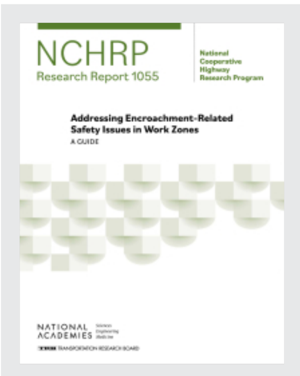

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP RESEARCH REPORT 1055

Addressing Encroachment-Related Safety Issues in Work Zones

A GUIDE

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NATIONAL ACADEMIES *Sciences Engineering Medicine*

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2023

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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NCHRP RESEARCH REPORT 1055

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FOREWORD

By Richard Retting
Staff Officer
Transportation Research Board

NCHRP Research Report 1055: Addressing Encroachment-Related Safety Issues in Work Zones: A Guide provides evidence-based guidelines to help address safety concerns associated with vehicle encroachment in work zones. Encroachment occurs when a vehicle inadvertently traverses across the boundaries of a work zone, creating safety concerns for highway workers and motorists. The research was further informed by feedback collected during a peer exchange workshop facilitated by the research team. This report will be of interest to state departments of transportation and other stakeholders concerned with reducing the incidence of vehicle encroachment in work zones.

Despite ongoing engineering and enforcement efforts to improve work zone safety, the frequency and severity of crashes in work zones remain stubbornly high. Vehicle intrusion into work areas is a significant safety concern for highway workers and motorists. Safety engineers have identified the need for additional data and analysis to determine areas for improvement in the design of work zones and the safety barriers used therein to improve safety for all road users in work zones.

Under NCHRP Project 03-134, the Texas A&M Transportation Institute was asked to develop materials for use by practitioners responsible for work zone design, operations, and maintenance.

In addition to the report, published as *NCHRP Research Report 1055*, documentation of the overall research effort is available as *NCHRP Web-Only Document 361: Determination of Work Zone Encroachments*. A PowerPoint presentation describing the research effort and the final deliverables is available on the National Academies Press website (nap.nationalacademies.org) by searching for *NCHRP Research Report 1055: Addressing Encroachment-Related Safety Issues in Work Zones: A Guide*.

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Note: Photographs, figures, and tables in this report may have been converted from color to grayscale for printing. The electronic version of the report (posted on the web at nap.nationalacademies.org) retains the color versions.

CHAPTER 1

Introduction

Over 102,000 work zone (WZ) crashes occurred in 2020 in the United States, which equates to a WZ crash every 5.2 minutes. A fatal WZ crash occurs every 10.2 hours and, in 2020, accounted for 2.2 percent of all U.S. roadway fatalities (857 of 38,824) (National Work Zone Safety Information Clearinghouse [NWZSIC] 2022). U.S. roadway WZ fatalities increased by 19 percent from 2015 to 2020, and the FHWA cited additional traffic, distracted driving, and an increase in construction projects as possible factors for the increase (Slowey and Zubrzycki 2018).

NCHRP Research Report 869: Estimating the Safety Effects of Work Zone Characteristics and Countermeasures: A Guidebook (NCHRP Project 17-61) listed reasons why WZs can adversely affect the safety of traffic approaching and passing through them (Ullman et al. 2018). Generally, WZ equipment, traffic control devices, and workers are in close proximity to travel lanes, which can increase the probability of vehicles crashing into the WZ equipment or hitting the roadway workers. Garber and Woo (1990) found a 57 percent increase in crashes on multilane highways in Virginia and a 168 percent increase on two-lane urban highways compared to crash rates in the period before the onset of WZs. Nemeth and Migletz (1978) showed that crash rates during construction increased significantly compared to the period before construction. Hall and Lorenz (1989) found that crashes during construction increased by 26 percent compared to crashes in the same period in the previous year when no construction occurred. Similarly, Rouphail et al. (1988) found that the crash rates during construction increased by 88 percent compared to the before period for long-term WZs; on the other hand, results from the same study indicated that the crash rates for short-term WZs were not affected by the roadwork.

Moreover, many WZs require drivers to temporarily change their travel path and, in some cases, their travel lanes, which can increase crash probability if the drivers are engaged in distracted behaviors and are not able to see the advance warning signals and pavement markings. Distracted driving, failure to yield, and traveling at unsafe speeds are among the most significant WZ crash-contributing factors. Liu et al. (2016) found that the likelihood of an injury was 10 percent higher when a driver involved in the crash committed an intentional improper action, such as speeding or following too closely. A review of 2014 Fatality Analysis Reporting System (FARS) data indicated that 71.4 percent of fatal WZ crashes were speeding related, while only about 30 percent of all fatal crashes were speeding related, indicating that driver behavior can have more devastating impacts on safety of WZs compared to non-WZs (NHTSA 2014).

WZ crashes are not only a problem for the traveling public—they are a serious concern for highway workers. In 2020, 117 WZ associated fatalities occurred, with 45 percent of those being workers struck by a highway vehicle (NWZSIC 2022). Addressing WZ crashes is critical for the traveling public and highway workers. A few researchers have attempted to investigate crashes that involve intrusions into the workspace. Bryden et al. (2000), Ullman et al. (2008), and Ullman et al. (2011) used data collected by New York State Department of Transportation (NYSDOT) staff on WZ crashes to investigate the frequency, severity, and causes of intrusion crashes occurring in that state. Researchers found that approximately nine percent of all WZ crashes involved intrusions into the workspace, but this percentage increased at night (possibly due to smaller, more focused work operations occurring during that time). Researchers also found that workers were struck in about nine percent of those intrusion crashes during daytime operations and about 31 percent during nighttime operations. Unfortunately, detailed information about the characteristics of the intruding vehicles (speeds, encroachment angles, trajectories, etc.) were not captured in that database.

Guideline Development

NCHRP Project 03-134, "Determination of Encroachment Conditions in Work Zones" was conducted to understand characteristics of encroachments in WZs such as departure angle, encroachment distance, and speed. One of the project objectives was to identify potential updates to the *Manual for Assessing Safety Hardware* (MASH), the *Roadside Design Guide* (RDG), and the *Manual on Uniform Traffic Control Devices* (MUTCD) to better address WZ encroachments. Such investigation developed guidelines addressed to state departments of transportation (DOTs) and research practitioners to improve safety for workers and the traveling public in roadway WZs. *NCHRP Research Report 1055: Addressing Encroachment-Related Safety Issues in Work Zones: A Guide* provides a complete description of project activities and findings.

CHAPTER 2

Encroachment Data: Needs and Collection Methods

While current data suggest that WZs have a higher risk than non-WZs for crashes and fatal injuries, data on the impact conditions associated with WZ crashes are not well documented. Previous research regarding WZ safety encroachments indicates that a higher frequency of fatalities occurs in WZ encroachments than in non-WZ encroachments.

Roadway encroachment is defined as travel by a vehicle on roadway areas outside the limits of the designated lane(s) of travel. The potential path a vehicle may take during an encroachment is affected by numerous factors, including speed limit, various roadway (e.g., horizontal and vertical alignment, lane/shoulder width) and roadside (e.g., side slope, access point density) characteristics, weather and lighting conditions, and driver behavior (e.g., steering, braking).

Currently, limited information exists regarding the encroachment conditions in WZs since there are no reliable datasets. Encroachment datasets were developed in two early studies: Hutchinson and Kennedy (1962) and Cooper (1980).

New encroachment database studies have since been conducted, including Hallmark et al. in 2015 and the currently active NCHRP Project 17-88, "Roadside Encroachment Database Development and Analysis." Hallmark et al. (2015) studied driver response to changing roadway characteristics and traffic conditions. The analysis evaluated the influence of roadway geometries or traffic conditions on drivers' lane-keeping behavior.

The objectives of the active NCHRP Project 17-88 are to develop a database of roadside encroachment characteristics for a variety of roadside conditions and roadway types and then analyze the database to evaluate (a) the factors that influence the nature and frequency of roadside encroachments; (b) the relationship between unreported and reported crashes; and (c) whether heavy vehicle, bus, and motorcycle encroachments resulting in a crash differ from passenger vehicle encroachments resulting in a crash. The NCHRP Project 17-88 encroachment database will record encroachments across the full range of highway vehicle types, including passenger vehicles, heavy vehicles, buses, and motorcycles, along with the entire spectrum of encroachment severities.

Overall, existing encroachment datasets are not representative of varying roadway characteristics, making it difficult to develop robust predictive models for encroachment conditions. Another under-researched area is how the rate of encroachment event is impacted by driver behaviors and the presence of in-vehicle distractions, such as cellphone use. These underlying datasets do not reflect the true relationship between encroachment frequency and traffic.

As a result, a more comprehensive approach to collecting encroachment data is needed to address these shortcomings.

State of the Practice Review

The project team used a variety of state DOT publications and results of a survey of DOTs to examine the state of the practice on use of positive protection in WZs. The survey was developed by the research team with the objective of gathering agencies' policies pertaining to roadside encroachment-intruding WZs, and it was distributed to 50 state DOTs. The survey resulted in a compilation of data elements used by the DOTs, which can be classified according to three major groups with the scope of assessing the need for positive protection in WZs: WZ criteria, roadway characteristics, and operational characteristics.

Most of the guidelines/input noted that states consider incorporating an escape path when deciding whether to use positive protection in WZs. However, no specific criteria were provided. The majority of the states consider presence of drop-off, presence of escape paths, duration, proximity of workers to moving traffic lanes, and WZ characteristics.

The most common roadway characteristics considered when deciding whether to use positive protection in WZs were shoulder type/width, lane type/characteristics, roadway geometry (presence/type of horizontal or vertical curves), sight distance, and type and class of roadway.

In terms of operational characteristics, agencies most often consider speed, which may include speed limit, operating speed, or design speed of the facility scheduled for construction. Volume and vehicle mix also were commonly listed as criteria for consideration.

Encroachment Data Collection

The encroachment data collected in early studies by Hutchinson and Kennedy (1962) and Cooper (1980) are available to state DOTs. These data are not generally used directly but rather indirectly through FHWA and AASHTO guidelines, such as the MUTCD, RDG, and MASH. Any potential changes to WZ encroachment data will have the potential to affect these guidelines, and therefore, the state practices.

Combined Data Needs

Researchers reviewed current practices used in the AASHTO guidelines and their related relevant information. Based on the list of data needs and relevant data sources, the research team developed a comprehensive data catalog to indicate what variables to include and collect, as well as the potential sources for these elements.

Data were collected mainly from naturalistic data studies (NDSs), state crash databases, and National Motor Vehicle Crash Causation Survey (NMVCCS) and NCHRP Project 17-43 project databases. The research team collected the data variables listed in Table 1 from all databases, wherever applicable.

Data Collection Process

Following is a brief description of the developed data collection process and the utilized sources.

Naturalistic Driving Studies

The research team identified and collected WZ encroachment data from readily available NDSs with WZ events.

The goal of NDSs is to address the role of driver behavior in highway safety. NDSs offer two key advantages: (a) detailed and accurate pre-crash information, including objective information

Table 1. Summary of data catalog.

Case Information	Event Description	Encroachment Description
• Date • Time and type of crash • Latitude & longitude of the crash location	• Event type • Sequence of events • Vehicle type • Vehicle stability at road departure • Damage location and severity • Rollover	• Impact speed • Impact angle • Encroachment direction (left or right)
Roadway Description	**Roadside Description**	**WZ Description**
• Road ID • Posted speed limit • Traffic volume • Number of lanes • Median type and width • Terrain • Lighting • Road alignment	• Shoulder type • Shoulder width • Presence of curbs • Pedestrian and bicycle facilities • Roadside cross section • Roadside businesses	• Type and duration of construction • Project location and configuration • MP at the beginning/end of WZ • Roadside hazards • Positive protection and traffic control
Access Management	**Driver Characteristics and Behavior**	
• Access control • Access density • Land use • Service level of the road	• Driver age • Sex • Driver distraction • Driver actions • Pre-incident maneuver • Post-maneuver control	

about driving behavior; and (b) exposure information, including the frequency of behaviors in normal driving as well as the larger context of contributing factors. NDSs have focused on different aspects of WZ safety characteristics. Thus, based on the aim of each study, the collected features vary, and extracting the information for this study required a comprehensive investigation of the provided data. To reach this goal, first, the designed data structure for this study was reviewed, and the categories of the qualitative variables were determined. The extracted data were presented in separate categories: case information, roadway description, access management, WZ attributes, roadside description, and encroachment description.

A dataset was created to incorporate the collected data. While variables on case information were readily available from the NDS data, the research team obtained the roadway description data from the SHRP 2 companion roadway inventory database. The rest of the variables on access management (e.g., access density), WZ description (e.g., lane closure type), roadside elements (e.g., type of barrier), and encroachment description (e.g., departure angle) were collected manually from NDS videos.

A total of 1,987 events were investigated. Encroachment in WZs was identified in 183 of the events, and road departures in non-WZ locations were found in 1,450 of the events.

State Crash Databases

Out of 27 contacted state DOTs that previously agreed to share their WZ crash data, 15 shared their crash data for the purpose of this project. The crash data obtained from states only included WZ crashes; non-WZ crashes were not available. Table 2 presents the DOTs that responded to the data request and shared their crash data.

Table 2. Summary of the collected crash data from state DOTs.

State	Period	Crash Details	Sequence of Events	Road and Roadside Info	Used in Analysis
California	2017–2019	–	–	–	N
Colorado	2014–2018	–	–	–	Y
Florida	2011–2019	✓	–	✓	Y
Idaho	2017–2019	✓	✓	✓	Y
Iowa	2016–2019	✓	–	–	Y
Massachusetts	2014–2018	✓	✓	–	Y
Missouri	2017–2019	–	–	✓	N
Montana	2017–2018	–	–	–	N
New Hampshire	2018–2020	–	–	✓	N
North Dakota	2017–2019	✓	–	✓	Y
Oklahoma	2016–2019	✓	–	✓	Y
Pennsylvania	2017–2018	✓	–	✓	N
Texas	2010–2019	✓	–	–	Y
Virginia	2013–2019	✓	–	✓	Y
Washington	2017–2019	✓	✓	–	Y

Each state has a specific data structure and dictionary for crash data collection. All databases were investigated, and those containing applicable information for further data analysis were determined for consideration in the development of a guide to filter and identify the WZ-related encroachment events:

1. The crash, vehicle, and driver data were merged through a unique crash identification number to create one single file. For the vehicle and driver data, just the vehicle contributing to the first harmful event was chosen, and from persons involved in the crash, just the driver information was selected.
2. WZ and WZ-related crashes were selected from the dataset. However, information about the WZ specifications was not available.
3. Due to the complexity and extension of the contributing factors to intersection- and junction-related crashes, these types of crashes were removed from the dataset. With that, the analysis focused on the encroachment and roadway departure crashes regardless of the intersection or junction location's specifications.
4. Encroachment is considered one of the significant crash types in single-vehicle crashes (SVCs). To determine encroachment crashes, first, SVCs were filtered from the collision type, and then harmful events were investigated. Events that contained encroachment, such as run-off-road (ROR), collision with a fixed object on the roadside, collision with maintenance equipment, and collision with a barrier, guardrail, etc., were selected.
5. From multiple-vehicle crashes, head-on, opposite sideswipe, and overturn events result from or will result in vehicle encroachment. Only these types of crashes were selected for multiple-vehicle crashes.
6. The left-side or right-side encroachment is a vital feature in encroachment analysis. The direction of the encroachment was determined from the available data on the location of the harmful event, type of crash, and type of fixed object included in the crashes.

7. After determining encroachment crashes in the dataset, each variable was investigated, and events with outlier values were removed. Also, redundant, unrelated, and less-informative features were removed from the dataset.

NCHRP Project 17-43 Database

The NCHRP Project 17-43 database is a collection of 1,581 road departure crashes extracted from the National Automotive Sampling System (NASS) Crashworthiness Data System (CDS). The database includes the encroachment trajectory of the vehicle as well as detailed information about the roadside environment, such as the clear zone width, object performance, and presence of a WZ. For crashes with a known vehicle change in velocity (delta-v) because of the impact event, the impact speed and departure speed were reconstructed.

Of the 1,581 crashes in the NCHRP Project 17-43 dataset, nine were related to a WZ based on the NASS CDS scene photographs. Within the NASS CDS database, each observation contributes a value of 1 to the unweighted frequency counts. However, a variable can assign a weight to each case to account for the NASS CDS sampling scheme. Therefore, when such a variable is utilized, each observation is expanded to the national level so that it contributes a weighted value for that observation, representing how often that type of crash occurs.

National Motor Vehicle Crash Causation Survey

One of the goals of NCHRP Project 03-134 was to characterize the nature of WZ encroachments by examining national databases of in-depth crash investigations in WZs. One promising source for these in-depth crash investigations was the NMVCCS. The NMVCCS is an NHTSA-sponsored nationwide survey of crashes involving light passenger vehicles, with a focus on the factors related to pre-crash events. A total of 6,949 crashes were investigated between January 1, 2005, and December 31, 2007. Of these crashes, 5,470 cases comprise a nationally representative sample. The remaining 1,479 cases are suitable for clinical study. The data collected through the investigated crashes can provide a unique perspective on driver behavior factors that lead to WZ crashes. Each investigated crash involved at least one light passenger vehicle that was towed due to damage. Data were collected on-scene for at least 600 data elements in the crash to capture information related to the drivers, vehicles, roadways, and environment. In addition, the NMVCCS database includes crash narratives, photographs, schematic diagrams, and vehicle information, as well as detailed crash scene diagrams, on-scene photos of the crash site, and interviews with the driver.

The NMVCCS dataset was queried for crashes meeting the following criteria.

1. Crash occurred in a WZ.
2. The first event in the crash was a departure either to the left or right of the roadway.
3. Vehicle was a car or light truck. Because the NMVCCS only investigated light vehicles, this restriction is inherent in an NMVCCS analysis.

The reasons for the initial departure could include drift-out-of-lane crash, loss of control, or avoidance of a collision with another car, object, or animal.

The resulting dataset after applying these inclusion criteria was a dataset of 31 crashes. Candidate cases were first selected from the NMVCCS electronic database. Each case was then examined in the NMVCCS electronic case viewer to ensure that the case met the inclusion criteria.

CHAPTER 3

Encroachment Conditions and Driver Behavior in WZs

This chapter presents the results of the exploratory data analysis on the encroachment, roadway, roadside, WZ, and driver behavior conditions.

Encroachment Conditions (Speed, Angle, Lateral Extension)

NDS Database

An in-depth analysis of encroachment speed, angle, and lateral extensions was conducted using NDS data. Lateral extension defines the lateral "trespass" beyond the travel lane edge line. The encroachment speed extracted from the NDS data indicates the speed at the time of encroachment or near-miss. The posted speed limit values for the investigated crashes were not available.

Table 3 depicts the distribution of encroachment (departure) speeds and angles observed in encroachment events (WZ and non-WZ).

Since the roadside safety feature impact conditions recommended in MASH approximate the 85th percentile of previously calculated distributions of speed and angle data, it is considered good practice to investigate the 85th percentile of the new datasets being developed. NDS analysis suggested that the 85th percentile for WZ related encroachment speeds was 49.7 mph and 51 mph for left- and right-side encroachments, respectively. This compared to the recorded 85th percentile for non-WZ related encroachment speeds of 60.9 mph and 51 mph for left- and right-side encroachments, respectively. When considering the 85th percentile for all recorded encroachments, the values were 59.7 mph and 51 mph for left- and right-side encroachments, respectively. There was no difference in the 85th percentile value encroachment speed when comparing WZ and non-WZ related encroachments happening on the right side (51 mph in both cases). Also, when combining the values for the left and right encroachment sides, the 85th percentile resulted in 50.4 mph and 55.4 mph for WZ and non-WZ related encroachments, respectively.

It was also found that the 85th percentile for WZ related encroachment angle was 31.8 degrees and 29.6 degrees for left- and right-side encroachments, respectively. This compared to the recorded 85th percentile for non-WZ related encroachment angle of 30 degrees and 31 degrees for left and right-side encroachments, respectively. When considering the 85th percentile for all recorded encroachments, the values were 31 degrees for both left- and right-side encroachments. There was not a significant difference in encroachment angle from a testing/design perspective when comparing WZ and non-WZ related encroachments happening on the right side (29.6 degrees vs. 31 degrees, respectively). The difference between the two values was less

Table 3. Encroachment speed and angle per encroachment type.

Encroachment Condition	Descriptive Statistics	WZ (n=129)		Non-WZ (n=399)		Grand Total (n=528)	
		LSE (n=61)	RSE (n=68)	LSE (n=179)	RSE (n=220)	LSE (n=240)	RSE (n=288)
Encroachment Speed (mph)	Min	6.2	4.97	2.48	3.1	2.48	3.1
	Max	75.1	68.3	83.26	83.26	83.26	83.26
	Mean	31.67	34.2	38.59	36.77	36.78	36.17
	St. Dev.	15.53	14.63	18.05	14.51	17.66	14.5
	85^{th} %	49.7	51	60.9	51	59.7	51
Encroachment Angle (degrees)	Min	0	0	0	0	0	0
	Max	68	90	80	70	80	90
	Mean	21.94	20.10	19.70	19.47	20.2	19.6
	St. Dev.	11.03	14.03	12.13	11.48	11.87	12.07
	85^{th} %	31.8	29.6	30	31	31	31
Lateral Extension	85^{th} %	5.2	8.5	9.2	8.2	6.2	8.2

Note: LSE = left-side encroachment; RSE = right-side encroachment.

than the current MASH tolerance value of 1.5 degrees from the nominal value considered for testing. Also, when combining the values for the left and right encroachment sides, the 85th percentile resulted in 30.6 degrees for WZ and non-WZ related encroachments.

Data investigation indicated the 85th percentile for WZ related encroachment lateral extension was 1.6 m (5.2 ft) and 2.6 m (8.5 ft) for left- and right-side encroachments, respectively. This compared to the recorded 85th percentile for non-WZ related encroachment lateral extension of 2.8 m (9.2 ft) and 2.5 m (8.2 ft) for left- and right-side encroachments, respectively. When considering the 85th percentile for all recorded encroachments, the values were 1.9 m (6.2 ft) and 2.5 m (8.2 ft) for left- and right-side encroachments, respectively. There was not a considerable difference in encroachment lateral extension when comparing WZ and non-WZ related encroachments happening on the right side (8.5 ft vs. 8.2 ft, respectively). Also, when combining the values for the left and right encroachment sides, the 85th percentile resulted in 7.1 ft and 8.7 ft for WZ and non-WZ related encroachments, respectively.

Further data analysis suggested the departure angle appeared to remain stable, and the mean value did not change significantly per encroachment speed. In terms of departure extension, this value seemed to be decreasing as the encroachment speed increased, although not significantly. This result may be because in WZs the travel lane is limited, thus not allowing for longer extensions as the vehicle departs the roadway.

NCHRP Projects 17-43 and 17-22 Databases

Impact speed and angle of eight WZ crashes were identified in the NCHRP Project 17-43 project database. Five of these crashes included information on the impact speed. Four out of the five crashes that included the information on the impact speed had impact speeds below the 85th percentile (Figure 1a). However, this did not account for the speed limit of the road. When accounting for the speed limit of the road, three crashes were above the 80th percentile for impact speed. In each of these three cases, it is likely that the recorded speed limit was a reduced speed for the construction zone. In the three cases with high impact speeds, the finding may indicate that the drivers did not reduce their speed from the original speed limit of the road. The impact angles for the crashes in WZs were compared to all road departure crashes and did not appear to be different (Figure 1b).

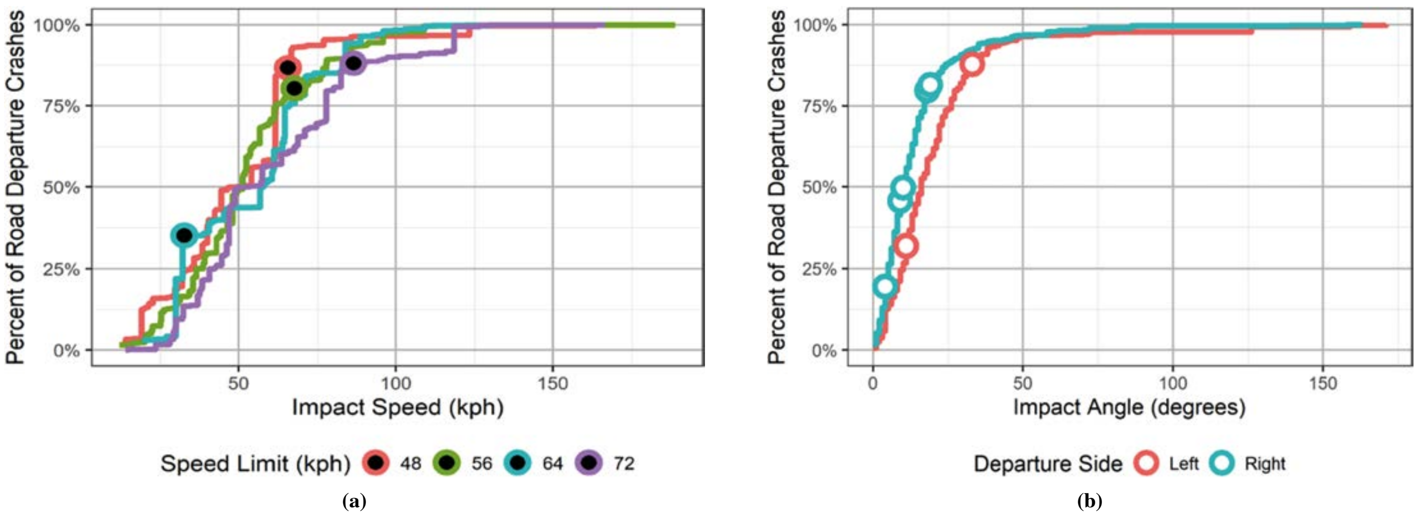

Figure 1. Distribution of impact speeds and angles, NCHRP Project 17-43: (a) impact speed and (b) impact angle.

The distance to the first impact in WZs was compared to all crashes in the NCHRP Project 17-43 database (Figure 2). The distance to the first impact in a WZ was not smaller than in the rest of the NCHRP Project 17-43 database. Surprisingly, one of the longest impact distances in the dataset occurred in a WZ. In that case, the vehicle departed when the road turned left to pass under an overpass. The vehicle climbed a hill and struck the bridge. Of the eight WZ encroachments in the NCHRP Project 17-43 database, six had a maximum lateral encroachment under 11.5 ft before impact, and one case involved the vehicle impacting a tree before leaving the roadway.

As part of the investigation, these values were compared to those derived from the NCHRP Project 17-22 dataset. Developed prior to 2009, the NCHRP Project 17-22 database includes reconstructed run-off-the-road crashes. The data are segregated by posted speed limits. The consideration of these encroachment conditions could be valid for potential impact conditions

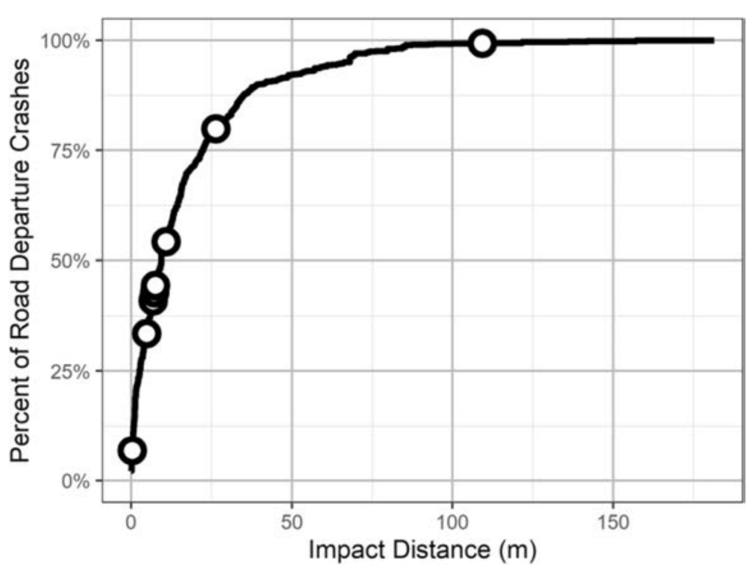

Figure 2. Distribution of impact distances, NCHRP Project 17-43.

Table 4. Summary of data results from NCHRP Projects 17-43 and 17-22 databases.

Database	Encroachment	Median Departure	85th percentile (right+left side)	85th percentile (right side only)	85th percentile (left side only)
NCHRP Project 17-43	Speed (mph)	39.3	57.8		
	Angle (deg)		22	18	31
NCHRP Project 17-22	Speed (mph)	40.7	57		
	Angle (deg)			23	29

for WZ safety barrier implementation, given their restricted nature and closer proximity of barriers to travel lanes.

The reconstructed speed at the first departure was similar between the NCHRP Project 17-43 and NCHRP Project 17-22 databases. The median departure speeds were 39.3 mph in the NCHRP Project 17-43 dataset and 40.7 mph in the NCHRP Project 17-22 dataset. The 85th percentile departure speeds were also similar, at 57.8 mph in the NCHRP Project 17-43 dataset and 57.0 mph in the NCHRP Project 17-22 dataset. The departure angle distribution was similar between the datasets as well. In general, right-side departures tend to have a smaller departure angle than left-side departures. For left-side departures, the 85th percentile angle was 31 degrees in the NCHRP Project 17-43 database and 29 degrees in the NCHRP Project 17-22 database. For right-side departures, the 85th percentile angle was 18 degrees in the NCHRP Project 17-43 database and 23 degrees in the NCHRP Project 17-22 database. Table 4 summarizes these data.

Additional analysis was performed under this project to investigate the 85th percentile for encroachments at both right and left sides. The analysis indicated that the 85th percentiles of the departure speed and angle were 55 mph and 22 degrees, respectively, when considering the right- and left-side encroachments collectively.

Roadway Conditions

The research team explored the roadway characteristics of locations where the WZ encroachments occurred using NDS and crash databases. Figure 3 shows the association of the roadway facility with encroachment direction. About 60 percent of the encroachments on the one-way and two-way with left lane roads were toward the right side of the road (Figure 3a). Almost 70 percent of the encroachments on the undivided two-way roads were toward the right side. On the other hand, most of the encroachments on two-way roads with medians were toward the left side of the road. As observed in Figure 3(b), interstate and principal arterials (high-speed roadways) were associated with left-side encroachments, while lower classes such as collector and local roads were associated with right-side encroachments. This finding indicates that in high-speed roadways, most of the WZ encroachments happen toward the median barriers, while in low-speed roadways, WZ encroachments happen toward the shoulder.

Roadside and WZ Conditions

Figure 4 depicts the roadside object and WZ location where the encroachment occurred. As observed in Figure 4(a), the majority of encroachments involved fixed objects on the right side of the road, except for barriers. Figure 4(b) depicts the percentage of encroachments per WZ location. As observed in WZ areas, most encroachments are to the right side of the road.

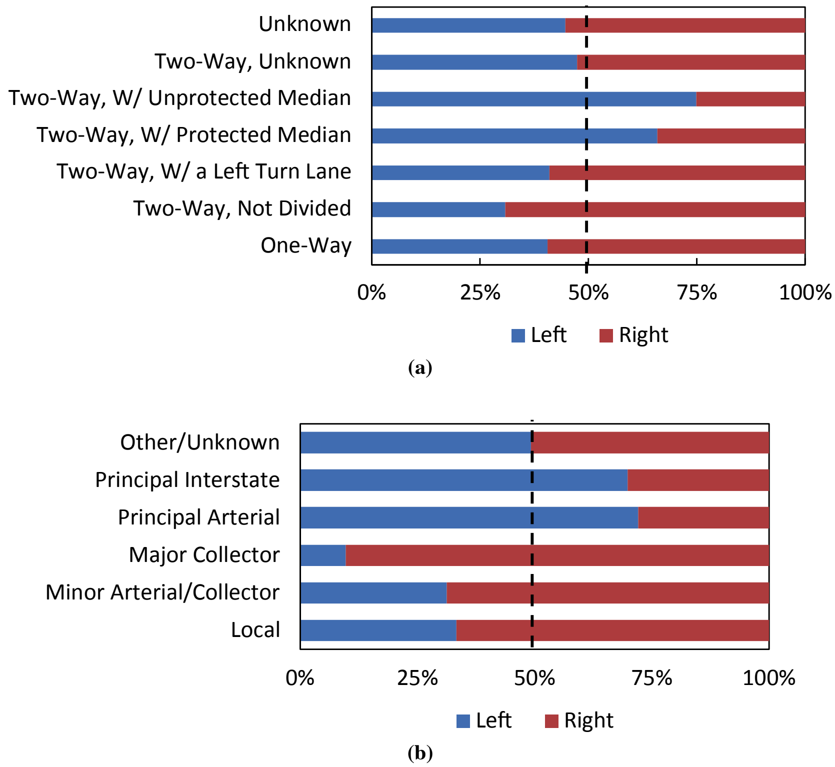

Figure 3. Roadway facility type in encroachment events: (a) travel lanes and median characteristics and (b) roadway functional class.

Driver Behavior Characteristics

Figure 5 depicts reported driver behavior where the encroachment occurred.

Among the driver contributing actions (Figure 5a), improper speed was observed in 15 percent of encroachments. This contributing factor had more weight than road-related factors. Other contributing factors found in the crash data included failure to dim lights, carelessness, disregard for traffic, and improper braking.

Figure 5(b) depicts reported driver distraction factors in WZ encroachment events. Most driver distraction events were related to improper driving activity (e.g., improper speed, improper lane change, etc.), external distraction (likely due to the built environment), cellphone and other electronic device use, and passengers.

Figure 5(c) depicts the reported driver distraction associated with the encroachment direction. Both right- and left-side encroachments involved distraction due to the passenger and internal distractions. Inattention and external distractions were mainly observed in right-side encroachment events. Cellphone use was found to be significantly associated with right-side encroachments, indicating that drivers using a cell phone will likely encroach on the right side of the road, which could result in fixed-object crashes.

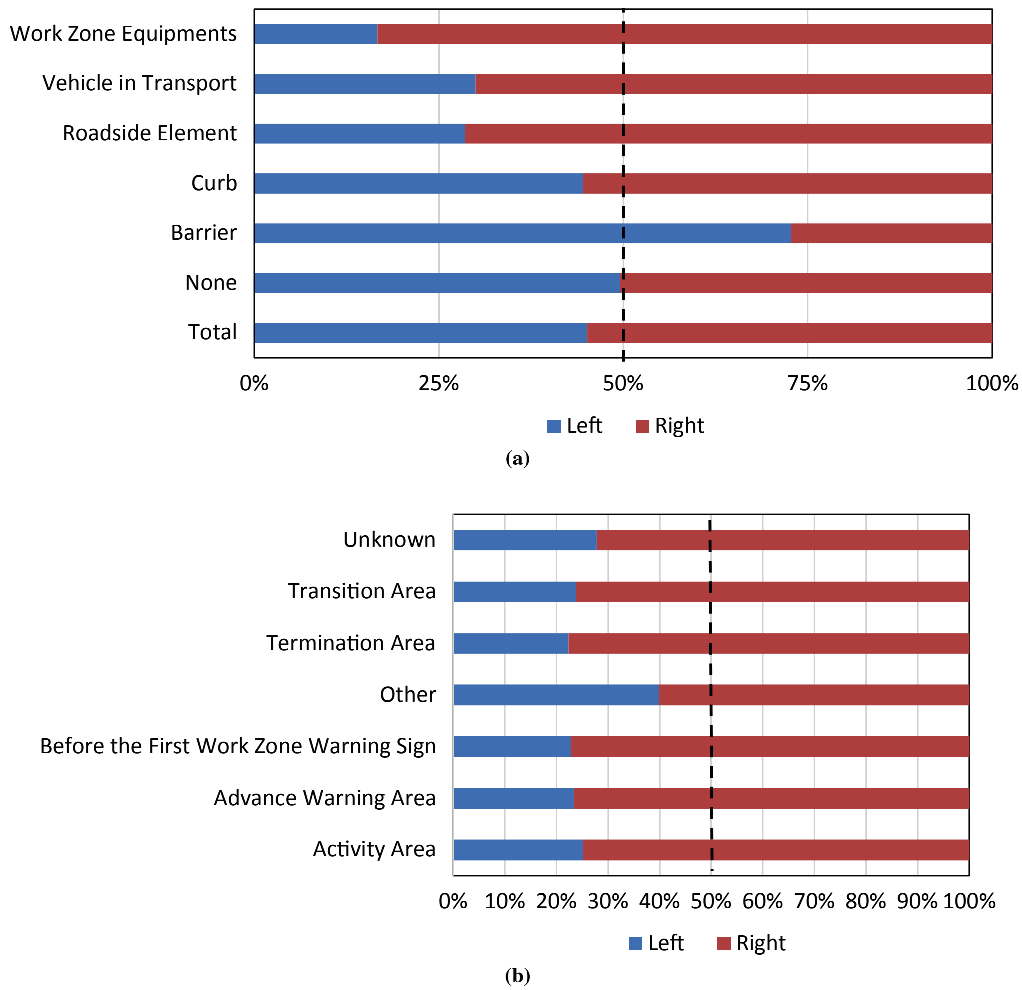

Figure 4. Roadside and WZ conditions in encroachment events: (a) roadside object and (b) WZ location.

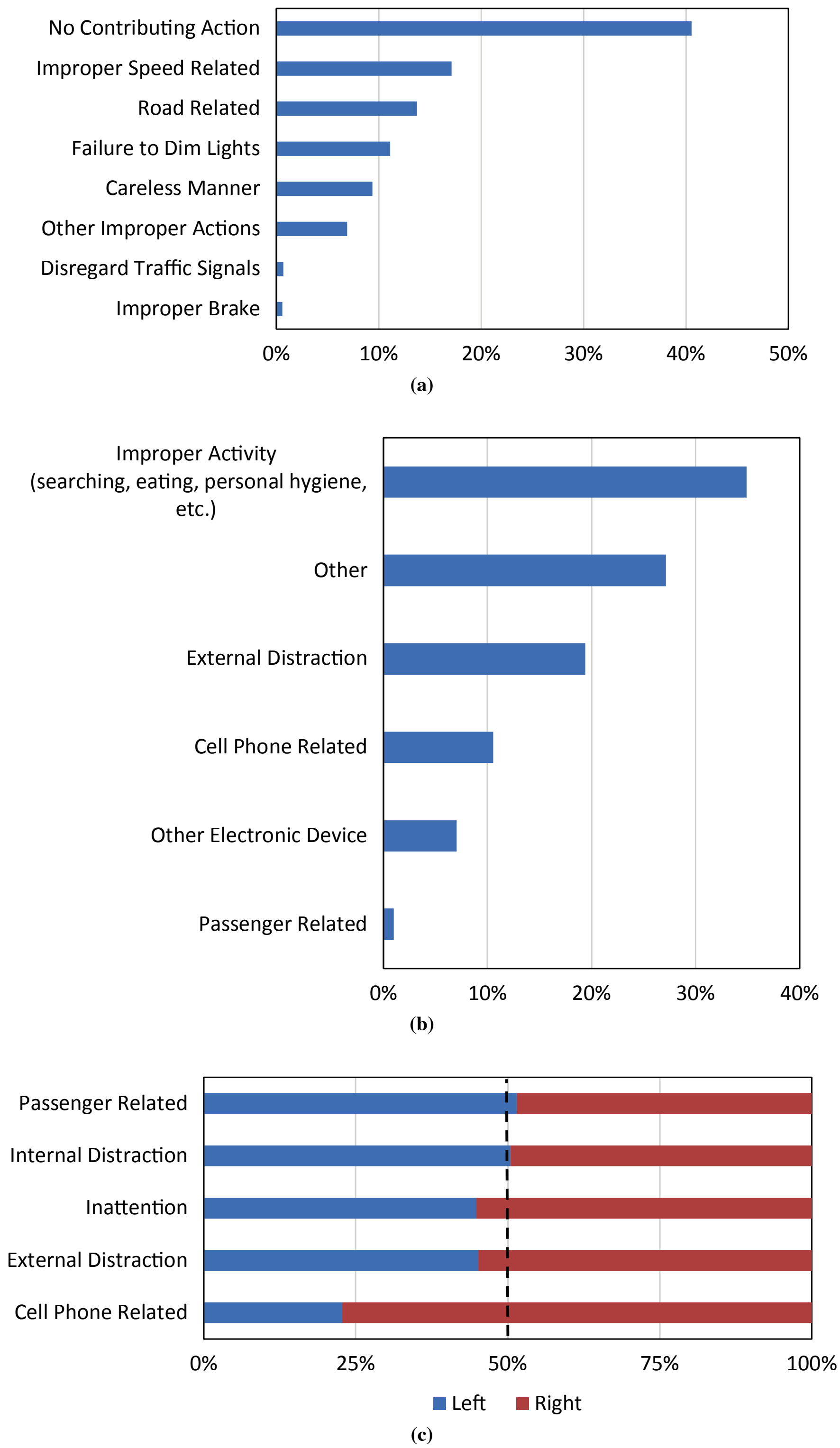

Figure 5. Reported driver behavior during encroachment events: (a) driver contributing actions; (b) driver distraction factors; and (c) driver distraction vs. departure direction.

CHAPTER 4

Identified and Proposed Guide Revisions

Results from the evaluation of WZ encroachments were reviewed to determine how they might provide additional guidelines for MASH, the RDG, and the MUTCD, as outlined in the following sections.

Manual for Assessing Safety Hardware

The AASHTO (2016) MASH provides specifications that govern full-scale crash testing and evaluation of roadside safety features, including WZ barrier systems. The recommended test matrixes in MASH prescribe impact conditions in terms of vehicle type and weight, impact speed, and impact angle. Each roadside safety feature category is associated with specific test matrixes and test levels, containing indications of impact locations, impact speed, and impact angle. For example, there are six test levels defined for longitudinal barriers: the first three MASH test levels involve use of only passenger vehicles (a 2,420-lb passenger car and 5,000-lb pickup truck) and vary by impact speed. Higher test levels incorporate commercial trucks in addition to passenger vehicles.

Although the characteristics of WZs are inherently different from normal operating conditions on main lane highways, the impact conditions used to evaluate WZ devices (e.g., barriers, signs, lighting, etc.) are the same as those used for other types of systems not implemented in WZ areas, such as guardrails, median barriers, bridge rails, and permanent sign supports, primarily due to a lack of data related to WZ encroachment and impact conditions.

The passenger vehicle impact conditions in MASH are based on historical precedence of previous crash test standards verified through analysis of ROR crash data. Under NCHRP Project 17-22, "Identification of Vehicular Impact Conditions Associated with Serious Ran-Off-Road Crashes," a database of approximately 890 single-vehicle ROR crashes was developed (Mak et al. 2010). These crashes are a subset of the NASS CDS crashes from 1997 to 2001 that occurred on highways with a posted speed of 45 mph or higher. The crashes were reconstructed using scene diagrams, narratives, scene and vehicle photographs, and roadway and roadside data (e.g., surface type, surface condition, and side-slope ratios) to estimate vehicle encroachment and impact conditions. The roadside safety feature impact conditions recommended in MASH approximate the 85th percentile speed and angle derived from distributions developed from the NCHRP Project 17-22 data. For high-speed roadways (Test Level [TL] 3 and higher), this corresponds to an impact speed of 62 mph and an impact angle of 25 degrees. This dataset does not include consideration of WZs. Thus, the impact conditions used in MASH for WZ roadside safety features are like other safety feature types by default, not design.

For example, WZ longitudinal barriers have several functions, including shielding motorists from hazards in the work area and providing positive protection for workers. Portable concrete barriers (PCBs) are the most widely used type of WZ barrier, although other types of barriers are available (e.g., steel). Due to the temporary and frequently changing nature of WZs, WZ barriers are designed to be easily transported, placed, and relocated. Therefore, unlike permanent concrete barriers, freestanding PCBs can undergo large displacements when subjected to a vehicle impact.

The design deflection of a WZ barrier is typically determined through full-scale crash testing. The magnitude of the barrier displacement is in large part attributable to the design impact conditions to which the barrier is tested. Several portable barrier systems tested to MASH TL-3 conditions have deflections greater than 5 ft.

This design deflection can have significant implications on the design of a WZ. A buffer space is typically required behind a WZ barrier to accommodate barrier deflection. The buffer space provides a recovery area for errant vehicles and separates traffic flow from workers or potential hazards (e.g., drop-offs) in the work activity area. Generally, no work activity should occur, and no equipment should be stored, within this space.

However, most WZs, besides those associated with new construction, are commonly restricted in terms of available space. Depending on the design deflection of the WZ barrier being used, an extra travel lane may have to be incorporated into the work activity area simply to provide the required buffer distance. Consequently, it is desirable to minimize the deflection of WZ barriers to reduce the required buffer distance behind the barrier and maximize the space available for traffic. If the desired buffer space cannot be accommodated, the barrier system may need to be restrained by anchoring it to the underlying pavement, deck, or soil through some means of pinning or bolting. Restraining barriers in this manner is expensive (due to required drilling, coring, epoxy, etc.), creates additional exposure for workers during installation, and can degrade barrier impact performance.

Some agencies reduce posted speed limits and operating speeds in WZs to justify a lower test level and lower barrier deflections. While speed reduction is a common safety measure to enhance the safety of motorists and workers, this measure is not necessarily appropriate for all WZ situations, and the effect of the speed reduction on encroachment and impact conditions is not known.

Recognizing that the impact conditions used for designing and testing longitudinal barriers may be too conservative for some WZ applications, researchers used an 85th percentile impact severity (IS) as a basis for establishing a design deflection for WZ barriers (Sicking et al. 2003). The IS is defined as follows:

$$IS = \frac{1}{2} m (v \sin\theta)^2 \quad (1)$$

The IS distribution was established using impact speed and impact angle distributions derived from reconstructed ROR crashes with poles and narrow bridges (Mak et al. 2010), and the mass distribution for vehicles involved in ROR crashes was developed from NASS CDS data (Ray 1999). Use of the 85th percentile results in a nearly 50 percent reduction in barrier deflection. Researchers recommended the use of this reduced deflection for all WZ applications other than the placement of a barrier on the edge of a bridge deck (Sicking et al. 2003).

This practice is an indication that further research is needed to better define appropriate impact conditions for WZ barriers. In fact, no research has been conducted to investigate whether the test impact speed and angle should be different for WZ barriers to reflect different encroachment and impact conditions associated with WZ locations. The design impact conditions should be relevant and appropriate to the conditions in which the barrier is implemented. Overly conservative impact conditions will result in barrier systems that are more expensive to construct (to achieve the required structural adequacy) and deploy (to achieve the required buffer distance associated with the barrier design deflection).

Another issue that requires further research is the appropriate MASH test level for different WZ locations. Most WZ barriers historically have been designed for MASH TL-3, which is only for passenger vehicles. However, WZs also are implemented in low-speed locations, where the posted speed limit is limited to 45 mph. MASH provides guidance for testing and evaluating roadside safety systems implemented at lower speeds: MASH TL-2 conditions involve passenger vehicles impacting safety systems at 44 mph nominal impact speed and at the critical angle considered appropriate for the specific investigated system category. More recently, PCBs are being designed to MASH TL-4, which includes an evaluation with a 22,000-lb single unit truck (Sheikh et al. 2018). Many permanent median barriers and bridge rails are designed for MASH TL-4, and some WZs may likewise benefit from the use of MASH TL-4 WZ barrier systems. More research is needed to determine the need for and appropriate use of MASH TL-4 WZ barriers based on factors such as speed and percent trucks.

Investigation Conclusions

The NCHRP Project 17-43 database was analyzed to investigate impact and encroachment conditions. There were only eight WZ crashes in the database, and five of those included a value for the impact speed. All but one had an impact speed below the 85th percentile of the NCHRP Project 17-43 data. The comparison of the reconstructed impact angles from the eight WZ crashes to the 85th percentile of the NCHRP Project 17-43 impact angle data (from all crashes) was inconclusive due to the limited available data. Encroachment conditions associated with the crashes in the NCHRP Project 17-43 database were also investigated. Although MASH is based on impact conditions rather than encroachment conditions, encroachment conditions will have more correlation than other types of roadside safety devices to impact conditions for WZ barriers and traffic control devices. This is based on the restricted nature of WZs and the proximity of WZ barriers and traffic control devices to the edge of travel lanes.

Of the eight cases identified in the NCHRP Project 17-43 database, six contained reconstructed impact and departure speeds (Table 5). Of these eight cases, only two impacted a temporary WZ sign and one impacted a concrete barrier protecting the WZ. This latter case involved a 2012 Ford Explorer that departed the road to the left within a WZ. The vehicle impacted the barrier at approximately 11 degrees and 53.7 mph. The vehicle was successfully redirected, and the barrier performed as intended.

Table 5. Summary of WZ crash cases identified in the NCHRP Project 17-43 database.

Case Number	Speed Limit (mph)	Impact Speed (mph)	Departure Speed (mph)
126014659	30	40.7	40.8
717016292	45	Unknown	Unknown
779014928	45	Unknown	Unknown
501014875	Unknown	41.9	42.3
510015803	40	Unknown	Unknown
877015332	45	53.7	53.7
554017111	40	20.3	78.5
554017572	35	42.1	53.7

There were not enough cases to statistically determine if any differences existed in the frequency or magnitude of encroachments between different roadside devices. Four of these cases had similar departure speeds and impact speeds because the impact occurred very close to the road edge. One case had a difference of more than 58 mph between departure and impact speeds due to the vehicle traveling over 300 ft through a WZ and up a large embankment. In WZ areas preventing large lateral encroachments, the impact speed remained similar to the departure speed.

Studies conducted under NCHRP Project 17-43 indicated that the reconstructed speed at the first departure (i.e., encroachment speed) was similar between the NCHRP Project 17-43 database and older NCHRP Project 17-22 database. The median departure speeds for all roadway departure crashes were 39.3 mph in the NCHRP Project 17-43 dataset and 40.7 mph in the NCHRP Project 17-22 dataset. The 85th percentile departure speeds also were similar, with a value of 57.8 mph in the NCHRP Project 17-43 dataset and 57.0 mph in the NCHRP Project 17-22 dataset.

The departure angle distribution was similar between the datasets. In general, right-side departures tended to have a smaller departure angle than left-side departures. For left-side departures, the 85th percentile angle was 31 degrees in the NCHRP Project 17-43 database and 29 degrees in the NCHRP Project 17-22 database. For right-side departures, the 85th percentile angle was 18 degrees in the NCHRP Project 17-43 database and 23 degrees in the NCHRP Project 17-22 database. An additional analysis of the NCHRP Project 17-43 database indicated that the 85th percentile of the departure angle was 22 degrees when considering right- and left-side encroachments collectively.

An in-depth analysis of encroachment speed and angle was conducted using the available NDS data. The encroachment data were not collected as part of the NDSs (e.g., impact or departure angle), and some of the data were manually collected from videos. Figure 6 illustrates the data collection approach for estimating the impact angle during the encroachment. No difference was observed in the 85th percentile encroachment speed when comparing WZ and non-WZ related encroachments happening on the right side (51 mph in both cases). When left- and right-side encroachments were combined, the 85th percentile speeds were 50.4 mph and 55.4 mph for WZ and non-WZ related encroachments, respectively.

When comparing encroachment angles for right-side encroachments in the NDS dataset, the 85th percentile encroachment angles were 29.6 degrees and 31 degrees for WZ and non-WZ related encroachments, respectively. The difference between these values is less than

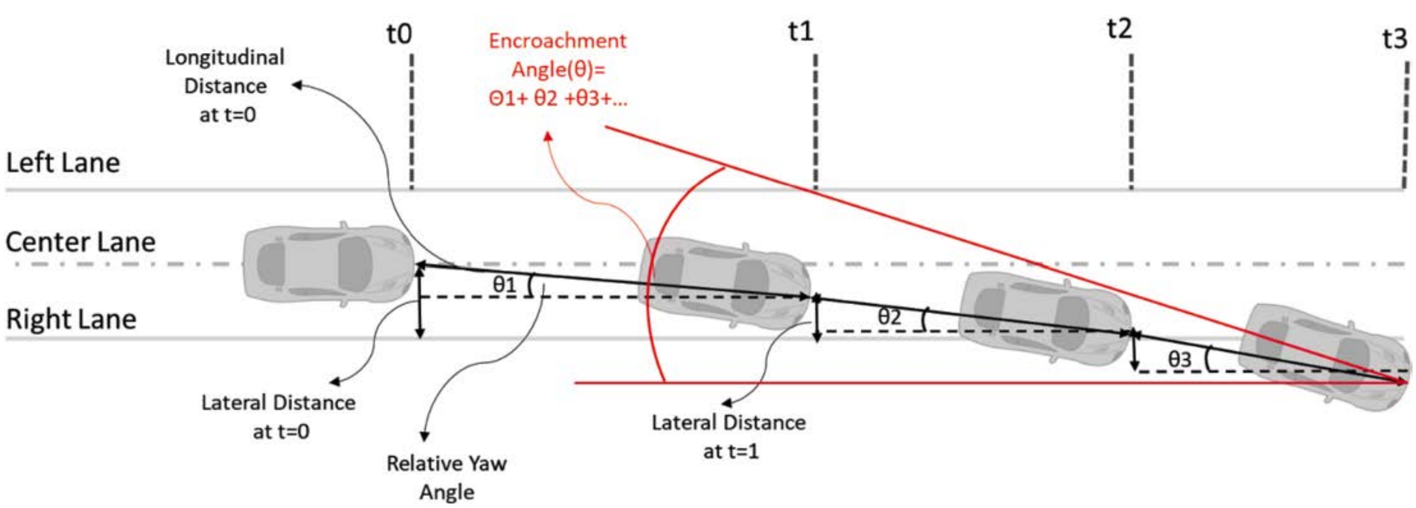

Figure 6. Calculating encroachment angle (NDS Data).

the 1.5-degree tolerance for impact angle in MASH. When left- and right-side encroachments were combined, the 85th percentile angle was 30.6 degrees for both WZ and non-WZ related encroachments.

A summary of the encroachment conditions (speed and angle) obtained from analysis of the NCHRP Project 17-43 database and the NDS data is reported in Table 6. Some accuracy limitations associated with the angle data manually collected from videos as part of the NDS data investigation may exist. The 85th percentile encroachment speeds from the NCHRP Project 17-43 and NCHRP Project 17-22 databases (57.8 mph and 57 mph, respectively) are similar to the 85th percentile speed calculated from the NDS data for non-WZ encroachments (55.4 mph). These three values are not significantly different from a barrier testing perspective when considering that the MASH tolerance for impact speed is 2.5 mph. The NDS data indicate that the 85th percentile speed for combined left- and right-side encroachments in a WZ is 50.4 mph, which is a 10 percent drop from the 55.4 mph representing the 85th percentile of the overall encroachment speeds in non-WZ areas.

As mentioned, the encroachment speeds obtained from NCHRP Project 17-43, NCHRP Project 17-22, and NDS data are comparable, with differences in the range of three to four percent. The differences in encroachment angle are considerably greater, with the NDS data having larger encroachment angles than both the NCHRP Project 17-43 and NCHRP Project 17-22 databases. This difference might be the result of the manual technique utilized to extract the encroachment angle values directly from videos as part of the NDS data effort. The differences that exist among these datasets may be due to several factors. For example, the NDS data are encroachment based, whereas the NCHRP Project 17-43 and NCHRP Project 17-22 databases are crash based. In other words, the encroachment conditions extracted from the NCHRP Project 17-43 and NCHRP Project 17-22 databases are based on ROR crashes, while the NDS data are based on encroachments, most of which did not result in a crash. Further, the posted speed limits for roadways on which the encroachments occurred in the NDS data are not available. There may also be differences associated with the different data collection periods of these datasets and the relative contribution of advancing vehicle safety technologies in each.

From the perspective of the impact/encroachment speed, the general conclusions are

- Impact speed in WZs: There are not enough data to support the need for a change in MASH impact conditions for testing and evaluating roadside safety hardware implemented in WZ locations (source is only five WZ related crashes with reconstructed impact speed).
- Encroachment speed in WZs: The NDS data indicate that the 85th percentile encroachment speed in WZs is 10 percent less than the 85th percentile encroachment speed in non-WZ

Table 6. Summary of encroachment results from 17-43 database, 17-22 database, and NDS data.

Source	Encroachment	85th percentile (right+left side)	85th percentile (right side only)
NCHRP Project 17-43	Speed (mph)	57.8	—
	Angle (deg)	22	18
NCHRP Project 17-22	Speed (mph)	57	—
	Angle (deg)	—	23
NDS WZ	Speed (mph)	50.4	51
	Angle (deg)	30.6	29.6
NDS No WZ	Speed (mph)	55.4	51
	Angle (deg)	30.6	31

areas. However, the functional classification and posted speed limits for the roadways on which these encroachments occurred is not available, so it is difficult to conclude that a reduction in MASH test speed is clearly indicated.

From the perspective of the impact/encroachment angle, the general conclusions are

- Impact angle in WZs: There are not enough data to support the need for a change in MASH impact conditions for testing and evaluating roadside safety hardware implemented in WZ locations (source is only eight WZ related crashes with reconstructed impact angle).
- Encroachment angle in WZs: The NDS data indicate that there is no difference in the 85th percentile of the overall encroachment angles for WZ and non-WZ locations (30.6 degrees in both cases). The 85th percentile of the NCHRP Project 17-43 overall encroachment angle is 22 degrees, which is very similar to the current MASH nominal impact angle of 25 degrees used for testing and evaluating roadside safety devices. The discrepancy between the NDS and NCHRP Project 17-43 encroachment angles is not fully understood, so there is not a strong basis for change of the MASH impact angle at this time.

Encroachment angles were also explored per encroachment speed bins in WZs to determine whether there is a correlation between encroachment angle and encroachment speed. The mean value of departure angle remained stable across the different speed ranges, meaning the encroachment angle is not correlated with encroachment speed.

Guidelines Recommendation

There were insufficient results to support the need to revise current guidelines pertaining to impact conditions in MASH.

Roadside Design Guide

Whereas MASH prescribes how the impact performance of a roadside safety device should be evaluated, the AASHTO RDG (2011) provides guidelines regarding implementation, placement, and use. There has been a concerted effort by AASHTO to update the guidelines in the RDG to reflect current data and enable better data-driven decision-making. Chapter 2 of the RDG discusses the importance of the economic evaluation of roadside safety alternatives to enable a designer to make the best safety decisions with limited funds. This evaluation is accomplished through a benefit–cost analysis wherein the benefits are defined as a reduction in crash cost or risk. The RDG discusses the use of tools such as the Roadside Safety Analysis Program for performing such analyses.

A key component of calculating the risks and/or benefits that can be derived from a roadside safety treatment is understanding encroachment characteristics for a particular type of roadway or at a particular location. It is recognized in the RDG that encroachment rate can vary based on factors such as traffic volume, roadway alignment, and lane width. The encroachment studies referenced by the RDG are Cooper (1980) and Hutchinson and Kennedy (1962). Much of the safety performance guidelines currently in the RDG, or being developed for incorporation into the next edition, stems from the use of old encroachment data in a risk– or benefit–cost-based analysis. Examples include guidelines on the guardrail and median barrier test level selection and guardrail length of need.

Chapter 9 of the AASHTO RDG specifically addresses traffic barriers, traffic control devices, and other safety features used in WZs. The chapter describes the safety and functional characteristics of these devices and provides guidelines on their application and use. The RDG recognizes that barrier needs within a WZ can be influenced by several factors, including traffic volume, operating speed, offset, and duration of the WZ. WZ encroachment data are needed in support of engineering risk or benefit–cost analysis related to use of barriers within WZs. Such analyses will result in guidelines on barrier need, placement, and test level and will be expressed in terms of key WZ variables.

Investigation Conclusions

The lateral distance to the first impact for the eight crashes in WZs was compared to all crashes in the NCHRP Project 17-43 database. The lateral distance to the first impact in a WZ was not smaller than in the rest of the NCHRP Project 17-43 database.

An in-depth analysis of encroachment lateral extensions was also conducted using the available NDS data. There was not a considerable difference in encroachment lateral extension when comparing WZ and non-WZ related encroachments happening on the right side (8.5 ft vs. 8.2 ft, respectively). Also, when combining the values for the left and right encroachment sides, the 85th percentile resulted in 7.1 ft and 8.7 ft for WZ and non-WZ related encroachments, respectively.

The average speed for right-side WZ encroachments (mean = 36.8 mph) was slightly lower than for left-side WZ encroachments (mean = 38.6 mph), but the 85th percentile was higher for right-side WZ encroachments (85th percentile = 51.0 mph) than for left-side WZ encroachments (85th percentile = 49.7 mph). In the case of non-WZs, right-side encroachment speeds were higher (max = 83.3 mph; mean = 34.2 mph) compared to left-side encroachments (max = 83.3 mph; mean = 31.7 mph).

These data provide a better understanding of the speed of vehicles at the moment of encroachment, showing that left–/right–side encroachments are reasonably similar.

Guideline Recommendation

The current guideline from the RDG on clear zone requirements seems to be appropriate considering the recorded lateral extensions of encroachments in WZ locations.

The collected and analyzed data provide a better understanding of the speed of vehicles at the moment of encroachment, showing that left–/right–side encroachments are reasonably similar. The speed difference between left– and right–side encroachments is fairly minimal and not statistically significant enough to support different barrier recommendations based on the lane side implementation (left vs. right).

Manual on Uniform Traffic Control Devices

The FHWA MUTCD (2009) refers to MASH and the RDG as governing publications regarding the design and use of temporary traffic control devices (including barrier use in WZs). Changes to those documents will, by reference, indirectly impact the MUTCD. In addition, the MUTCD is relatively silent on when and where positive protection in WZs should be used. However, the Code of Federal Regulations (23 CFR 630 Subpart K) requires agencies to establish criteria and guidelines regarding positive protection use in WZs.

The following guidelines are provided in the MUTCD to improve worker safety in WZs.

- Training: Training for workers on how to work next to motor vehicles and on temporary traffic control (TTC) techniques should be provided.
- Temporary traffic barriers: Barriers are placed depending on factors such as lateral clearance, duration of work, traffic characteristics, and so forth.

- Speed reduction: Regulatory speed zoning, lane reduction, funneling, and the like should be considered to reduce traffic speeds to increase safety.
- Activity area: Work areas should be planned in such a way that minimum risk to workers due to construction vehicles exists.
- Worker safety planning: A basic hazard assessment of the WZ area and the jobs must be conducted as per "Occupational Safety and Health Administration Regulations, General Safety and Health Provisions." Based on this assessment, it must be determined whether engineering, administrative, or personal protection measures are required. If so, these should be planned in accordance with the Occupational Safety and Health Act of 1970.

The project team anticipates that the WZ encroachment database developed in NCHRP Project 03-134 will have implications on TTC practices. Each TTC zone is different, and the type of TTC to be used is determined based on many variables, such as time and location of work, highway type, geometrics, intersections, road vehicle mix (buses, trucks, or cars), road user speeds, and more. In addition, when conditions are complex, the general applications are modified by incorporating devices such as signs, arrow boards, screens, crash cushions, and rumble strips; upgrading devices, for example, larger/brighter signs and pavement markings; improving geometrics at detours and crossovers; improving lighting, using floodlights, illuminated signs, and so on; providing pedestrian routes; providing bicycle diversions; and providing temporary facilities.

Investigation Conclusions

Several of the analyses resulted in information that could be used to develop guidance for incorporation into the MUTCD.

An in-depth analysis of encroachment lateral extensions was conducted using the available NDS data. The 85th percentile lateral encroachment to the right in WZs was 8.5 ft compared to 8.2 ft in non-WZs. The 85th percentile left-side encroachment in WZs was 5.2 ft compared to 9.2 ft in non-WZs.

The average speed for right-side WZ encroachments (mean = 36.8 mph) was slightly lower than for left-side WZ encroachments (mean = 38.6 mph), but the 85th percentile was higher for right-side WZ encroachments (85th percentile = 51.0 mph) than for left-side WZ encroachments (85th percentile = 49.7 mph). In the case of non-WZs, right-side encroachment speeds were higher (max = 83.3 mph; mean = 34.2 mph) compared to left-side encroachments (max = 83.3 mph; mean = 31.7 mph).

These data provide a better understanding of the speed of vehicles at the moment of encroachment, showing that left– or right–side encroachments are reasonably similar.

Speed was noted as the highest contributing factor (17 percent), which was second to no contributing factor (41 percent) in WZ encroachment crashes. External distraction accounted for 18 percent of WZ crashes, which may be due to drivers paying attention to WZ traffic control devices. Additionally, interaction with electronic devices or cell phones accounted for about 18 percent of WZ crashes.

As noted in Figure 7, evaluation of crash data indicated that a curb was the most typical object struck in WZ crashes involving an encroachment. The next most common objects struck were WZ equipment (8 percent) and barriers (7 percent). Barriers were more likely to be struck during left-side encroachments than right side.

Evaluation of crash data also indicated that the majority of WZ encroachments occur in the activity area of the WZ (72 percent) versus the transition area (13 percent) or advance warning area (9 percent), as shown in Figure 8.

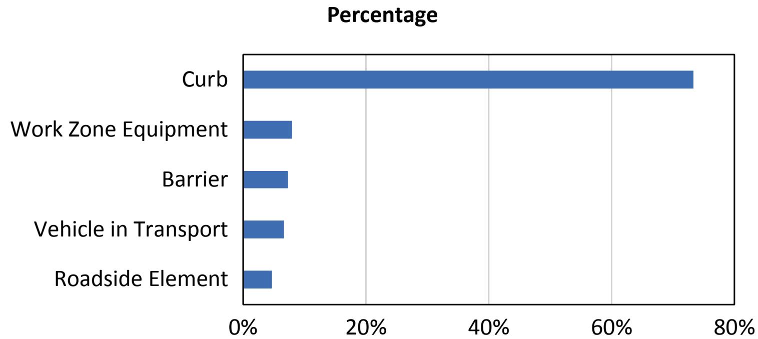

Figure 7. Objects struck in WZ crashes involving an encroachment.

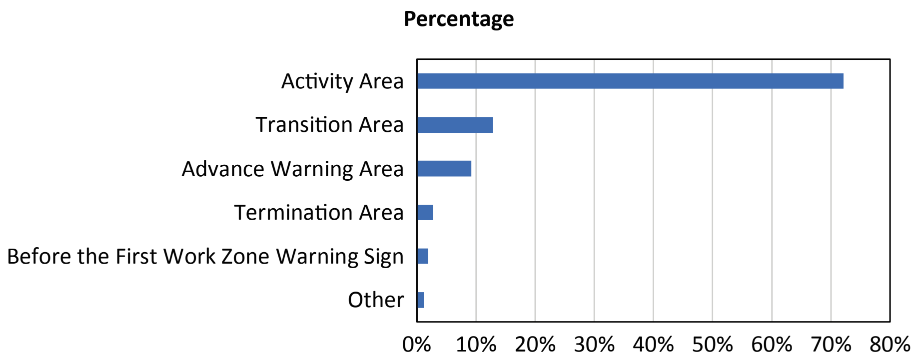

Figure 8. Location of WZ crashes involving an encroachment.

Guideline Recommendation

The project findings and potential guidance implications for the MUTCD include the following:

- Section 6C.04. Advance Warning Area. This section discusses traffic control devices for the advance warning area. The findings suggest that around 9 percent of WZ encroachment-related crashes occur in the advance warning area. However, no other information was available to suggest additional guidance needs to be provided.
- Section 6D.03. Worker Safety Considerations. This section discusses use of temporary traffic barriers, which is based on factors such as lateral clearance of workers from adjacent traffic and speed reduction. The findings suggest encroachment speeds are 49.7 mph for left-side encroachment and 51.0 mph for right-side encroachment. Additionally, 8 percent of encroachment crashes in WZs strike WZ equipment. The suggested recommendations in this section could be examined to determine whether they are sufficient given likely lateral clearance when a vehicle encroaches into the WZ environment.
- Section 6F. TTC Devices. This section outlines considerations for traffic devices in WZs. The findings suggest lateral clearance for right-side encroachments are higher than left-side encroachments in WZs (8.5 vs. 5.2 ft). Section 6F could offer guidance on the amount of lateral clearance that should be provided with use of traffic control devices placed on the left or right shoulder.

CHAPTER 5

Considerations and Limitations

One conclusion reached by the research team was that there is not sufficient evidence to support the need to revise current guidelines pertaining to impact conditions in MASH. As explained previously, this conclusion was supported by a variety of observations, some of which related to lack of data and/or differences in data collection. For example:

- There are not enough data to support the need for a change in MASH speed impact conditions for testing and evaluating roadside safety hardware implemented in WZ locations.
  - Only five WZ related crashes with reconstructed impact speed were identified in the NCHRP Project 17-43 database.
  - The posted speed limits and the functional classification for the roadways on which these encroachments occurred are not available in the NDS data.
  - There may be differences associated with the different data collection periods of the utilized datasets and the relative contribution of advancing vehicle safety technologies in each.
- There are not enough data to support the need for a change in MASH angle impact conditions for testing and evaluating roadside safety hardware implemented in WZ locations.
  - Only eight WZ related crashes with reconstructed impact angle were found.
  - The encroachment angles obtained from NCHRP Project 17-43, NCHRP Project 17-22, and NDS data were fairly different, potentially due to the manual technique utilized to extract the encroachment angle values directly from videos as part of the NDS data effort.
- The encroachment conditions extracted from the NCHRP Projects 17-43 and 17-22 databases are based on ROR crashes, while the NDS data are based on encroachments, most of which did not result in a crash.

CHAPTER 6

Conclusions

This research investigated vehicle encroachment conditions associated with WZ locations. Data were collected mainly from NDSs, state crash databases, and NMVCCS and NCHRP Project 17-43 project databases.

There was insufficient evidence to support the need to revise current guidance pertaining to impact conditions in MASH.

From the perspective of the impact/encroachment speed, the general conclusions are

- **Impact speed in WZs.** There are not enough data to support the need for a change in MASH impact conditions for testing and evaluating roadside safety hardware implemented in WZ locations (source is only five WZ related crashes with reconstructed impact speed).
- **Encroachment speed in WZs.** The NDS data indicate that the 85th percentile encroachment speed in WZs is 10 percent less than the 85th percentile encroachment speed in non-WZ areas. However, the functional classification and posted speed limits for the roadways on which these encroachments occurred is not available, so it is difficult to conclude that a reduction in MASH test speed is clearly indicated.

From the perspective of the impact/encroachment angle, the general conclusions are

- **Impact angle in WZs.** There are not enough data to support the need for a change in MASH impact conditions for testing and evaluating roadside safety hardware implemented in WZ locations (source is only eight WZ related crashes with reconstructed impact angle).
- **Encroachment angle in WZs.** The NDS data indicate that there is no difference in the 85th percentile of the overall encroachment angles for WZ and non-WZ locations (30.6 degrees in both cases). The 85th percentile of the NCHRP Project 17-43 overall encroachment angle is 22 degrees, which is very similar to the current MASH nominal impact angle of 25 degrees used for testing and evaluating roadside safety devices. The discrepancy between the NDS and NCHRP Project 17-43 encroachment angles is not fully understood, so there is not a strong basis for change of the MASH impact angle at this time.

Encroachment angles were also explored per encroachment speed bins in WZs to determine whether there is a correlation between encroachment angle and encroachment speed. The mean value of departure angle remained stable across the different speed ranges, meaning that the encroachment angle is not correlated with encroachment speed.

The provided current guidance from the RDG on clear zone requirements seems to be appropriate considering the recorded lateral extensions of encroachments in WZ locations.

Speed differences for left-side versus right-side encroachments could inform recommendations for barrier type use in WZs. For instance, additional consideration could be given for use of more forgiving barriers in WZs on the left.

The project findings and potential guidance implications for the MUTCD include the following.

- Section 6C.04. Advance Warning Area. This section discusses traffic control devices for the advance warning area. The findings suggest that around 9 percent of WZ encroachment-related crashes occur in the advance warning area. However, no other information was available to suggest additional guidance needs to be provided.
- Section 6D.03. Worker Safety Considerations. This section discusses use of temporary traffic barriers, which is based on factors such as lateral clearance of workers from adjacent traffic and speed reduction. The findings suggest encroachment speeds are 49.7 mph for left-side encroachment and 51.0 mph for right-side encroachment. Additionally, 8 percent of encroachment crashes in WZs strike WZ equipment. The suggested recommendations in this section may be examined to determine whether they are sufficient given likely lateral clearance when a vehicle encroaches into the WZ environment.
- Section 6F. TTC Devices. This section outlines considerations for traffic devices in WZs. The findings suggest lateral clearance for right-side encroachments are higher than left-side encroachments in WZs (8.5 vs. 5.2 ft). Section 6F could offer guidance on the amount of lateral clearance that should be provided with use of traffic control devices placed on the left or right shoulder.

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List of Abbreviations

AASHTO	American Association of State Highway and Transportation Officials
CDS	Crashworthiness Data System
DOT	Department of Transportation
FARS	Fatality Analysis Reporting System
FHWA	Federal Highway Administration
IS	Impact Severity
MASH	Manual for Assessing Safety Hardware
MUTCD	Manual on Uniform Traffic Control Devices
NASS	National Automotive Sampling System
NCHRP	National Cooperative Highway Research Program
NDS	Naturalistic Driving Study
NWZSIC	National Work Zone Safety Information Clearinghouse
PCB	Portable Concrete Barrier
RDG	Roadside Design Guide
ROR	Run-Off-Road
SHRP 2	Second Strategic Highway Research Program
SVC	Single-Vehicle Crash
TL	Test Level
TTC	Temporary Traffic Control

Abbreviations and acronyms used without definitions in TRB publications:

A4A	Airlines for America
AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FAST	Fixing America's Surface Transportation Act (2015)
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
GHSA	Governors Highway Safety Association
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S. DOT	United States Department of Transportation

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