in that area, as it can affect the performance of the model. A user guide for the Excel model, along with the program CD, is included in Appendix B.



	A	B	C	D	E	F	G	H	I	J
14	**WZ Configuration**	Lane Closure								
15	**Upstream Speed (mph)**	72								
16	**Point Number**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
17	**WZ Location**	Lane Taper	Within WZ	Within WZ	Within WZ	Within WZ	Within WZ	Within WZ	Within WZ	Within WZ
18	**Distance (mi)**	0	0.4	0.5	0.6	0.9	3.7	5.8	5.9	6
19	**Posted Speed (mph)**	50	50	50	50	50	50	50	50	50
20	**Roadway Type**	Permanent	Temporary	Temporary	Temporary	Permanent	Permanent	Temporary	Temporary	Temporary
21	**R (ft)**	99999	2870	99999	1911	99999	99999	2870	99999	2871
22	**VA**	Crest	Downgrade	Downgrade	Downgrade	Sag	Upgrade	Downgrade	Sag	Upgrade
23	**TWW (ft)**	18	16	16	11	11	11	16	14	11
24	**RSW (ft)**	0	2	2	4	4	4	4	4	2
25	**LSW (ft)**	4	4	4	0	0	0	0	4	4
26	**TPW (ft)**	22	22	22	15	15	15	20	24	17
27	**RSDL**	None	Guardrail	Guardrail	Barrier	Barrier	Barrier	Barrier	Guardrail	None
28	**Loffset (ft)**	18	7	7	0	0	0	0	7	11
29	**RSDR**	None	Vertical Panel	Vertical Panel	Guardrail	None	Guardrail	None	None	Barrier
30	**Roffset (ft)**	2	2	2	7	11	7	16	8	2
31	**Predicted Variance**	20.85	33.28	29.65	20.08	20.45	21.92	23.25	16.00	18.66
32	**Predicted 15th Percentile Car Speed (mp**	52.10	44.42	43.22	43.48	45.25	43.39	43.12	43.10	44.13
33	**Predicted Mean Car Speed (mph)**	56.83	50.39	48.86	48.13	49.93	48.24	48.12	47.25	48.61
34	**Predicted 85th Percentile Car Speed (m**	61.56	56.37	54.50	52.77	54.62	53.10	53.11	51.39	53.08

Figure 26. Screenshot of speed profile model in Excel.

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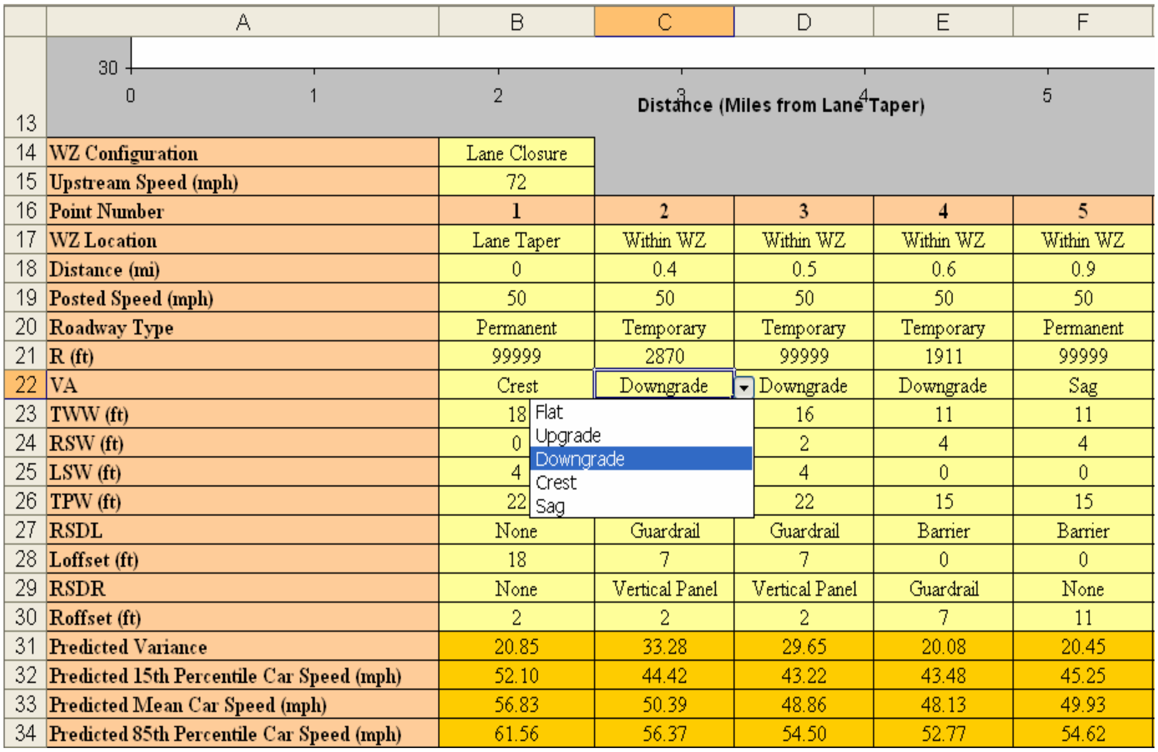

	A	B	C	D	E	F
13						
14	WZ Configuration	Lane Closure				
15	Upstream Speed (mph)	72				
16	Point Number	1	2	3	4	5
17	WZ Location	Lane Taper	Within WZ	Within WZ	Within WZ	Within WZ
18	Distance (mi)	0	0.4	0.5	0.6	0.9
19	Posted Speed (mph)	50	50	50	50	50
20	Roadway Type	Permanent	Temporary	Temporary	Temporary	Permanent
21	R (ft)	99999	2870	99999	1911	99999
22	VA	Crest	Downgrade	Downgrade	Downgrade	Sag
23	TWW (ft)	18		16	11	11
24	RSW (ft)	0		2	4	4
25	LSW (ft)	4		4	0	0
26	TPW (ft)	22		22	15	15
27	RSDL	None	Guardrail	Guardrail	Barrier	Barrier
28	Loffset (ft)	18	7	7	0	0
29	RSDR	None	Vertical Panel	Vertical Panel	Guardrail	None
30	Roffset (ft)	2	2	2	7	11
31	Predicted Variance	20.85	33.28	29.65	20.08	20.45
32	Predicted 15th Percentile Car Speed (mph)	52.10	44.42	43.22	43.48	45.25
33	Predicted Mean Car Speed (mph)	56.83	50.39	48.86	48.13	49.93
34	Predicted 85th Percentile Car Speed (mph)	61.56	56.37	54.50	52.77	54.62

Figure 27. Excel speed profile model detail.

4.2.7 Conclusions

The goal of this part of the research was to develop a speed profile model that will enable designers to detect design inconsistencies in construction work zone designs for high-speed highways before their implementation. An ANN was selected for model generation because of the advantages it offers. Two advantages include the elimination of the need to guess the form of the model and the capability to automatically model most relationships. Input data for the model were collected from 17 work zones in Pennsylvania and Texas. A total of 119 sample points (excluding the upstream points) was obtained. Once developed, the ANN model was implemented in Microsoft Excel for ease of use. The model exhibits good prediction accuracies. However, accuracies can be improved further by collecting data points at closer intervals throughout the work zones and by increasing the sample size. Overall, this research has shown the potential that ANN models offer for future applications involving transportation safety.

4.3 PRELIMINARY AND DETAILED DESIGN OF SPECIFIC WORK ZONE TYPES AND FEATURES

Guidance has been developed on many subjects. It is desirable that all guidance be based on a thorough understanding of how each decision will affect traffic safety and mobility and other outcomes of interest (e.g., speeds, driver comfort). Some design

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factors have been the subjects of previous research, while many others have not. Therefore, guidance that provides for documented relationships among all design factors and performance is not achievable. As a practical matter, work zone design decisions are a routine part of transportation agency processes. The guidance used to make these decisions was regarded as baseline information that carries some level of empirical validation. However, guidance published by the various state DOTs is not uniform. The guidance on specific subjects sometimes varies, which may be attributable to setting (e.g., climate, terrain), service demands (traffic), organizational priorities or differing technical approaches. The scope of coverage also varies, presumably reflecting the needs and priorities of individual DOTs. Access to state DOT procedures was generally attained by survey instrument responses and procedures submitted with the survey or information available from an agency Web site. Additionally, several DOTs provided information as part of informal communications during the course of the research.

The span and coverage of the guidance was identified early in the research. Priorities were identified using state DOT survey input and direction from NCHRP, leading to detailed studies on several subjects. For other topics, the general approach was to develop guidance on the basis of various sources (e.g., existing state policies and practices, published research and design principles). The purpose of this section is to document the origin and basis for areas of design guidance, designated by subheadings.

4.3.1 Work Zone Strategies and Planning

It was found that work zone guidance publications of some DOTs provide information on the identification and evaluation of candidate work zone strategies, while others do not. Inclusion of this information was considered desirable and consistent with the scope of the research. Definitions and basic information for specific work zone configurations and mitigation strategies is provided. Definitions were developed by the research team for work zone types that appeared in state DOT design guides and literature. Terms are not always used in the same manner. For example, “detour” and “diversion” are sometimes used to describe the same work zone type. When different meanings are applied to the same term, the more common or clearly established usage was adopted. In the example cited, the *MUTCD* Part 6 distinguishes between detour and diversion.

Several state DOTs (e.g., Connecticut, Illinois) use an identical matrix-formatted exhibit, “Identification of Feasible Work Zone Types,” presumably derived from *Planning and Scheduling Work Zone Traffic Control* (*55)*. The work zone design guidance Exhibits 3-4 and 3-5 in Appendix A were developed as an extension of previous work, in the following manner. First, an effort was made to distinguish work zone types that reduce capacity from those that mitigate. For example, in practitioner discussions, a project work zone type might be referred to simply as a “detour” or alternatively a “diversion.” In these examples, it is clear that the permanent road is closed. However, in other cases a single term may not be self-explanatory. For example “lane constriction,” which is one of the work zone types listed in the Identification of Feasible Work Zone Types matrix (*55*), may or may not include capacity mitigation by maintaining the same

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number of lanes. Another enhancement is the development of separate exhibits for two-lane and multi-lane facilities. This was provided to facilitate use by designers. Additionally, numerical rankings for the various strategies were included. These are subjectively established based on general impacts to traffic, cost and feasibility. The guidance document clearly states that the numerical rankings are not an indication of the appropriate choice for a specific set of conditions but rather are a general guide to establish an order or range of alternatives that should be evaluated using the factors provided in the same chapter.

Several state DOTs (e.g., Illinois, Indiana) included information on one or more contracting strategies in work zone design guidance. It was concluded that this information may be useful to other agencies, even though some agencies may have policy or legal restriction against some strategies. The information included in the guidance was prepared after reviewing the FHWA Web site on innovative contracting (*56*) and state DOT guidance.

4.3.2 Controls and Principles

Design controls are defined in the guidance as factors that lie outside the designer's discretion but may affect the design process and the designed solution. The categories of controls and associated narrative description were developed by the research team.

Highway design in general and work zone design in particular are not exact sciences, governed entirely by deterministic processes. However, a body of knowledge has evolved, including principles that apply to many specific design areas. These principles are largely empirical and rise above complex subsystems through an often simple expression. An example is the forgiving roadside concept, which implicitly embraces the cumulative performance of driver, infrastructure and vehicle subsystems. Yet the guiding principle has continued relevance and benefit in the design process. The *Green Book* includes an explanation of (driver) expectancy. The guidance provides a principle of design consistency that is based on expectancy. Although these topics are closely related, design consistency is generally recognized as an objective of the design process, while expectancy describes a human factor. The principle of primacy is described and applied in the guidance in a manner similar to that in the *Green Book.*

Guidance on speed management and consideration of speed in design decisions was developed by the research team based on several sources. General information on speed management was obtained from the FHWA Web site (*57*). The term and definition for "work zone design speed" was developed after reviewing how various DOTs consider speed in work zones, the role of "design speed" in the *Green Book*, and the *MUTCD* Part 6 provision on work zone speed limits. Speed, and especially speed in work zones, has been a controversial subject for some time. The research team attempted to develop guidance that is consistent with general speed management doctrine, reinforces the *MUTCD*, is generally consistent with the practices of some DOTs, and is useful to practitioners at the project level.

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Linkages were identified between construction work zones, desirable speed behavior, work zone design, and implementing speed management and control techniques. This guidance (section 2.2.4 of Appendix A) extends beyond any existing agency guidance reviewed during the research. It was developed as a step toward reconciling the inconsistencies among design, regulatory and operating speeds that pervade work zones and permanent facilities.

Guidance on roadside safety, roadside design and barrier placement in construction work zones builds on previous research and design guidance, notably that reflected in the *Roadside Design Guide* and state DOT design practices, as outlined in section 4.2 of Appendix A. An extensive effort was made to the development of objective guidance for commonly occurring work zone design scenarios.

4.3.2.1 Sight Distance

Development of guidance related to sight distance presented a quandary. There is no doubt that some amount (length) of sight distance is needed to avoid collisions. Sight distance criteria based on speed, as in the existing *Green Book* approach for stopping sight distance, seems appropriate.

Several studies investigating a possible relationship between available sight distance and crash rates have been conducted and are summarized by Fambro et al. (*58*) in their research report that is the source of the stopping sight distance criteria in the current *Green Book*. That report concluded that “in the sight distance ranges studied, limited stopping sight distances had no discernable effect on accident frequency or rate.” However, one of the studies (*59*) reported that crash frequencies on crest vertical curves with sight distances of less than 300 feet were more than 50 percent higher than on crest vertical curves with very long sight distances. No research on the relationship between sight distance in work zones and safety was identified.

Practice among state DOTs in this area is divided. Half (16 of 32) of the state DOT respondents indicated that a stopping sight distance criterion is used in work zone design. Under these conditions, specific stopping sight criteria were not recommended. Instead, the design guidance includes a discussion of sight distance and the criteria used by some agencies.

The literature on this subject leads to the conclusion that extended sight distance approaching and within work zones is desirable from an operations perspective. Safety considerations also point to some minimum sight distance need, but not necessarily as a function of a speed parameter. Many state DOTs use stopping sight distance criteria based on the *Green Book* and corresponding to work zone design speed. These values are not unreasonable for use in designing work zones but do not necessarily represent the minimums that can be accepted. Based on these considerations the design guidance recommends at least 300 feet of sight distance for construction work zones with work zone design speeds of 40 mph and greater. For work zone design speeds of less than 40

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mph, *Green Book* stopping sight distance values are recommended. *Green Book* values for driver eye height and object height are recommended.

4.3.2.2 Roadway Surface and Cross Section

Exhibit 2-2 in the design guidance document is an adaptation of Montana DOT's guidance. As outlined in section 3.2.4.2 of this report, several states (Connecticut, Montana, North Carolina, Texas, Wisconsin) selectively use lower-level road surfaces for low levels of exposure. The Montana DOT guidance accounts for both traffic volume and duration and is therefore considered the most appropriate format. The values also appear appropriate in the context of practice by other states.

Roadway and shoulder cross slope guidance is based on permanent road design.

4.3.2.3 Horizontal Alignment-Superelevation

Horizontal alignment design in work zones is generally limited to temporary roadways, such as diversions and median crossovers. As outlined in section 3.2.3 of this report, a number of alignment design practices and corresponding superelevation distribution methods are in use by various states. *Green Book* superelevation distribution Methods 2 and 5 are the most common. Both of these methods are identified in the guidance document as appropriate for designing curve-superelevation relationships in construction work zones on high-speed highways. Minimum radii values for work zone design speed and superelevation rates were computed using Method 2 and are provided as design aids. An example was developed demonstrating the use of the Method 2 design aid and its application to negative superelevation (adverse cross slope).

4.3.2.4 Vertical Alignment

Guidance on maximum grades was developed primarily from a review of state DOT work zone design guidance, which is often based on design of permanent roads. Vertical curve designs for permanent roads are based on stopping sight distance criteria. Since specific sight distance criteria are not recommended by the guidance, it follows to not recommend minimum vertical curve lengths on that basis. However, the guidance references the influence of limited sight distance on operating speed and suggests that designers consider this effect in designing crest vertical curves. The guidance contains information from the *Green Book* on how to design a sag vertical curve for comfort, which is an appropriate basis for design absent another controlling consideration (i.e., sight distance, drainage).

4.3.3 Detailed Guidance by Work Zone Type

Each work zone type is unique and poses distinctive design challenges. This uniqueness prevents any set of general principles from being complete or fully applicable to all design features for all work zone types. Therefore, specific design guidance is organized by work zone type. Much of the guidance relies on general principles, and

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these provisions are referenced, rather than repeated or summarized, when applicable. The following discussion outlines the basis for work zone types and strategies.

4.3.3.1 Diversion

Design of a diversion, a temporary roadway, involves the typical roadway design decisions. Guidance on horizontal alignment and superelevation, vertical alignment, and roadway surface for diversions references general guidance provisions that are considered applicable.

Guidance on minimum roadway width was developed in consideration of state DOT guidance and general design-related safety principles. Permanent rural road design criteria, including those for minimum traveled way and shoulder widths and minimum widths for new and reconstructed bridges and existing bridges to remain in place, were also reviewed as bases of reference.

The DOTs for Illinois, Indiana, Mississippi and North Carolina provide guidance for traveled way and shoulder widths for diversions. The range of recommended traveled way widths for conditions that would exist on a two-lane diversion of a high-speed facility vary from 18 to 24 feet. The guidance of two agencies does not include consideration of traffic characteristics (volume, mix) or curvature. One agency considers volume, and one considers both traffic mix and curvature. (For curve radii below 400 feet, recommended traveled way widths extend above 24 feet) The design recommendations for diversion shoulder widths by the same agencies vary from 2 to 8 feet. One agency recommends 6-foot shoulder widths for all diversions. The other three agencies recommend ranges of values: in two cases the specific value is based on traffic volumes; in the other case, the 2- to 4-foot range is simply stated.

Diversions are temporary facilities that typically exist for a period of several months rather than several days. Traveled way width and exposure have been related to safety on permanent two-lane rural highways. For these reasons, recommended minimum widths are based on traffic volumes. For a two-lane bi-directional roadway, a minimum 22-foot traveled way width is recommended for lower volumes. Higher volumes warrant wider cross sections, especially shoulders that provide for recovery and disabled vehicle refuge. The values in Exhibit 4-5 of the design guidance are recommended values for traveled way and roadway (traveled way plus shoulder) widths. They are not regarded as minimum values. Feedback on the draft recommendations indicates that values below those listed as frequently used, and without reported adverse safety experience. Exceeding minimum values is not discouraged.

4.3.3.2 Lane Constriction

Guidance for lane constrictions was developed after reviewing responses to the survey of state DOTs and considering factors that affect safety and operations. An additional objective was to establish a framework that provides guidance based on combinations of factors that are often identified individually. A research study (*10*)

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summarized in Chapter 2, section 2.2.4, reports on crash rates for projects with and without reduced lane widths during construction. The results suggest reducing lane widths increase crash rates. A relationship between crash rate and magnitude of the reduction or the reduced lane width was not reported.

Lane constrictions reduce the width of the traveled way and are therefore inherently undesirable from a safety and operations perspective. They are also an appropriate work zone type selection under certain circumstances. As outlined in section 3.2.4.1 of this report, nearly every state uses reduced traveled way widths under certain conditions. Factors that are often considered include:

- Traffic volume and composition (high volumes and high percentages of heavy vehicles, and truck network route designation, weigh in favor of wider minimum width);
- Facility type (higher minimum traveled way widths often pertain more to divided highways than to undivided facilities);
- Constraint (the effect of a constraining feature [e.g., temporary barrier curb, structural element] along one or both borders of a traveled way influences driver performance).

Several other factors were mentioned less frequently, including design speed, curvature, and the length (distance) and duration (time) of the lane constriction. One state (Colorado) also uses curvature and design speed, in addition to truck traffic. Most state DOT survey responses and guidance documents identify factors but do not indicate how the factors are considered in combination. All of the factors listed above are considered appropriate in design decisions and hence as bases in design guidance. Because of the many different combinations and uniqueness of each application this is understandable. However, a framework that provides guidance on the basis of several pertinent factors is desirable.

Exhibit 4-6 of Appendix A was developed as an example of how various factors can be considered in combination. The tabulated values and accompanying notes are not based on safety or operational analysis. The exhibit is intended to illustrate how an agency might choose to establish guideline values.

Guidance on the placement of temporary barriers within lane closures with minor encroachments was developed, as outlined in this report in sections 5.5.1, 5.5.2, and 5.5.3 of Appendix A.

4.3.3.3 Median Crossover

Median crossovers are a common freeway work zone configuration comprised of temporary and permanent roadway elements, with design decisions required for each. General guidance provisions for work zone design speed selection, sight distance, vertical alignment, horizontal alignment and superelevation are considered applicable and referenced.

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The design guidance of Illinois, Indiana and Wisconsin DOTs all provide for a 16-foot traveled way width. Oklahoma DOT's guidance calls for a 12-foot minimum traveled way on median crossovers. A width at or approaching 16 feet is considered appropriate because of the curvature, speeds and traffic customarily associated with freeways. No research exists to indicate the safety and operational consequences of variations in temporary work zone roadway and travel lane widths. The Illinois, Indiana, North Carolina and Wisconsin DOTs provide the same shoulder on both sides of a crossover; shoulder widths in conjunction with travel lane vary from 2 to 5 feet. Sample project plans were reviewed with shoulders up to 7 feet in width. The guidance recommends consideration of a wider right shoulder to reinforce its customary role as the location of refuge and to reduce potential conflict with temporary barriers. The guidance defers to agency experience.

The design recommendations for multi-lane temporary roads, including shoulders, are based on limited published guidance. No research has been published specifically on safety consequences of multi-lane traveled way or shoulder widths for temporary roads in work zones.

Guidance on the placement of temporary barriers within median crossovers was developed, as outlined in sections 5.5.5 and 5.5.6.

4.3.3.4 Use of Shoulder

Connecticut, Illinois and Indiana DOTs provide guidance on this work zone type and were used to identify key issues. Some of the specific agency practices (e.g., replacement of shoulder pavement) were outlined in the guidance as possible action rather than a requirement. The research team expanded the scope of the guidance to address consideration of existing rumble strips and roadside design. The use of selective exclusion signs assigning heavy truck traffic to permanent traveled way lanes (i.e., prohibited from using shoulder as temporary lane) was gleaned from Illinois DOT guidance and was outlined in the guidance as an alternative, but one requiring enabling legal authority.

The effects of relocating traffic closer to roadside hazards common to permanent roadways (e.g., culvert ends) was modeled with RSAP. Although more annual crashes with the hazard could result when a shoulder is converted to a travel lane, the short exposure time of one year (and often less for work zone durations) resulted in a benefit-cost ratio smaller than in the 25-year permanent roadway analysis (i.e., less than 0.5).

These results indicate that it is not cost effective to install temporary guardrail to shield a hazard that does not justify shielding under permanent roadway conditions, even if traffic is shifted to the outside shoulder.

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4.3.3.5 Interchange Ramps

One study on safety at interchanges within work zones was identified and is summarized in section 2.2.3 of this report. The conclusions are not useful in developing interchange ramp design work zone design guidance. The results of the state DOT survey documented in section 3.2.6.4 of this report show a wide variation in practice related to entrance ramp acceleration lane length within construction work zones. The range is illustrated by the state DOTs of Arkansas, Michigan, Oregon, New Jersey and Connecticut. As a result of this wide variation in practice and the absence of any established relationships between design of work zone acceleration lane lengths and safety, the formulation of guidance is left to operational considerations and judgment. The guidance describes the practices of Michigan and Oregon, without attribution, which are characterized as “rules of thumb.”

The *MUTCD* Part 6 provides examples of temporary traffic control (TTC) at entrance ramps within work zones. Maryland State Highway Administration has developed guidance on TTC (i.e., stop and yield control with related signage) for acceleration lane length. A summary of the Maryland information is included in the work zone design guidance document produced in this research (Appendix A).

Guidance pertaining to exit ramps is based on permanent road guidance. Dimensional values for taper and parallel deceleration lane lengths were obtained from New Jersey and Wisconsin DOT survey responses.

4.3.3.6 At-Grade Intersections

The guidance was developed primarily on the basis of avoiding and managing traffic conflicts, using general strategies such as relocation, channelization and TTC. Several specific strategies (e.g., changing control type from yield to stop) were obtained from state DOT guidance documents.

4.3.4 Ancillary Design Features

The work zone design guidance of several state DOTs addresses drainage in a general manner to determine that the same general practices (e.g., rationale formula, design charts) used for permanent roads are also used for general practice. The Florida DOT *Drainage Handbook*, *Temporary Drainage Design* (*60*) and AASHTO *Model Drainage Manual* (*61*) were the primary references for the guidance. The example of using a design storm with 10-year recurrence interval as the basis for designing a temporary bridge is based on Missouri DOT’s design guidance. The guidance on slotted drains was developed from field observations and review of the Texas DOT Web-accessible *Hydraulic Design Manual* (*62*).

Design guidance for Enforcement Pullout Areas was developed by the research team based on other ongoing research on the same topic, separate from this project.

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A characterization of use and spacing of emergency turnouts was based on responses from 12 state DOTs to the survey. The schematic geometry layout is based on the guidance of New York and Wisconsin DOTs and a Pennsylvania DOT example project.

Information related to the use of screens was developed from responses to the survey of state DOTs. Guidance on lighting was developed based on the policies of Indiana and Illinois DOTs and the cited research and reference publications.

Information on rumble strips that supplements the *MUTCD* was based on research publications (*63,64*) and field observations.

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CHAPTER **5**

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

The conclusions of this research are:

1. Many aspects of work zone design are not covered by any nationally recognized guidance publication.
2. Work zone design embraces many subjects and decisions beyond temporary traffic control (TTC); however, TTC remains important to work zone operations and safety.
3. Despite extensive work zone research, there are a very limited number of findings that relate design decisions to probable safety and operational consequences.
4. Databases that can be analyzed to determine relationships between work zone design decisions and probable safety consequences do not exist.
5. Highway safety is a relative, rather than categorical or discrete, characteristic and should be so recognized in developing design decision guidance for work zones.
6. Development of comprehensive design decision guidance for work zones requires extending and adapting numerous design principles and information developed for permanent roads to roads in work zones, despite some significant differences between roads in work zones and permanent roads.
7. Exposure is a key factor in highway safety and differs substantially between permanent roads and roads in work zones; the difference should be accounted for in design guidance and design decisions.
8. Roadside design and barrier placement guidance currently in widespread use for work zones do not explicitly account for exposure.
9. Development of generalized barrier placement and roadside design guidance for practitioners that is based on cost-effectiveness principles is feasible. The Roadside Safety Analysis Program (RSAP) (*48*), despite some current flaws, increases the feasibility of developing guidance for generalized conditions. (Design aids for generalized conditions were developed and are included in Appendix A of this report).
10. RSAP is amenable to analysis of specific roadside hazard conditions in work zones, but it could be enhanced for this purpose by eliminating program errors and adding additional functions specifically related to work zones.
11. An encroachment model and a severity prediction tool are critical elements of roadside safety analysis and roadside design decisions. Current encroachment models and crash severity indices may not be well suited for construction work zones on high-speed highways.
12. Work zone speed is a subject of widespread interest and research. Despite this interest, there is very little guidance addressing the subject as a related set of

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regulatory, driver information, geometric and enforcement factors. Basic speed management principles should be applied to work zones.

13. An Artificial Neural Network speed model for work zones, capable of making useful predictions of vehicle speeds in two types of work zones on high-speed highways, was developed and is included in Appendix B of this report. The model is appropriate for use where actual conditions are within, but not beyond, the limits of the data used for its development. The model may be used toward integrating work zone design into work zone speed management.
14. Work zone design criteria and guidance of various state DOTs vary substantially on several topics. Examples of disparity are in the areas of sight distance; superelevation rates; minimum travel lane widths; traveled way and shoulder widths for temporary roads; speed change lanes at interchanges; barrier placement; and ancillary items.
15. Several state DOTs have comprehensive work zone design guidance. The most comprehensive guidance publications are similar and based on the same information.

5.2 RECOMMENDATIONS

The recommendations of this research are:

1. Guidance for construction work zones on high-speed highways in Appendix A of this report should be considered for adoption and implementation by AASHTO and/or individual transportation agencies.
2. Current coordination efforts related to the contents of the *Manual on Uniform Traffic Control Devices* and *Roadside Design Guide* should be extended to recognize the contents of Appendix A of this report.
3. A robust database of work zone characteristics, exposure and corresponding safety performance should be planned, collected and analyzed to relate work zone design decisions to probable safety consequences. The database should include characteristics of the underlying facility (i.e., permanent condition) and work zone (i.e., work zone type, cross-sectional features and dimensions, alignment characteristics, access type and density, traffic control). A location reference system (e.g., milepost marker) should be used in both the work zone and safety records to enable matching of crash locations with specific work zone characteristics. Safety records should be matched to work zone conditions and appropriate statistical procedures used to account for vehicle and time-of-day exposure differences, regression-to-the-mean phenomena, and other external influences that can also affect crash frequency. Relationships between work zone decisions and safety consequences should be developed and integrated into future work zone design guidance.
4. The roadside design and barrier placement guidance for construction work zones on high-speed highways included in Appendix A of this report should be considered for adoption and implementation by AASHTO and/or individual transportation agencies and serve as a foundation for future progress.

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5. An encroachment and crash consequence prediction model(s) for work zones on high-speed highways should be developed to improve the cost-effectiveness of roadside safety and design decisions.
6. RSAP should be enhanced to eliminate current programming errors and include roadside conditions in common work zones (e.g., median crossover, construction in a closed lane adjacent to an active lane), hazards (e.g., equipment, opposing-direction vehicles, partial bridge and pavement structures), and countermeasures. A model with these capabilities would facilitate analysis of very specific conditions and diminish use of or replace generalized design aids, such as those provided in Appendix A of this report.
7. The Artificial Neural Network speed model for work zones developed under this project and included as Appendix B of this report is recommended for use within the limits of the data used for its development. The model was developed for two types of work zones using data within observed ranges. These work zone types and data ranges might not encompass the values common in some locales and jurisdictions. Expansion of the model's capability is recommended.
8. For work zones within the range of its applicability, the Artificial Neural Network speed model for work zones should be used for design and regulatory (speed limit) decisions.

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REFERENCES

1. Ullman, G. L. and Krammes, R. A., "Analysis of Accidents at Long-Term Construction Projects in Texas." *Report No. FHWA/TX-90/1108-2,* Texas Transportation Institute, College Station, TX (June 1991).

2. Migletz, J., Graham, J. L., Anderson, I. B., Harwood, D. W., and Bauer, K. M., "Work Zone Speed Limit Procedure." *TRR 1657,* Transportation Research Board, National Research Council, Washington, DC (1999) pp.24-30.

3. Federal Highway Administration, "Moving Ahead: The American Public Speaks on Roadways and Transportation Communities." *FHWA-OP-01-017,* Washington, DC (2001).

4. Federal Highway Administration, *Manual on Uniform Traffic Control Devices*. Washington, DC (2003).

5. American Association of State Highway and Transportation Officials, *A Policy on Geometric Design of Highways and Streets*. Washington, DC (2004).

6. American Association of State Highway and Transportation Officials, *Roadside Design Guide*. Washington, DC (2002).

7. Walker, V. and Upchurch, J., "Effective Countermeasures to Reduce Accidents in Work Zones." *Report No. FHWA-AZ99-467,* Arizona Department of Transportation, Phoenix, AZ (Nov. 1999).

8. Daniel, J., Dixon, K., and Jared, D., "Analysis of Fatal Crashes in Georgia Work Zones." *TRR 1715,* Transportation Research Board, National Research Council, Washington, DC (2000) pp. 18-23.

9. Garber, N. J. and Zhao, M., "Crash Characteristics at Work Zones." *Report No. VTRC 02-R12,* Virginia Transportation Research Council, Charlottesville, VA (May 2002).

10. Graham, J. L., Paulsen, R. J., and Glennon, J. C., "Accident Analyses of Highway Construction Zones." *TRR 693,* Transportation Research Board, National Research Council, Washington, DC (1978) pp. 25-32.

11. Lisle, F. N., "Evaluation of Timber Barricades and Precast Concrete Traffic Barriers for Use in Highway Construction Areas." *TRR 693,* Transportation Research Board, National Research Council, Washington, DC (1978) pp. 18-25.

12. Hall, J. W. and Lorenz, V. M., "Characteristics of Construction Zone Accidents." *TRR 1230,* Transportation Research Board, National Research Council, Washington, DC (1989) pp. 20-27.

Copyright National Academy of Sciences. All rights reserved.

13. Pal, R. and Sinha, K. C., “Analysis of Crash Rates at Interstate Work Zones in Indiana.” *TRR 1529*, Transportation Research Board, National Research Council, Washington, DC (1996) pp. 43-53.

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

15. Casteel, D. B. and Ullman, G. L., “Accidents at Entrance Ramps in Long-Term Construction Work Zones.” *TRR 1352,* Transportation Research Board, National Research Council, Washington, DC (1991) pp. 46-55.

16. Venugopal, S. and Tarko, A., “Safety Models for Rural Freeway Work Zones.” *TRR 1715*, Transportation Research Board, National Research Council, Washington, DC (2000) pp. 1-9.

17. Khattak, A. J. and Targa, F., “Injury Severity and Total Harm in Truck-Involved Work Zone Crashes.” 83rd Annual Meeting, Transportation Research Board, National Research Council, Washington, DC, *TRB 2004 Annual Meeting CD-ROM* (Jan. 2004).

18. Pigman, J. G. and Agent K. R., “Highway Accidents in Construction and Maintenance Work Zones.” *TRR 1270*, Transportation Research Board, National Research Council, Washington, DC (1990) pp. 12-21.

19. Ha, T. J. and Nemeth, Z. A., “Detailed Study of Accident Experience in Construction and Maintenance Zones.” *TRR 1509,* Transportation Research Board, National Research Council, Washington, DC (1995) pp. 38-45.

20. Wang, J., Hughes, W. E., Council, F. M., and Paniati, J. F., “Investigation of Highway Work Zone Crashes: What We Know and What We Don’t Know.” *TRR 1529*, Transportation Research Board, National Research Council, Washington, DC (1996) pp. 54-62.

21. Nemeth, Z. A. and Migletz, D. J., “Accident Characteristics before, during, and after Safety Upgrading Projects on Ohio’s Rural Interstate System.” *TRR 672,* Transportation Research Board, National Research Council, Washington, DC (1978) pp. 19-24.

22. National Highway Traffic Safety Administration. *Fatality Analysis Reporting System,* http://www.transtats.bts.gov/.

23. Griffin, L. I., “Three Procedures for Evaluating Highway Safety Improvement Programs.” Annual Convention of American Society of Civil Engineers, New Orleans (Oct. 29, 1982).

Copyright National Academy of Sciences. All rights reserved.

24. Burns, E. N., Dudek, C. L., and Pendleton, O. J., "Construction Costs and Safety Impacts of Work Zone Traffic Control Strategies." *Report No. FHWA-RD-89-209*, Vol. 1, Federal Highway Administration, Washington, DC (Dec. 1989).

25. Ullman, G. L., A.J. Holick, S.M. Turner, and T.A. Scriba. Estimates of Work Zone Exposure on the National Highway System in 2001. In *Transportation Research Record 1877*. 2004, pp. 62-68.

26. Burns, E. N., Dudek, C. L., and Pendleton, O. J., "Construction Costs and Safety Impacts of Work Zone Traffic Control Strategies." *Report No. FHWA-RD-89-209*, Vol. 1, Federal Highway Administration, Washington, DC (Dec. 1989).

27. Transportation Research Board, National Research Council, *Highway Capacity Manual*, Washington, DC (2000).

28. Federal Highway Administration, "*Identifying Acceptable Highway Safety Features.*" Memorandum from Director, Office of Engineering, Washington, DC (July 25, 1997).

29. Federal Highway Administration, "*Crash Tested Work Zone Devices.*" Memorandum from Director, Office of Engineering, Washington, DC (August 28, 1998).

30. Krammes, R. A. and Lopez, G. O., "Updated Capacity Values for Short Term Freeway Work Zone Lane Closures." *TRR 1442*, Transportation Research Board, National Research Council, Washington, DC (1994) pp. 49-56.

31. Dudek, C. L., "Notes on Work Zone Capacity and Level of Service." Texas Transportation Institute, Texas A&M University, College Station, TX (1984).

32. Dudek, C. L., Richards, S. H., and Buffington, J. L., "Improvements and New Concepts for Traffic Control in Work Zones, Vol. I: Four Lane Divided Highways." *Report FHWA-RD-85-034*, Federal Highway Administration, Washington, DC (1985).

33. Burns, E. N., Dudek, C. L., and Pendleton, O. J., "Construction Costs and Safety Impacts of Work Zone Traffic Control Strategies, Vol. I: Final Report." *Report FHWA-RD-89-209*, Federal Highway Administration, Washington, DC (1989).

34. Ressel, W., "Traffic Flow and Capacity at Work Sites on Freeways." Highway Capacity and Level of Service, International Symposium on Highway Capacity, Karlsruhe, Germany, Balkema, Rotterdam, The Netherlands, Proceedings (1991) pp. 321-328.

35. Federal Highway Administration, Advanced Notice of Proposed Rulemaking, Work Zone Safety. *Federal Register*, Vol. 67, No. 25, Docket No. FHWA-2001-11130. Washington, DC (February 6, 2002).

Copyright National Academy of Sciences. All rights reserved.

36. Fitzpatrick, K., Carlson, P., Brewer, M. A., Wooldridge, M. D., and Miaou, S. P., "Design Speed, Operating Speed, and Posted Speed." *NCHRP Report 504*, Transportation Research Board, National Research Council, Washington, DC (2003).

37. Zegeer, C. V. and Council, F. M., "Safety Effectiveness of Highway Design Features: Volume III, Cross Sections." *Report FHWA-RD-91-048*, Federal Highway Administration, Washington, DC (1991).

38. Harwood, D. W., Council, F. M., Hauer, E., Hughes, W. E., and Vogt, A., "Prediction of the Expected Safety Performance of Rural Two-Lane Roads." *Report FHWA-RD-99-207*, Federal Highway Administration, Washington, DC (2000).

39. American Association of State Highway and Transportation Officials, *Model Drainage Manual*. Washington, DC (2002).

40. American Association of State Highway and Transportation Officials, *Highway Design and Operational Practices Related to Highway Design.* Washington, DC (1974).

41. American Association of State Highway Transportation Officials, *Guide for Selecting, Locating and Designing Traffic Barriers*. Washington, DC (1977).

42. American Association of State Highway Transportation Officials, *Standard Specifications for Structural Supports for Highway Signs, Luminaires, and Traffic Signals.* Washington, DC (2001).

43. American Association of State Highway Transportation Officials, *A Policy on the Accommodation of Utilities within Highway Right-of-Way.* Washington, DC (1994).

44. American Association of State Highway Transportation Officials, *A Policy on the Accommodation of Utilities within Freeway Right-of-Way.* Washington, DC (1989).

45. Ross, H. E., Jr., Sicking, D. L., and Zimmer, R. A., "Recommended Procedures for Safety Performance Evaluation of Highway Features." *NCHRP Report 350*, Transportation Research Board, National Research Council, Washington, DC (1993).

46. Ross, H. E. and Sicking, D. L. "Guidelines for Use of Temporary Barriers in Work Zones." Final Report, Volume I, *Research Report 4151-1,* Texas Transportation Institute, Texas A & M University, College Station, TX, 1983.

47. Michie, J. D. "Development and Application o Positive Barrier Warrants in Highway Construction Zones." *Reports on Traffic Flow and Safety Applications of Road Barriers*, Federal Highway Administration, Washington, DC (2000).

Copyright National Academy of Sciences. All rights reserved.

48. Mak, K., and Sicking, D. L., "Roadside Safety Analysis Program (RSAP) – Engineer's Manual." *NCHRP Report 492*, Transportation Research Board, National Research Council, Washington, DC (2003).

49. Glennon, J. C., "Roadside Safety Improvement Programs on Freeways: A Cost-Effectiveness Priority Approach." *NCHRP Report 148*, Transportation Research Board, National Research Council, Washington, DC (1974).

50. Cooper, P., "Analysis of Roadside Encroachments – Single-Vehicle Run-off-Road Accident Data Analysis for Five Provinces," B.C. Research, Vancouver, British Columbia, Canada, March 1980.

51. United States Department of Transportation, "Motor Vehicle Accident Costs," Technical Advisory T7570.2, October 31, 1994. accessed at http://www.fhwa.dot.gov/legsregs/directives/techadvs/t75702.htm

52. The Pennsylvania Department of Transportation Bureau of Design, "Construction Cost Catalog for Standard Construction Items," January 2003.

53. M. T. Hagan, Demuth, H. B., and Beale, M., *Neural Network Design*. PWS Publishing Company (1996).

54. Demuth, Howard and Beale, Mark. *Neural Network Toolbox User's Guide: For Use with MATLAB*. The Mathsworks, Inc., Natick, MA (2004).

55. Abrams, C.M. and Wang, J.J. *Planning and Scheduling Work Zone Traffic Control*. Report No. FHWA-IP-81-6. Federal Highway Administration, Washington DC. October 1981.

56. Federal Highway Administration, Briefing on FHWA Innovative Contracting Practices: Special Experimental Project No. 14 (SEP-14). Washington DC. Accessed at http://www.fhwa.dot.gov/programadmin/contracts/sep_a.htm.

57. Federal Highway Administration, Speed Management. Washington DC. Accessed at http://safety.fhwa.dot.gov/speed_manage.

58. Fambro, D. B., Fitzpatrick, K., Koppa, R. J., "Determination of Stopping Sight Distances." *NCHRP Report 400*, Transportation Research Board, National Research Council, Washington, DC (1997).

59. Olson, P. L., Cleveland, D. E., Fancher, P. S., Kostyniuk, L. P., and Schneider, L. W., "Parameters Effecting Stopping Sight Distance." *NCHRP Report 270*, Transportation Research Board, National Research Council, Washington, DC (1984).

60. Florida Department of Transportation Office of Design, Drainage Section, *Drainage Handbook: Temporary Drainage Design*. Tallahassee, FL (2001).

Copyright National Academy of Sciences. All rights reserved.

61. American Association of State Highway and Transportation Officials, *Model Drainage Manual*. Washington, DC (2002).

62. Texas Department of Transportation, *Hydraulic Design Manual* (2004). Accessed at http://manuals.dot.state.tx.us/dynaweb/colbridg/hyd/@ebt-link;cs=default;ts=default;pt=45275?target=IDMATCH(id,g100007);book=hyd.

63. Morgan, R.L., “Temporary Rumble Strips,” *Special Report 140*. Report FHWA/NY/SR-03/140, Federal Highway Administration, Washington, DC (2003).

64. Fontaine, M.D. and Carlson, Paul J., “Evaluation of Speed Displays and Rumble Strips at Rural Maintenance Work Zones.” *Proceedings,* 80th Annual Meeting of the Transportation Research Board, Washington, D.C., January 7-11, 2001.

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APPENDIXES

The following appendixes are not published herein, but are available online at www.trb.org/news/blurb_detail.asp?id=7363

- "Appendix A: Design of Construction Work Zones on High-Speed Highways." This appendix has been published separately as *NCHRP Report 581*, which can be viewed or purchased at the above URL.

- "Appendix B: Work Zone Speed Prediction Model and User's Manual." This appendix, which consists of a PDF and an Excel file, can be downloaded from the above URL.

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