Effectiveness of Temporary Rumble Strips in Work Zones

February 2022 Final Report	Project number TR202209 MoDOT Research Report number cmr 22-004

PREPARED BY:

Henry Brown

Praveen Edara

Carlos Sun

Sungyop Kim

Jill Bernard Bracy

Qingzhong Zeng

Ho Jun Baek

Gladwell Ndungu

Missouri Center for Transportation Innovation

PREPARED FOR:

Missouri Department of Transportation

Construction and Materials Division, Research Section

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. cmr 22-004	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle Effectiveness of Temporary Rumble Strips in Work Zones		**5. Report Date** February 2022 Published: February 2022 **6. Performing Organization Code**
7. Author(s) Henry Brown Praveen Edara Carlos Sun Sungyop Kim Jill Bernard Bracy Qingzhong Zeng Ho Jun Baek Gladwell Ndungu		**8. Performing Organization Report No.**
9. Performing Organization Name and Address Department of Civil and Environmental Engineering University of Missouri-Columbia E2509 Lafferre Hall, Columbia, MO 65201		**10. Work Unit No.** **11. Contract or Grant No.** MoDOT project # TR202209
12. Sponsoring Agency Name and Address Missouri Department of Transportation (SPR-B) Construction and Materials Division P.O. Box 270 Jefferson City, MO 65102		**13. Type of Report and Period Covered** Final Report (August 2021-February 2022) **14. Sponsoring Agency Code**

15. Supplementary Notes

Conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration. MoDOT research reports are available in the Innovation Library at https://www.modot.org/research-publications.

16. Abstract

Temporary rumble strips, including short-term temporary rumble strips and long-term temporary rumble strips, are used by the Missouri Department of Transportation (MoDOT) to help reduce vehicle speeds in work zones and to alert drivers they are approaching a work zone. This research study investigated the effectiveness of temporary rumble strips used by MoDOT and other state Departments of Transportation (DOTs). The research methodology included a review of existing literature, synthesis of MoDOT and other DOT practices, field observations of driver behavior and installation of temporary rumble strips, collection and analysis of speed data, and economic analysis. A synthesis of existing DOT practices found differences in levels of implementation and standards for temporary rumble strips among DOTs. Field observations of driver behavior noted minimal erratic driver behavior. Overall, the study found that temporary rumble strips can be an effective tool to lower vehicle speeds and reduce crashes and can lead to high benefit-cost ratios. Modifications to existing MoDOT practices may potentially reduce cost, increase installation efficiency, enhance worker safety, and improve performance of temporary rumble strips.

17. Key Words Temporary rumble strip; Work zone speed; Work zone safety	**18. Distribution Statement** No restrictions. This document is available through the National Technical Information Service, Springfield, VA 22161.

19. Security Classif. (of this report) Unclassified.	**20. Security Classif. (of this page)** Unclassified.	**21. No. of Pages** 231	**22. Price**

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

EFFECTIVENESS OF TEMPORARY RUMBLE STRIPS IN WORK ZONES

Final Report
February 2022

Principal Investigator
Henry Brown., P.E., Research Engineer
University of Missouri-Columbia

Co-Principal Investigators
Praveen Edara, Ph.D., P.E., Professor
Carlos Sun, Ph.D., P.E., Professor
University of Missouri-Columbia

Sungyop Kim, Ph.D., Professor
University of Missouri-Kansas City

Jill Bernard Bracy, Ph.D., Professor
University of Missouri-Saint Louis

Authors
Henry Brown
Praveen Edara
Carlos Sun
Sungyop Kim
Jill Bernard Bracy
Qingzhong Zeng
Ho Jun Baek
Gladwell Ndungu

Sponsored by
Missouri Department of Transportation

A report from the
University of Missouri
Department of Civil and Environmental Engineering
E2509 Lafferre Hall
Columbia, MO 65211

COPYRIGHT

DISCLAIMER

The opinions, findings, and conclusions expressed in this document are those of the investigators. They are not necessarily those of the Missouri Department of Transportation, U.S. Department of Transportation, or Federal Highway Administration. This information does not constitute a standard or specification.

ACKNOWLEDGMENTS

The authors would like to thank the Missouri Department of Transportation (MoDOT) and the Missouri Center for Transportation Innovation (MCTI) for sponsoring this research. The authors would also like to acknowledge the assistance provided by MoDOT personnel with several aspects of the research, such as identifying work zone locations for the study, checking on project schedules, collecting speed and count data, and providing other data relevant to the research. The authors would also like to acknowledge the contributions of Sulli Wallisch in helping to compile and analyze information for the report. Finally, the authors appreciate the efforts of personnel from various DOTs who provided information about the practices of their DOTs for temporary rumble strips.

ABSTRACT

Temporary rumble strips, including short-term temporary rumble strips and long-term temporary rumble strips, are used by the Missouri Department of Transportation (MoDOT) to help reduce vehicle speeds in work zones and to alert drivers they are approaching a work zone. The objective of this research study is to investigate the effectiveness of temporary rumble strips used by MoDOT and other state Departments of Transportation (DOTs). The research methodology to meet this objective includes a review of existing literature, synthesis of MoDOT and other DOT practices, field observations of driver behavior and installation of temporary rumble strips, collection and analysis of speed data, and economic analysis. A synthesis of existing DOT practices found differences in levels of implementation and standards for temporary rumble strips among DOTs. Field observations of driver behavior noted rare instances of erratic driver behavior. Overall, the study found that temporary rumble strips can be an effective tool to lower vehicle speeds and reduce crashes and can lead to high benefit-cost ratios. Modifications to existing MoDOT practices may potentially reduce cost, increase installation efficiency, enhance worker safety, and improve performance of temporary rumble strips.

EXECUTIVE SUMMARY

A significant component of any strategy to improve work zone safety includes managing work zone speeds. Temporary rumble strips (both long-term and short-term) are used by the Missouri Department of Transportation (MoDOT) to help reduce vehicle speeds in work zones and to alert drivers that they are approaching a work zone. The objective of this research study is to investigate the effectiveness of temporary rumble strips used by MoDOT and other state Departments of Transportation (DOTs). The research methodology to meet this objective includes a review of existing literature, synthesis of MoDOT and other DOT practices, field observations of driver behavior and installation of temporary rumble strips, collection and analysis of speed data, and economic analysis. The project scope includes both short-term temporary rumble strips, which are held in place by their weight and removed during inactive work zone periods, and long-term temporary rumble strips which are held in place by adhesive and remain in place during both active and inactive work zone periods.

Existing literature on temporary rumble strips, including guidance documents and evaluation studies, was reviewed and synthesized. Notable was a publication from the American Traffic Safety Services Association (ATSSA) that provides guidance on various aspects of temporary rumble strips, such as advantages and disadvantages, work zone duration, configuration, parameters, and other considerations (ATSSA 2013). Prior research studies have shown temporary rumble strips to be effective in reducing vehicle speeds by 4 miles per hour (mph) to 12 mph, increasing driver braking, alerting drivers to the presence of the work zone, and reducing crashes by 11 to 60 percent.

Existing DOT practices for temporary rumble strips were assessed through a review of DOT standards, written correspondence with DOTs, and phone interviews with eight DOTs. The researchers corresponded with 18 DOTs and conducted interviews with 8 of them. The results of this analysis indicate that DOT practices for temporary rumble strips differ significantly with respect to level of implementation and various attributes such as size, color, speed, spacing, materials, installation, maintenance, and removal. DOTs generally find that temporary rumble strips are effective in reducing vehicle speeds and alerting drivers to the presence of work zones. Concerns noted by some DOTs include the heavy weight of short-term temporary rumble strips, requirements for installation, potential for erratic driver behavior, and the need for maintenance of the temporary rumble strips.

The field study of temporary rumble strips included the following components: observations of installation of temporary rumble strips and driver behavior post-installation, and the collection and analysis of speed and count data at various work zones with and without temporary rumble strips. The installation of temporary rumble strips was observed at five work zones: three MoDOT contractor projects (MO 370 in St. Charles County, US 24 in Randolph County, and US 63 near Ashland in Boone County) and two MoDOT maintenance projects (I-55 in Ste. Genevieve County and US 63 north of Columbia in Boone County). Three of the five work

zones (MO 370, I-55, and US 63 north of Columbia) used long-term temporary rumble strips and two (US 24 and US 63 near Ashland) used short-term temporary rumble strips. An observation checklist was completed for each of the five locations and feedback was obtained from the installation personnel.

Results from these observations indicated the spacing between strips and/or number of strips deviated from the MoDOT Engineering Policy Guide (EPG) at four of the five work zones. For long-term temporary rumble strips, the EPG specifies two sets of five strips with a spacing of 10 to 12 feet between strips. For the observed installations, the number of strips per set varied from three to five, and the spacing ranged from 2 feet to 12 feet. For short-term rumble strips at work zones with a permanent posted speed limit of 60 mph to 70 mph, the EPG calls for two sets of three strips with 35-foot spacing between strips. The spacing for the observed installations (both with permanent posted speed limits of 60 mph to 70 mph) ranged from 16 feet to 26 feet.

Perceptions of the effectiveness of temporary rumble strips varied between the installers, but the installers generally thought temporary rumble strips can be effective in certain situations. Concerns noted by the installers include the heavy weight of short-term temporary rumble strips, difficulty in removing long-term temporary rumble strips on asphalt pavements, time required for installation of long-term temporary rumble strips, and worker exposure to traffic when installing short-term temporary rumble strips on a divided highway.

Driver behavior was observed for four hours after installation of temporary rumble strips at three work zones, including one work zone with short-term temporary rumble strips and two work zones with long-term temporary rumble strips. Observations focused on whether vehicles braked after traversing the temporary rumble strips or swerved to avoid the temporary rumble strips. Results indicated that 52.4 percent of drivers braked for short-term temporary rumble strips in a nighttime flagger situation and 0.7 percent to 6.7 percent of drivers braked for long-term temporary rumble strips on a divided highway during daytime. Only one erratic driving maneuver, in which a motorcycle drove around short-term temporary rumble strips in a flagger work zone, was observed.

To assess the effects of temporary rumble strips on managing vehicle speeds, vehicle speed and count data were collected by traffic personnel from MoDOT's seven districts. The research team provided guidance on the data collection and coordinated with MoDOT to identify suitable locations for the study. Data were requested for 42 work zones and received for 18 work zones, including four of the work zones where the research team observed installation of the temporary rumble strips. After receiving the speed and count data from the MoDOT districts, the research team performed data processing prior to analysis to organize the data and provide consistency.

The safety analyses involved descriptive and statistical analyses. The overall speed compliance rate in the work zone speed data was only 23.4 percent. However, the analyses revealed positive

effects of temporary rumble strips on the work zone speed compliance. With the complete survey data, the marginal effects (that is, effects of the rumble strips) showed that the speed violation decreased by 21.2 and 18.2 percent for short-term and long-term rumble strips, respectively. The analysis of before and after entering the rumble strips segment also shows long-term rumble strips decreased the speed violation by 68.0 percent. However, the analyses were inconclusive on the difference between short-term and long-term rumble strips' effects on the work zone speed violation and compliance.

The economic evaluation of short-term, portable rumble strips and long-term, adhesive rumble strips provides an overview of the cost-effectiveness of temporary rumble strips implementation in work zones. The benefit-cost analysis calculated and compared the implementation costs relative to the estimated crash-related cost savings rendered from enhanced work zone safety. The purchase, installation, maintenance, removal costs were measured, the pavement damage, reusability, and noise were considered, and the annual crash cost savings was calculated using the estimated crash cost multiplied by the estimated annual crash reduction due to improved safety. Findings suggest that temporary rumble strips lead to a reduction in work zone crashes, which renders cost savings greater than costs incurred from purchasing, installation, and removal. To illustrate the computation of benefit-cost ratios, some rural and urban examples were presented with various levels of AADT. These examples resulted in benefit-cost ratios of 4.3 to 26.3. Positive benefit-cost ratio examples illustrate that the benefits of temporary rumble strip implementation outweigh the costs, and therefore they are reported to be a positive investment that are economical and efficient for work zone implementation.

Overall, the study found temporary rumble strips can be an effective tool to lower vehicle speeds and reduce crashes. Modifications to existing MoDOT practices may potentially improve performance of temporary rumble strips and compliance with MoDOT standards. Such modifications could include specifying the use of one set of temporary rumble strips instead of two sets, changes in terminology, providing greater flexibility in the type of temporary rumble strip used based on project conditions (such as duration, project type, and location characteristics), adding a "Rumble Strips Ahead" sign to the temporary traffic control plan for temporary rumble strips, increasing verification and monitoring of temporary rumble strip layout and spacing in the field, and updating procedures for installing short-term temporary rumble strips on divided highways to reduce worker exposure to traffic (such as using a TMA, crib carrier, or handling machine). Language for possible inclusion in the EPG regarding selection of temporary rumble strip type is provided. For example, short-term temporary rumble strips are recommended for use in flagging operations and both long-term and short-term temporary rumble strips are recommended for use on lane closures on divided highways (with TMA or other worker protection during installation and removal).

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

ARTBA	American Road and Transportation Builders Association
ATM	Advance Traffic Markings
ATSSA	American Traffic Safety Services Association
AADT	Annual Average Daily Traffic
Caltrans	California Department of Transportation
CMF	Crash Modification Factor
CMV	Commercial motor vehicle
DOT	Department of Transportation
DSCF	Dwass, Steel, Critchlow-Fligner
EOQWS	End-of-Queue Warning System
EPG	Engineering Policy Guide
FHWA	Federal Highway Administration
GDOT	Georgia Department of Transportation
IDOT	Illinois Department of Transportation
mph	Miles per hour
MUTCD	Manual on Uniform Traffic Control Devices
MDOT	Maine Department of Transportation
MoDOT	Missouri Department of Transportation
PSS	Plastic Safety Systems, Inc.
SHA	State Highway Administration
SR	State Route
TPRS	Temporary portable rumble strips
TTRS	Temporary transverse rumble strips
TMA	Truck Mounted Attenuator
TRB	Transportation Research Board

1. INTRODUCTION

Background and Motivation

Improving work zone safety is a major goal for engineering practitioners. In the United States in 2018, there were 1.84 fatal work zone crashes per day, and a work zone crash occurred every 4.3 minutes (FHWA 2020, ARTBA 2020). Vehicle speeds and speed variance are important factors that play a role in work zone safety (The Roadway Safety Consortium, n.d.). A significant component of any strategy to reduce work zone crashes includes managing work zone speeds. Temporary rumble strips are sometimes used by the Missouri Department of Transportation (MoDOT) to help reduce vehicle speeds in work zones and to alert drivers they are approaching a work zone. MoDOT would like to learn more about the effectiveness of the temporary rumble strips and about the practices of other Departments of Transportation (DOTs) for their use.

Study Objectives and Scope

The objective of this research study is to investigate the effectiveness of temporary rumble strips (both long-term and short-term) that are used by MoDOT and other state DOTs. The research methodology to meet this objective includes a review of existing literature, synthesis of MoDOT and other DOT practices, field observations of driver behavior and installation of temporary rumble strips, collection and analysis of speed data, and economic analysis. Attainment of the project objective will help MoDOT to implement temporary rumble strips more effectively in work zones.

The scope of the study encompasses a review of literature and existing DOT practices, driver behavior, installation and removal considerations, vehicle speeds, safety, and economic analysis. Both short-term and long-term temporary rumble strips were included in the study. Short-term temporary rumble strips (Figure 1-1), also known as temporary portable rumble strips (TPRS), are held in place by their self-weight and removed when there is no active work in the work zone. Long-term temporary rumble strips (Figure 1-2) are held in place with adhesive and remain in place continuously for the duration of the work zone regardless of whether there is active work.

Figure 1-1. Short-term temporary rumble strips installed on US 63 southbound in Ashland

Figure 1-2. Long-term temporary rumble strips installed on US 63 southbound in Columbia

Study Methodology

The study methodology includes a review of existing research studies, general guidance documents, and DOT standards and specifications; written correspondence and interviews with other DOTs; field observations of driver behavior after temporary rumble strips are installed; field observations of the installation of temporary rumble strips; collection of speed and count data from work zones at various locations in Missouri; analysis of speed and count data to assess the impacts of temporary rumble strips on vehicle speeds; and economic evaluation of the costs and benefits of temporary rumble strips.

Report Organization

The following chapters of this report are organized as follows:

- Chapter 2 describes the comprehensive literature review of research studies, guidance,

policies, standards, and specifications.

- Chapter 3 provides information on DOT practices based on interviews and written responses.
- Chapter 4 presents an analysis of driver behavior with temporary rumble strips.
- Chapter 5 describes results from field observations of installation of temporary rumble strips.
- Chapter 6 presents some information from manufacturers of temporary rumble strips.
- Chapter 7 discusses the methodology used to collect the vehicle speed and count data.
- Chapter 8 includes a safety assessment of temporary rumble strips.
- Chapter 9 offers an economic evaluation of temporary rumble strips.
- Chapter 10 presents the conclusions of the research study.

Table 1-1 lists the supplemental information for the report included in the appendices.

Table 1-1. Report Appendices

Appendix	Title
A	Summary of Existing Literature for Temporary Rumble Strips
B	Summary of DOT Standards and Specifications for Temporary Rumble Strips
C	Example DOT Standards and Guidance for Temporary Rumble Strips
D	Summary of DOT Practices Based on Interviews and Written Responses
E	Checklists for Observation of Driver Behavior
F	Checklist Used for Observation of Installation of Temporary Rumble Strips
G	Installation Observations
H	Memorandum Sent to MoDOT Districts to Request Speed and Count Data
I	Summary of Requested Locations for Speed and Count Data
J	Attribute Data for Sites and Time Periods

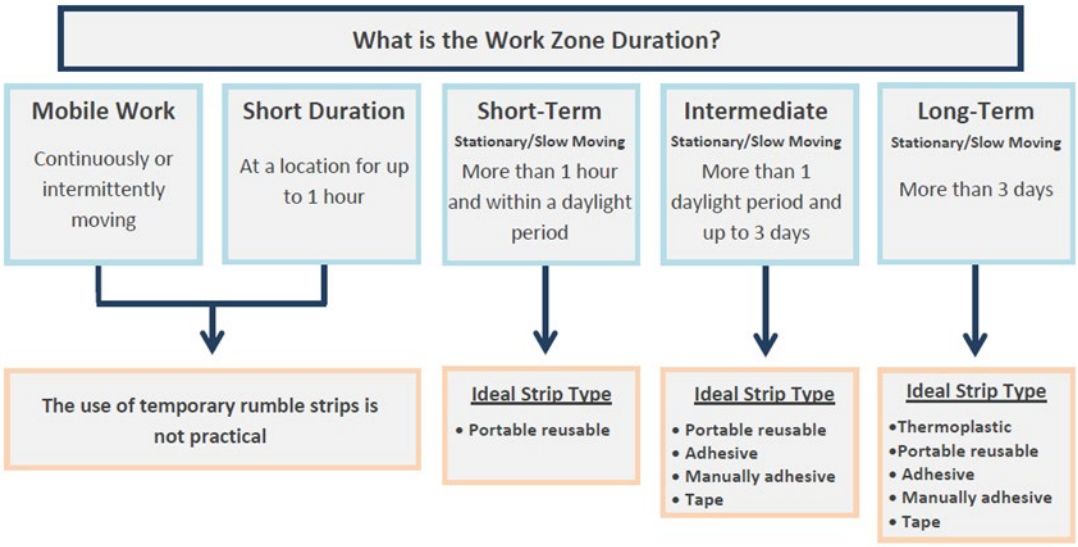
2. LITERATURE REVIEW

This chapter provides an overview of the existing literature for temporary rumble strips, including guidance documents and research studies. Additional details regarding existing literature may be found in Appendix A.

General Guidance for Temporary Rumble Strips

Limited guidance on the use of temporary rumble strips is presented in Section 6F.87 of the Manual on Uniform Traffic Control Devices (MUTCD) (FHWA, 2009). The MUTCD indicates the color of transverse temporary rumble strips should be white, black, or orange if not the pavement color. The MUTCD recommends transverse temporary rumble strips not be deployed on sharp horizontal or vertical curves and a minimum clear path of four feet be provided on roadways used by bicyclists.

In addition to the MUTCD, a publication from the American Traffic Safety Services Association (ATSSA) provides guidance on the use of various types of temporary rumble strips, including adhesive rumble strips, manually adhesive rumble strips, and Temporary Portable Rumble Strips (TPRS) (ATSSA, 2013). The ATSSA guide provides information on the advantages (for example, ease of installation and removal, increased driver awareness, increased braking, and reduced speeds) and disadvantages (for example, possible erratic driver maneuvers, possible movement, and challenges for motorcycles or bicyclists) of temporary rumble strips. Other topics in the ATSSA guide include work zone duration, configuration of temporary rumble strips, temporary rumble strip parameters, and other considerations. For example, Figure 2-1 shows a flowchart that recommends a type of temporary rumple strip based on the work zone duration.

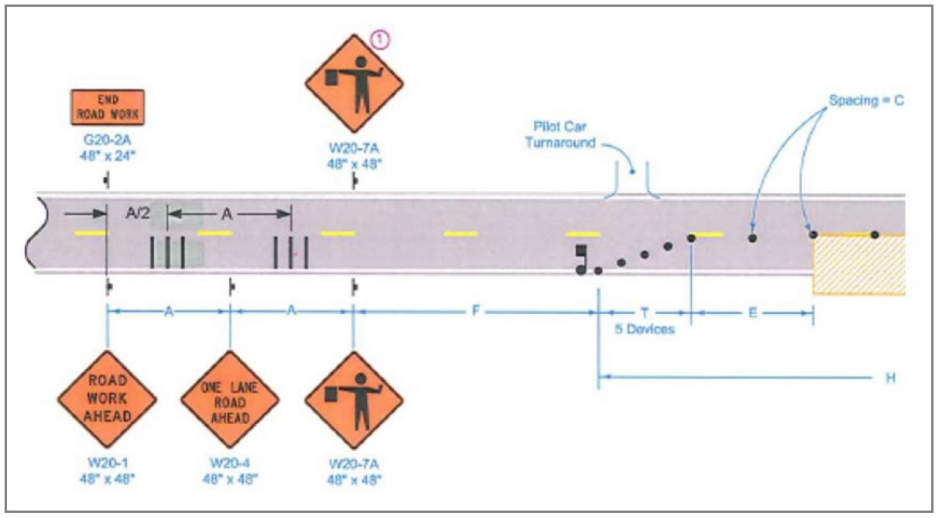


(ATSSA 2013)

Figure 2-1. Flowchart for type of temporary rumble strip based on work zone duration

Research Studies

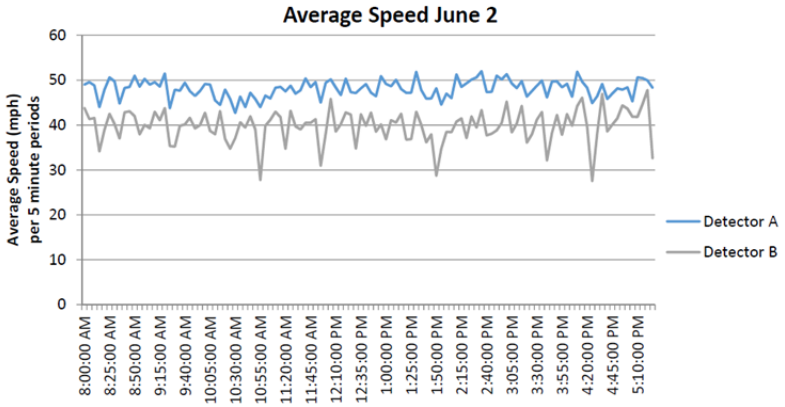
Research studies have shown temporary rumble strips to be effective in reducing vehicle speeds. For example, an Iowa DOT field study (Hawkins and Knickerbocker 2017) assessed two layouts of TPRS: Developmental Specification layout (two sets of TPRS) (Figure 2-2) and a modified TPRS layout (one set of TPRS and "Rumble Strips Ahead" sign). Results showed that 29 percent of vehicles braked for the Developmental Specification layout and 33 percent of vehicles braked for the modified layout at the upstream TPRS location. In contrast, only 10 percent of vehicles braked with no TPRS in place. The use of TPRS also led to significant speed reductions, with mean speed reductions of 5.5 miles per hour (mph) (Developmental Specification layout) and 3.7 mph (modified layout) compared to a 0.1 mph increase in mean speed when TPRS were not used.



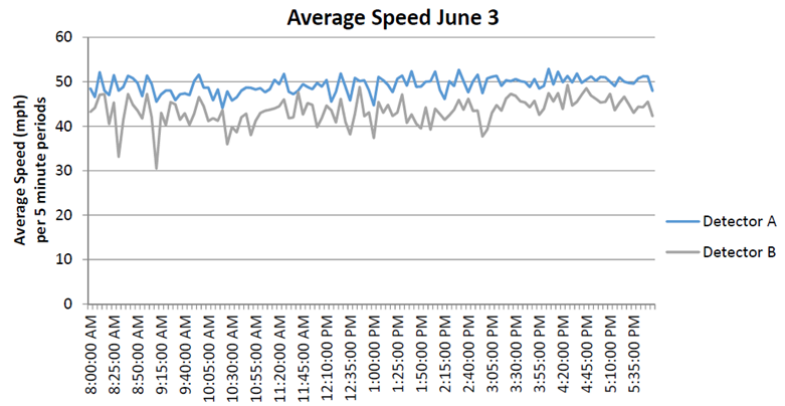
(Hawkins and Knickerbocker 2017)

Figure 2-2. Layout of temporary portable rumble strips (TPRS) in Iowa study (Developmental Specification layout with two sets of temporary rumble strips)

A Wisconsin study found reductions in 85th percentile speeds of 4.7 to 5.0 mph with TPRS, compared to a 1.5 mph decrease without TPRS (Sippel and Schoon 2016). There was less of a speed reduction on the second day (Figure 2-3), indicating a possible effect of driver familiarity. In addition, 33.3 percent to 39.2 percent of drivers braked with TPRS compared to 2.8 percent without TPRS. However, avoidance maneuvers were detected for about 5.5 percent of drivers. The Wisconsin study also included a survey of project leaders and region staff regarding the effectiveness of the TPRS. All eight of the survey respondents recommended the use of TPRS, and respondents indicated that they thought the TPRS improved safety and helped to get drivers' attention. Concerns noted by survey respondents include avoidance maneuvers, development of traffic queues beyond the TPRS, employee safety during set up, the heavy weight of TPRS, and cost.



(a)



(b)

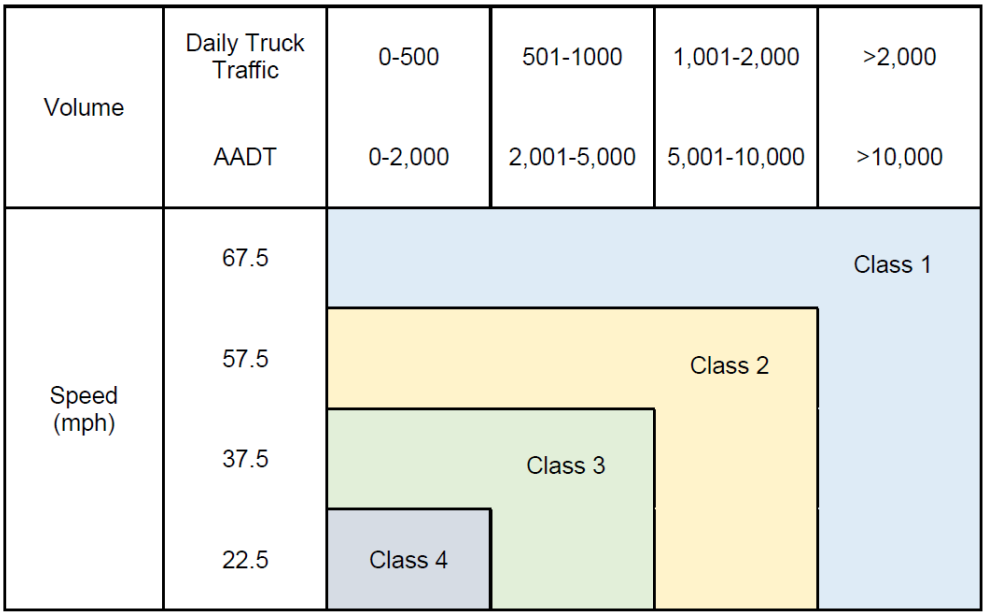
(Sippel and Schoon 2016)

Figure 2-3. Average speeds by 5-minute time periods in Wisconsin study (a) First day of use (b) Second day of use

Other studies in New Jersey, Missouri, and Kansas also showed speed reductions associated with the use of TPRS. An assessment of the deployment of TPRS at eight short-term survey work zones in New Jersey found that mean operating speeds decreased by 10 percent in the right lane and 13.8 percent in the left lane (Yang et al. 2015). In addition, the proportion of vehicles that braked increased by an average of 12 percent. A comparison of TPRS with no TPRS on a one-lane two-way operation on a low volume road in Missouri found a 10 percent increase in the number of vehicles that braked, an average speed reduction of 3.71 mph for braking vehicles, and a 2.9 percent increase in speed compliance (Sun et al. 2011). Field evaluations of TPRS at three-short-term maintenance work zones with flaggers in Kansas found speed reductions of between 4.6 and 11.4 mph for cars and between 5.0 and 11.7 mph for trucks (Wang et al. 2011). In addition, approximately 5 percent of vehicles swerved to avoid the strips.

Research has also shown that the use of TPRS leads to crash reductions. Crash data was collected on the I-35 corridor in Texas for combined TPRS and End-of-Queue Warning Systems (EOQWS) deployment for queued (traffic queue of stopped vehicles exists) and non-queued (traffic queue of stopped vehicles does not exist) conditions (Ullman et al. 2018). In queued conditions, the following Crash Modification Factors (CMFs) were reported: 0.40 (TPRS only) and 0.47 (EOQWS and TPRS used together). These CMFs correspond to crash reductions of 60 percent and 53 percent, respectively. For non-queued conditions, the CMFs were determined to not be statistically significant with the following values: 0.89 (TPRS only) and 0.72 (EOQWS and TPRS used together). These CMFs represent crash reductions of 11 percent and 28 percent, respectively.

In a research study sponsored by Kansas DOT, a decision matrix for different classes of TPRS was developed based on daily truck traffic, Annual Average Daily Traffic (AADT), and speed (Figure 2-4) (Schrock et al. 2016). To develop the matrix, a closed-course test with two models of TPRS (RoadQuake 2F and TrafFix Alert) was conducted to test the rotational and linear movement of the strips and sound generated by the passing vehicles. RoadQuake2F strips showed movement of less than an inch by vehicles passing by at 67.5 mph which placed them in Class 1 of the decision matrix that the research team developed. TrafFix Alert strips were categorized as Class 4 due to excessive movements by vehicles at speeds of 37.5 mph or more. Because vehicle type and sound generation were not statistically significant, the research team made the decision matrix with the traffic volume.



(Schrock et al. 2016)

Figure 2-4. Decision matrix for TPRS from Kansas DOT study

The viability of long-term temporary rumble strips in terms of vehicle vibration, sound levels inside the vehicle, roadside noise, durability, and speed control was assessed compared to original asphalt permanent rumble strips in a study by Meyer (2006b). Results indicated that the use of long-term temporary rumble strips led to speed reductions of 3.9 to 8.7 mph. The long-term temporary rumble strips performed comparably to the asphalt rumble strips, with greater ease of installation and removal.

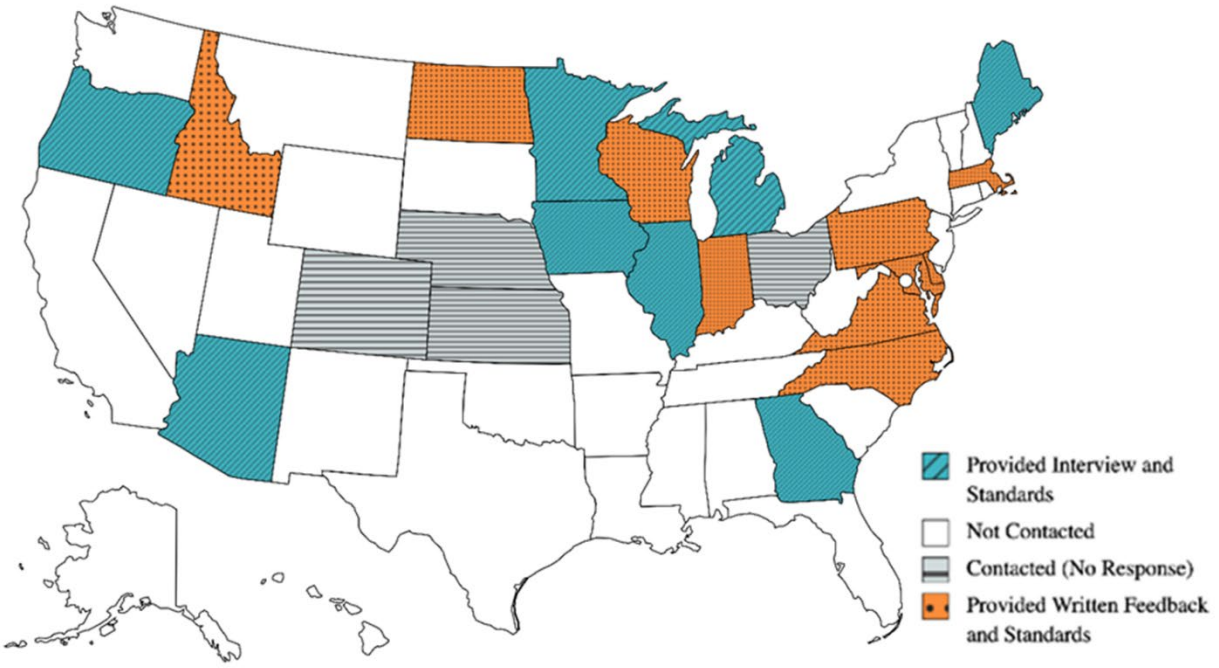
3. SYNTHESIS OF MODOT AND OTHER DOT PRACTICES FOR TEMPORARY RUMBLE STRIPS

This chapter presents the methodology and results for a synthesis of DOT practices for temporary rumble strips based on a review of DOT standards, guidance, and specifications; written correspondence; and interviews with select DOTs.

Methodology for Reviewing DOT Practices

A synthesis of existing DOT practices for temporary rumble strips was undertaken by reviewing DOT standards, guidance, and specifications and obtaining DOT feedback regarding their use of temporary rumble strips. As shown in Figure 3-1, 22 DOTs were contacted to solicit input regarding experience with temporary rumble strips and to request DOT standards. Information regarding standards and feedback was received from 18 DOTs, and interviews were conducted with eight of these 18 DOTs. Additional DOT resources were identified through a search by the research team. During the interviews, DOTs were asked various questions such as the following:

- How frequently does your DOT use temporary rumble strips?
- What products does your DOT use? How are the rumble strips held in place (weight or adhesive)?
- What types of speed reductions have you seen with the temporary rumble strips?
- What types of driver behavior have you observed with the temporary rumble strips?
- What types of concerns have you received from contractors regarding the temporary rumble strips?



(Map created with mapchart.net ©)

Figure 3-1. Map showing DOTs that provided interviews, written feedback, and standards for temporary rumble strips

DOT Standards, Guidance, and Specifications for Temporary Rumble Strips

This section provides an overview of standards, guidance, and specifications for temporary rumble strips for MoDOT and other DOTs. Additional information on DOT standards, guidance, and specifications for temporary rumble strips may be found in Appendix B and Appendix C.

MoDOT Standards, Guidance, and Specifications

As described in the following sections, MoDOT provides standards, guidance, and specifications for long-term and short-term temporary rumble strips in its Engineering Policy Guide (EPG) (Missouri DOT 2021a), job special provisions (Missouri DOT 2021c), and General Services Specifications (Missouri DOT 2021b).

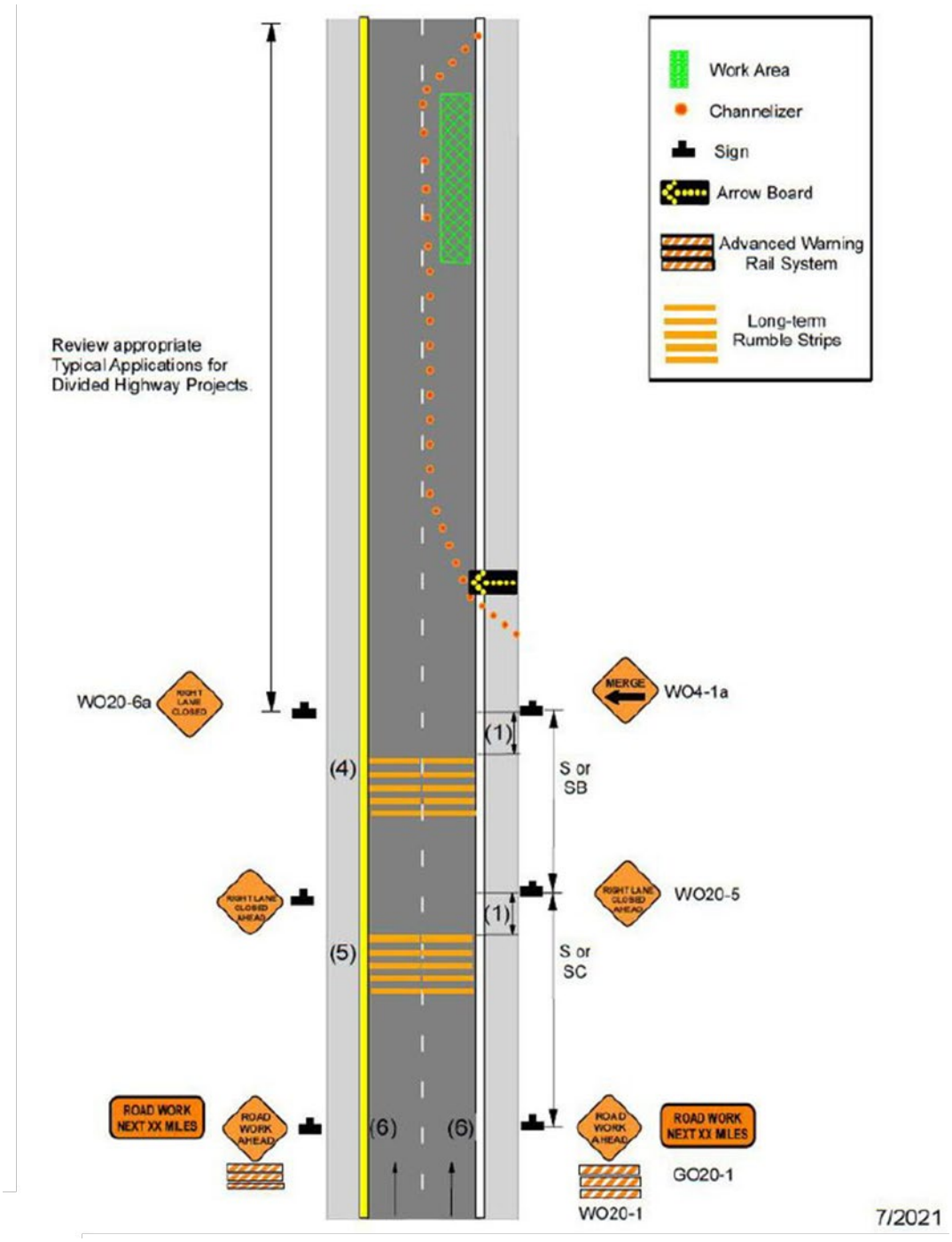
MoDOT Standards, Guidance, and Specifications for Long-Term Temporary Rumble Strips

MoDOT specifies that long-term temporary rumble strips should be made of polymer material, orange in color, 10 to 12 feet long, four to six inches wide, and 0.25 to 0.50 inches thick (Missouri DOT 2021b, Missouri DOT 2021c). They should be placed based on the plans or direction of the Engineer (as defined in MoDOT specifications) in accordance with the manufacturer's recommendations. Two sets are normally used with five strips per set spaced at

10 to 12 feet (Table 3-1); however, the option to only use one set of strips is provided. Typical applications, such as the one shown in Figure 3-2, are provided in the EPG (Missouri DOT 2021a). The contractor must repair any pavement damage incurred during removal of the strips. Measurement and payment are based on each set of long-term temporary rumble strips.

Table 3-1. MoDOT spacing requirements for long-term temporary rumble strips (Missouri DOT 2021a)

Permanent Posted Speed (mph)	Distance (ft.)	Spacing (ft.)
0-45 (Optional)	120	10-12
50-55	160	10-12
60-70	200	10-12



(Missouri DOT 2021a)
(for notes, please see Figure C-38)

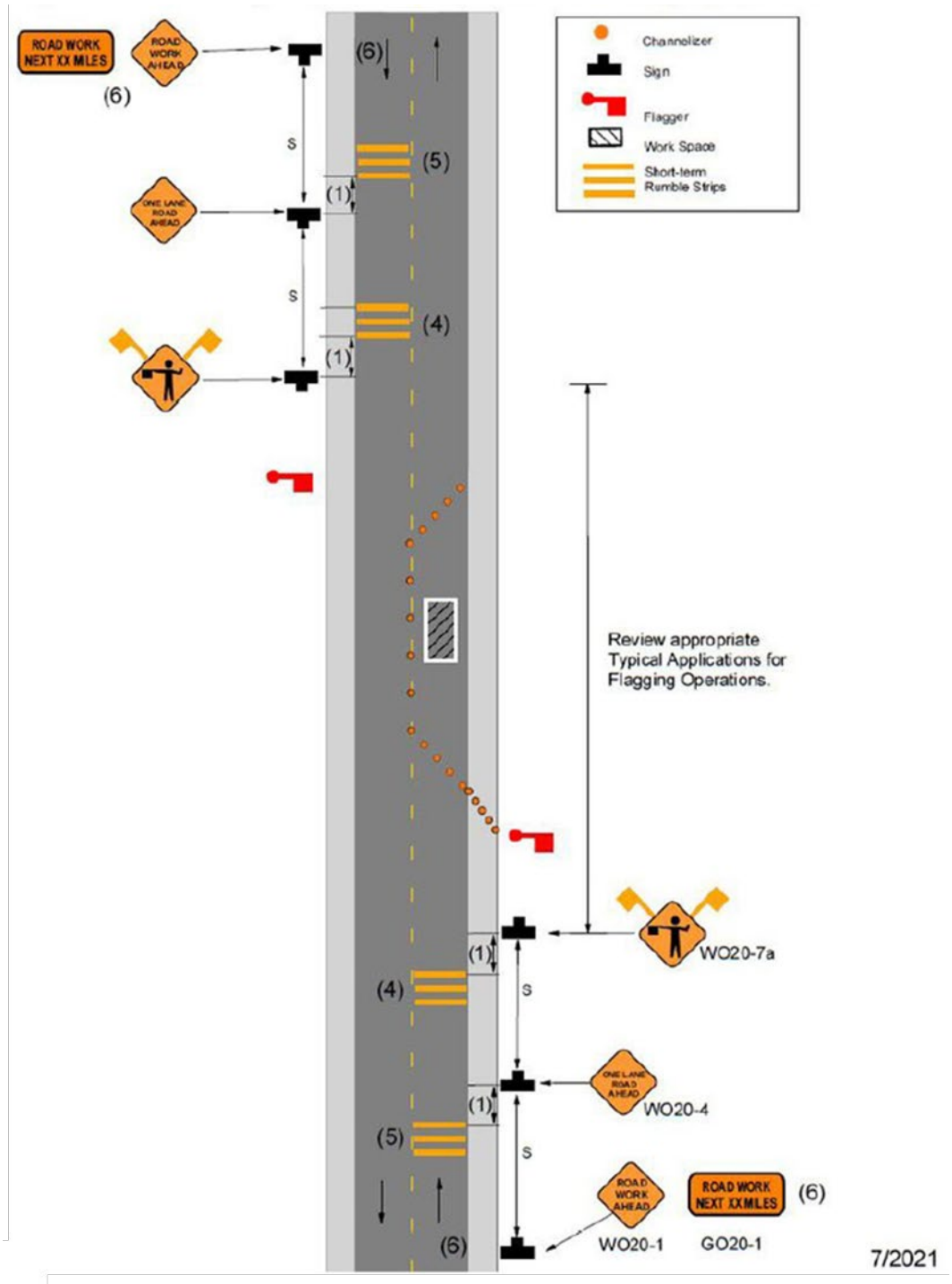
Figure 3-2. MoDOT typical application for long-term temporary rumble strips for lane closure on divided highway

MoDOT Standards, Guidance, and Specifications for Short-Term Temporary Rumble Strips

MoDOT prescribes short-term temporary rumble strips should be made of polymer material, orange in color, 10 to 12 feet long, at least eight inches wide, and 0.75 to 1.25 inches thick (Missouri DOT 2021b, Missouri DOT 2021c). They should be placed based on the plans or Engineer's direction in accordance with the manufacturer's recommendations. They should not be deployed when there is no active work in the work zone. Two sets are generally used with three strips per set spaced at 10 to 35 feet based on the permanent posted speed limit (Table 3-2), and there is an option to only use one set of strips. Typical applications, such as the one shown in Figure 3-3, are provided in the EPG (Missouri DOT 2021a). The contractor must monitor the rumble strips and realign or repair them as needed. Measurement and payment are based on each set of short-term temporary rumble strips.

Table 3-2. MoDOT spacing requirements for short-term temporary rumble strips (Missouri DOT 2021a)

Permanent Posted Speed (mph)	Distance (ft.)	Spacing (ft.)
0-45 (Optional)	120	10
50-55	160	20
60-70	200	35

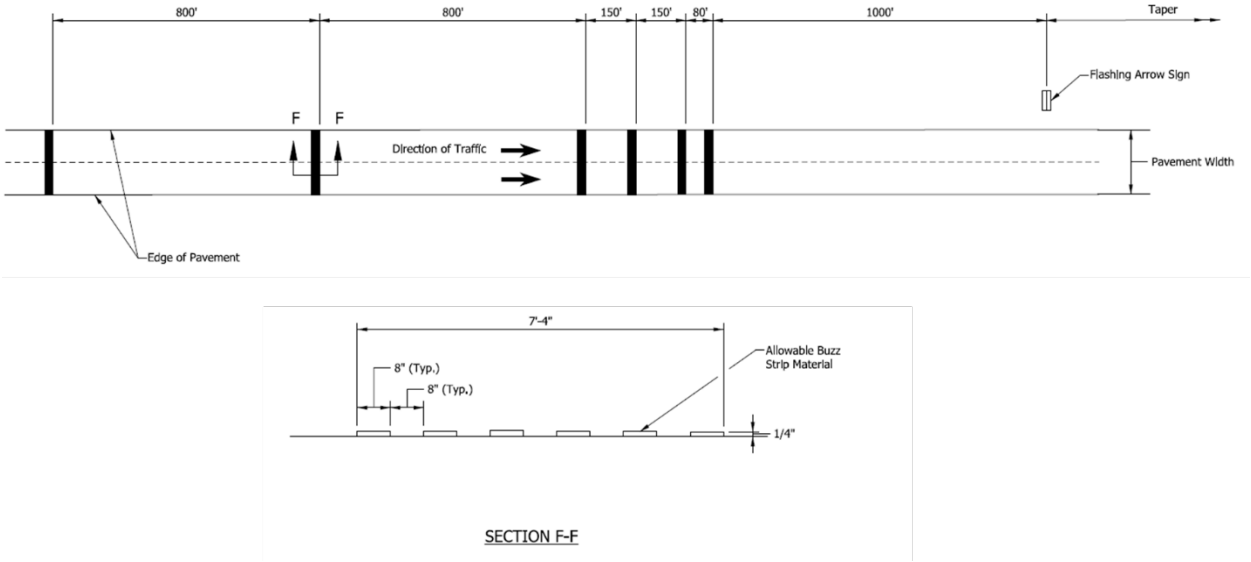


(Missouri DOT 2021a)
(for notes, please see Figure C-35)

Figure 3-3. MoDOT typical application for short-term temporary rumble strips in flagging operations

Other DOT Standards, Guidance, and Specifications for Long-Term Temporary Rumble Strips

DOT standards for materials, placement, and other aspects of long-term temporary rumble strips vary. For example, Minnesota DOT specifies that the strips should be white in color and placed in sets of 10 strips (five per wheel path) (Minnesota DOT 2021b, Minnesota DOT 2020). Indiana DOT requires removable or durable marking material to be placed in sets of six strips with varied spacing as shown in Figure 3-4 (Indiana DOT 2021c, Indiana DOT 2022). The Michigan DOT configuration includes three sets of nine rumble strips (orange in color) in advance of the lane closure using a polymer with a pre-applied adhesive (Michigan DOT 2020). Oregon DOT's standards prescribe the application of two sets of three strips (black in color) using thermoplastic or removable tape for wearing courses, milled strips for base courses, or TPRS for the pavement surface (Oregon DOT 2021a). Nebraska DOT utilizes sets of ten strips per wheel path with asphalt, epoxy and aggregate, or other durable material (Nebraska DOT 2021).



(Indiana DOT 2021c)

Figure 3-4. Layout of long-term temporary rumble strips from Indiana DOT Standard Drawing E 801-TCDV-09

To summarize DOT standards and specifications for long-term temporary rumble strips, various materials are used, such as removable or durable marking material, polymer with pre-applied adhesive, milled strips, and thermoplastic or removable tape. Placement parameters include three to 25 strips per set, one to six sets of strips, spacing between strips of 8 inches to 20 feet, and spacing between sets of 15 feet to 1100 feet. Placement may be across the entire lane or just the wheel path. Typical colors for the strips are white or orange.

Other DOT Standards, Guidance, and Specifications for Short-Term Temporary Rumble Strips

DOT specifications vary with respect to TPRS characteristics such as size and color. For example, the maximum allowable TPRS thickness is 0.75 inches for the Idaho Transportation Department and 1 inch for Indiana DOT (Idaho Transportation Department 2021, Indiana DOT 2021b). Colors typically allowed by DOTs include black or orange (for example, Virginia DOT) or black, orange, or white (for example, Pennsylvania DOT) (Virginia DOT 2020a and Pennsylvania DOT 2021). Some DOTs maintain an approved product list for TPRS, with RoadQuake 2 and RoadQuake 2F approved for use by the California Department of Transportation (Caltrans) (2018b), Wisconsin DOT (2021b), and South Dakota DOT (2021) and TraFix Alert High Speed Rumble Strips also approved for use by Wisconsin DOT (2021b).

DOTs also provide various requirements for TPRS spacing and speed. For example, the Idaho Transportation Department prescribes that the TPRS should be suitable for 80 mph while Michigan DOT prescribes that TPRS should perform at speeds up to 65 mph (Idaho Transportation Department 2021, Michigan DOT 2021a). Colorado DOT standards indicate spacing of 40 feet between strips within a set, while Ohio DOT uses 6 feet 8 inches and Virginia DOT utilizes 10 feet to 20 feet based on the posted/statutory speed limit (Table 3-3) (Colorado DOT 2019, Ohio DOT 2019, Virginia DOT 2020b).

Table 3-3. TPRS spacing used by Virginia DOT (adapted from Virginia DOT 2020b)

Posted/Statutory Speed Limit	≤ 40 mph	41 – 55 mph	> 55 mph
TPRS Spacing (Center to Center)	10 feet	15 feet	20 feet

Some DOTs provide specifications for the installation, maintenance, and removal of TPRS. For example, Oregon DOT requires that TPRS be installed within 10 minutes, while Iowa specifies maximum installation and removal times of five minutes (Iowa DOT 2021b, Oregon DOT 2020). Regarding maintenance, Indiana DOT requires the contractor to correct the positioning of the TPRS if the movement exceeds six inches (Indiana DOT 2021b). Arizona DOT and Tennessee DOT provide specifications for the use of a hitch mounted carrier to store, transport, deploy, and retrieve TPRS (Arizona DOT 2021, Tennessee DOT n.d.). Tennessee DOT prescribes that the carrier should have the capacity to hold and transport six TPRS. Ohio DOT specifies that TPRS should be removed if erratic driver behavior is observed (Ohio DOT 2019). Measurement and payment of TPRS is typically per set although Minnesota DOT (2020) and New York State DOT (2020) use a lump sum pay item.

Overall, there is significant variability in the DOT standards and specifications for TPRS. Speed specifications range from 65 mph to 80 mph. Placement parameters include spacing between

strips of 6 feet to 40 feet, one to three sets of strips, and typically three strips per set. Various colors are utilized, including the pavement color, black, orange, white, a combination of black and white, and a combination of white and orange. A "Rumble Strips Ahead" sign is often deployed with the TPRS.

Results from DOT Interviews and Written Responses

This section provides discussion of the results from the DOT interviews and responses, including descriptions of the practices of three DOTs and general observations. Additional details from the interviews of eight DOTs may be found in Appendix D.

Georgia

The Georgia Department of Transportation (GDOT) deployed TPRS on four pilot projects for work zones involving flagger operations on rural two-lane highways during daytime. An example deployment is shown in Figure 3-5. GDOT has not used TPRS on divided highways. GDOT developed a special detail for the TPRS with two sets of TPRS, 15-foot spacing between strips, and a "Rumble Strips Ahead" sign (Hancock 2020, Georgia DOT 2017). Results from a pilot deployment on State Route (SR) 20 indicated that 80 to 90 percent of vehicles reduced their speeds. GDOT conducted a driver survey regarding the TPRS on three of the pilot projects. In all 243 survey responses received, drivers indicated that the TPRS caught their attention and led them to slow down (Hancock 2020).

GDOT is assessing possible future use of TPRS and working towards getting more buy-in from contractors regarding their use. Contractors have expressed concerns regarding the weight of the TPRS. Other concerns noted during the pilot deployments include traffic backups beyond the TPRS, the potential for truck back tires to wheel hop when traversing the TPRS, and the need for a learning curve by the traveling public.

(Hancock 2020)

Figure 3-5. Example TPRS layout and flagger signage on State Route (SR) 20 in Floyd County, Georgia

Illinois

The Illinois Department of Transportation (IDOT) uses long-term temporary rumble strips [also known as temporary rumble strips (special)] on most lane closures on multi-lane highways to increase drivers' awareness of work zones. The rumble strips are used typically on contractor projects on high-speed roadways (permanent posted speed limit of 70, 65, or 55 mph) in locations determined from impact analysis in advance of where the longest back of queue is expected, typically before the advanced warning area. Deployment of temporary rumble strips (special) is recommended in conjunction with the use of smart work zone technologies when there is the potential for queue buildup. The material typically used for the temporary rumble strips (special) consists of six layers of preformed plastic or Type 3 tape. The typical standard for the temporary rumble strips (special) calls for four sets of three strips (20-foot spacing between strips) and "Rumble Strips Ahead" signs (Illinois DOT 2017). An example deployment is shown in Figure 3-6. The temporary rumble strips (special) are deployed using work trucks and TMAs in accordance with IDOT highway standards (Illinois DOT 2020). In IDOT's experience, the temporary rumble strips (special) stay in place but tend to flatten over time. IDOT believes that the use of the temporary rumble strips (special) has helped to reduce the number of traffic incidents. IDOT also sometimes utilizes temporary rumble strips made of high strength

polycarbonate and held in place by adhesive on two-lane two-way highways when poor alignment or restricted sight distance create potential operational concerns (Illinois DOT 2020, Illinois DOT 2022). IDOT performed some trials of TPRS on maintenance projects but did not pursue implementation due to concerns about movement of the TPRS.

(Courtesy Illinois DOT)

Figure 3-6. Example Illinois Department of Transportation (IDOT) deployment of long-term temporary rumble strips [temporary rumble strips (special)]

Maine

The Maine Department of Transportation (MDOT) begun using TPRS in 2017 through a joint initiative with contractors to improve work zone safety and reduce vehicle speeds. After several successful pilot projects, MDOT started deploying them on most interstate projects (excluding high density areas) and some selected work zones on two-lane roadways with flaggers. Speed feedback signs were also added to work zones to help get drivers' attention. MDOT developed a special provision with construction and materials requirements for TPRS (Maine DOT 2018). MDOT specifies the use of one set of three strips in each direction, and a "Caution Rumble Strips" sign is required. An example deployment is shown in Figure 3-7. On multi-lane highways, TPRS are installed and removed either by waiting for a gap in traffic and dragging the TPRS into place or using a rolling roadblock with an attenuator truck and the State Police.

MDOT uses TPRS at night and finds that they show up well due to the color along with the speed feedback signs and sequential flashing lights. MDOT has noted some movement of TPRS at night, possibly due to higher truck speeds.

MDOT has been satisfied with the performance of TPRS and finds they help to reduce vehicle speeds, increase drivers' awareness of the work zone, and increase worker alertness by providing auditory alerts of approaching vehicles. MDOT is currently reevaluating its use of TPRS due to the increased frequency of erratic driver behavior such as driving around TPRS or stopping prior to the TPRS. Other challenges in the use of TPRS noted by MDOT include contractor concerns regarding weight and deployment in live traffic, frequent need to paint the TPRS on site, some instances of TPRS breaking, the need for maintenance by the Contractor, and concerns about bumps experienced by motorcycles, bicycles, and small cars while traversing the TPRS. MDOT plans to continue to put them in bid packages while working with contractors to address their concerns. MDOT is also exploring the use of enhanced signage or additional traffic control devices to help notify drivers of the upcoming TPRS.

(Courtesy Maine DOT)

Figure 3-7. Example Maine Department of Transportation (MDOT) deployment of TPRS

Summary of DOT Interviews and Written Responses

A summary of key findings from the DOT interviews and written responses is provided below. Additional details are shown in Appendix D.

- Among these 18 DOTs, short-term temporary rumble strips appear to be used more

frequently than long-term temporary rumble strips.

- Temporary rumble strips are used by DOTs in a variety of applications, such as lane closures on multi-lane highways, flagging operations, flagging operations with pilot car, changes in traffic control at intersections, and smart work zones.
- Types of materials used for long-term temporary rumble strips include preformed plastic marking, Type 3 tape, thermoplastic, and preformed pavement marking tape.
- These 18 DOTs have varying levels of experience with the implementation of temporary rumble strips, including no current use (Delaware DOT), pilot use (Pennsylvania DOT), recommended use (Minnesota DOT), and mandatory use for specific conditions (Virginia DOT, Wisconsin DOT).
- Some DOTs currently only use temporary rumble strips for maintenance work (Arizona DOT) while other DOTs only implement them solely on contractor work (IDOT).
- DOTs have used both static and rolling lane closures with a TMA for installing long-term temporary rumble strips.
- The extent of use of TPRS at night varies among DOTs. Issues noted by DOTs for nighttime use of TPRS include movement of the strips and concerns regarding noise in residential areas.
- These 18 DOTs generally find temporary rumble strips to be effective in reducing vehicle speeds, getting drivers' attention, providing alerts to workers, and reducing traffic incidents.
- Weight and placement of TPRS is frequently noted as a concern from contractors. Strategies being used to address these concerns include a trailer mounted carriage and device for deployment of temporary rumble strips.
- Other concerns noted by DOTs in using temporary rumble strips include erratic driver behavior (for example, braking before the temporary rumble strips or swerving to avoid them), some instances of TPRS breaking, and the need for Contractor maintenance.
- Some DOTs (Iowa and Wisconsin) have reduced the number of required temporary rumble strip sets from two to one.

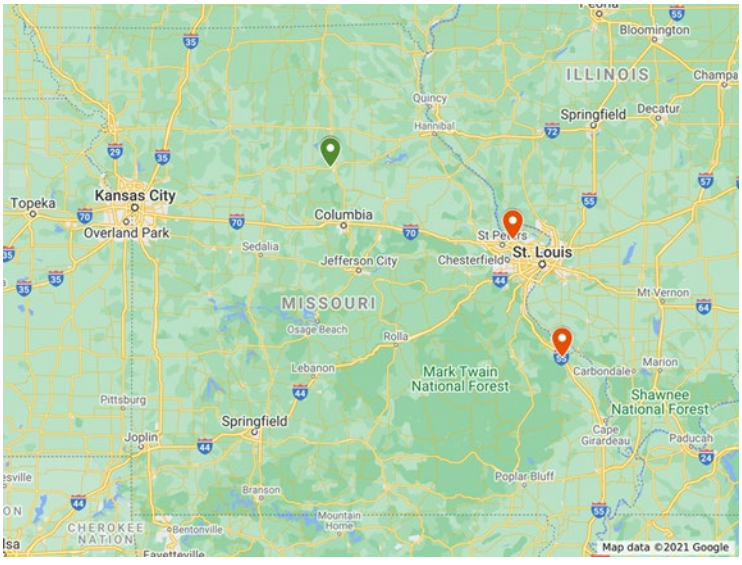
4. DRIVER BEHAVIOR

As part of the study, driver behavior was studied to see if the temporary rumble strips caused any erratic driver maneuvers. This chapter presents the methodology and results for observing driver behavior after installation of temporary rumble strips at three locations in Missouri.

Methodology for Observing Driver Behavior

Driver behavior was studied for four hours after installation of temporary rumble strips at the following three work zones: US 24 in Moberly (at nighttime), MO 370 in St. Charles County, and I-55 in Ste. Genevieve County (Figure 4-1).

Table 4-1 shows various characteristics were represented by these three sites, including the number of lanes, type of rumble strip, pavement type, and permanent and work zone speed limits. The I-55 work zone was a MoDOT maintenance project, while the other two locations were MoDOT contractor projects. After the temporary rumble strips were installed, driver's reactions to the temporary rumble strips were observed and documented. Observations focused on whether vehicles braked after traversing the temporary rumble strips or swerved to avoid the temporary rumble strips. Traffic back-ups or any incidents that could affect the traffic pattern were noted, and data during those time periods were excluded because those conditions prevent drivers from reacting normally to temporary rumble strips.



(Map data © 2021 Google)

Figure 4-1. Locations of work zones where driver behavior was observed after installation

Table 4-1. Attribute data for work zone locations where driver behavior was observed after installation

Route	County	Total No. of Lanes	Type of Temporary Rumble	Day of Week	Start Time	End Time	Pavement Type	Speed Limit (Permanent / Work Zone) (mph)
MO 370	St. Charles	6	Long-term	Friday	9:15 am	1:15 pm	Concrete	60 / 45
I-55	Ste. Genevieve	4	Long-term	Monday	10:40 am	2:40 pm	Asphalt	70 / 70
US 24	Randolph	2	Short-term	Monday	9:05 pm	1:10 am	Concrete	60 / 60

Note: For additional information on study locations, please see Table 7-3

Results for Observations of Driver Behavior

Overall results for the three locations are shown in Table 4-2. For the MO 370 and I-55 locations, information regarding the number of vehicles was obtained from vehicle count data collected by MoDOT, as described in Chapter 7. For the MO 370 work zone, vehicle count data were not available for the day of observation, so vehicle counts from a different day with available data were used instead. At the I-55 work zone, driver behavior at both the upstream and downstream sets of strips was noted to see if there were any differences between the two locations. The results indicate that approximately half of the vehicles braked at the US 24 work zone, while only 0.7 percent of drivers braked at MO 370 and 5 percent to 6.1 percent of drivers braked on I-55. Swerving maneuvers were infrequent, with one motorcycle out of over 8,000 vehicles leaving the travel lane to avoid the temporary rumble strips. The results for each work zone are discussed further in the following sections, and observation checklists are provided in Appendix E.

Table 4-2. Overall results for observations of driver behavior after installation of temporary rumble strips

Route	County	Type of Temporary Rumble Strip	Number of Vehicles	Percent of Vehicles That Braked	Percent of the Vehicles That Swerved
MO 370	St. Charles	Long-term	4309*	0.7	0
I-55 (upstream set of strips)	Ste. Genevieve	Long-term	2111	6.1	0
I-55 (downstream set of strips)	Ste. Genevieve	Long-term	2111	5.0	0
US 24	Randolph	Short-term	105	52.4	1.0

* Vehicle count data from same time period but different day due to data availability issues

US 24 (Moberly)

The field study on US 24 in Moberly was conducted during flagger operations at nighttime. The observations were made on the first night that the short-term temporary rumble strips were deployed in the work zone. Due to the low traffic volumes, all vehicles were counted manually. As shown in Table 4-3, 55.0 percent of the passenger cars and 38.5 percent of trucks (commercial motor vehicles, or CMVs) braked after they encountered the short-term temporary rumble strips. In addition, there was one motorcycle that departed from its lane to avoid the temporary rumble strips by driving in the opposing lane. Overall, traffic counts were low as 105 vehicles were observed in a four-hour period.

Table 4-3. Driver behavior by vehicle type for temporary rumble strips on US 24 in Moberly

Vehicle Type	Number of Vehicles	Percent of Vehicles That Braked
Passenger Car	91	55.0
Truck (CMV)	13	38.5
Motorcycle	1*	0
All	105	52.4

* One motorcycle swerved to avoid strips

MO 370 (St. Charles County)

For the observation for MO 370 in St. Charles County, long-term temporary strips were deployed near the Elm Street on-ramp for MO 370 eastbound (Figure 4-2). Although two sets of strips were placed, observations were made from only one set because the other set was located near a bridge with no suitable location for the researchers. Due to data availability issues, vehicle counts were obtained from sensor data collected by MoDOT for the same location on a different day (see Chapter 7). The vehicle classification for braking vehicles was determined visually, while the vehicle classification for all vehicles was determined from the sensor data (CMV = large, passenger car = medium or small). As shown in Table 4-4, 0.3 percent of passenger cars and 5.8 percent of trucks (CMVs) braked after traversing the temporary rumble strips. There was a traffic backup downstream of the temporary rumble strips for approximately 30 minutes in the morning. Data for motorists that slowed down due to the traffic backup were excluded from the analysis.

Figure 4-2. Vehicles traversing temporary rumble strips on MO 370 in St. Charles County

Table 4-4. Driver behavior by vehicle type for temporary rumble strips on MO 370 in St. Charles County

Vehicle Type	Numb.er of Vehicles*	Percent of Vehicles That Braked
Passenger Car	3782	0.3
Truck (CMV)	278	5.8
All	4060	0.7

* Vehicle counts obtained from sensor data for same time period on a different day due to data availability issues. Truck (CMV) considered large vehicle type from sensor data and passenger car considered medium or small vehicle type from sensor data.

I-55 (Ste. Genevieve County)

Long-term temporary rumble strips were deployed on I-55 northbound approaching the interchange at Route Z in Ste. Genevieve County (Figure 4-3) for a bridge repair project performed by MoDOT maintenance personnel. Observations were recorded at both the upstream and downstream sets of temporary rumble strips. Vehicle counts were obtained from sensor data collected by MoDOT during the time period of the observations (see Chapter 7). The vehicle classification for braking vehicles was determined visually, while the vehicle classification for all vehicles was determined from the sensor data (CMV = large, passenger car = medium or small). As shown in Table 4-5, 3.8 percent of passenger cars and 27.7 percent of trucks (CMVs) braked after traversing the temporary rumble strips at the upstream location, and 2.8 percent of passenger cars and 25.7 percent of trucks (CMVs) braked after traversing the temporary rumble strips at the downstream location.

Figure 4-3. Temporary rumble strips on I-55 in Ste. Genevieve County

Table 4-5. Driver behavior by vehicle type for temporary rumble strips on I-55 in Ste. Genevieve County

Vehicle Type	Number of Vehicles*	Percent of Vehicles That Braked
Passenger Car (Upstream Set of Strips)	1909	3.8
Truck (CMV) (Upstream Set of Strips)	202	27.7
Passenger Car (Downstream Set of Strips)	1909	2.8
Truck (Downstream Set of Strips)	202	25.7
All (Upstream Set of Strips)	2111	6.1
All (Downstream Set of Strips)	2111	5.0

* Vehicle counts obtained from sensor data for observation period. Truck (CMV) considered large vehicle type from sensor data and passenger car considered medium or small vehicle type from sensor data.

Summary of Results of Observations of Driver Behavior

Results from the observations of driver behavior indicate that erratic maneuvers were rare, with only one motorcycle swerving to avoid the temporary rumble strips out of over 8,000 vehicle observations. Approximately half of the vehicles braked on US 24 with short-term temporary

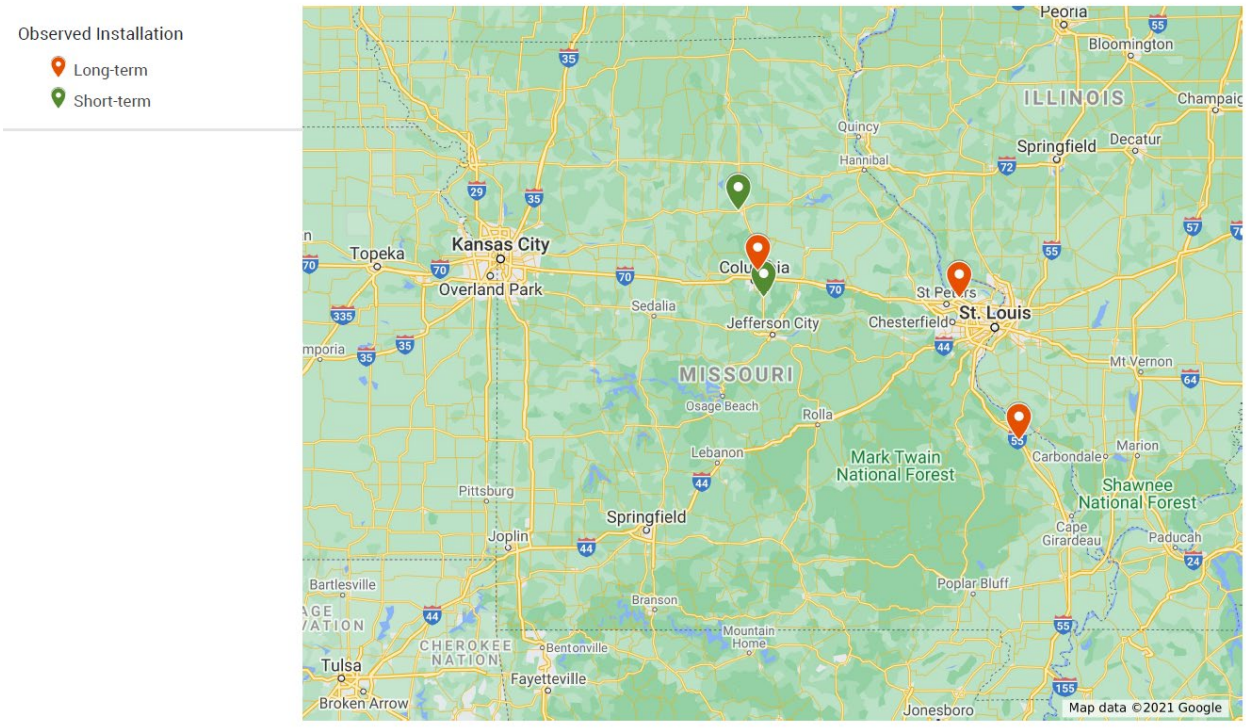
rumble strips, possibly because they were approaching a flagger at nighttime. The percentage of vehicles that braked at the work zones MO 370 and I-55, which involved the use of long-term temporary rumble strips on a divided highway during daytime, ranged from 0.67 percent to 6.1 percent. On MO 370 and I-55, the percentage of trucks that braked (5.8 percent to 27.7 percent) was greater than the percentage of passenger cars (0.3 percent to 3.8 percent) that braked. A greater percentage of vehicles braked on I-55 than on MO 370, a result that could be possibly due to differences in driver behavior, level of driver familiarity with temporary rumble strips, urban versus rural setting, and work zone speed limit (70 mph on I-55 versus 45 mph on MO 370).

5. INSTALLATION AND REMOVAL

This chapter presents observations regarding the installation and removal of temporary rumble strips, including methodology and results.

Methodology for Collecting Information on Installation and Removal

The installation of temporary rumble strips was observed by the research team at five work zones as shown in Figure 5-1 and Table 5-1. MoDOT Central Office personnel participated in the observations for three of the five work zones (US 24 and both US 63 work zones). Three of the work zones used long-term temporary rumble strips, and two of the work zones deployed short-term temporary rumble strips. In two of the work zones, the temporary rumble strips were installed by MoDOT maintenance personnel. A checklist provided by MoDOT (Appendix F) was completed for each installation. The checklist included fields for information such as product used, installation time, and feedback on installation and removal from the installation crew obtained through interviews. The completed checklists are provided in Appendix G. Driver behavior was observed at three of these work zones (Chapter 4), and speed and count data were obtained from MoDOT for four of these work zones (Chapter 7).



(Map data © 2021 Google)

Figure 5-1. Map showing work zone locations where installation of temporary rumble strips was observed

Table 5-1. Site characteristics for work zone locations where installation of temporary rumble strips was observed

Route	County	Type of Temporary Rumble Strip	Installation Personnel	Pavement Type	Work Type	Speed Limit (Permanent / Work Zone) (mph)
I-55	Ste. Genevieve	Long-term	MoDOT Maintenance	Asphalt	Bridge repair	70 / 70
MO 370	St. Charles	Long-term	Contractor	Concrete	Pavement repair	60 / 45
US 24	Randolph	Short-term	Contractor	Concrete	Concrete patching	60 / 60
US 63	Boone	Long-term	MoDOT Maintenance	Concrete	Concrete replacement	70 / 70
US 63	Boone	Short-term	Contractor	Asphalt	J-turn installation	70 / 60

Observations for Installation and Removal

US 24 (Moberly)

Two sets of three short-term temporary rumble strips in each direction (eastbound and westbound) were installed for nighttime flagger operations on US 24 in Moberly as part of a concrete patching project (Figure 5-2). The research team observed the installation on the first night of the work zone at this location. The strips were transported in the bed of a pickup truck and lowered from the truck bed for installation. The flagger operation was set up prior to installation, and the strips were installed in under five minutes. The spacing between strips varied from approximately 16 feet to approximately 20 feet. Based on the 60-mph permanent posted speed limit, the EPG calls for a spacing of 35 feet between strips (Missouri DOT 2021a). The contractor indicated that he found the strips difficult to work with due to their weight.

Figure 5-2. Short-term temporary rumble strips on US 24 in Moberly

MO 370 (St. Charles County)

As part of a concrete pavement repair project on MO 370 in St. Charles County, the contractor deployed two sets of five long-term temporary rumble strips across all three lanes of eastbound traffic (Figure 5-3 and Figure 5-4). The strips were installed in 15 minutes by placing primer and then laying down the strips. A Truck Mounted Attenuator (TMA) was utilized for the installation. The spacing between strips was approximately 12 feet in accordance with the EPG (Missouri DOT 2021a). The lengths of the strips were not measured but visually appeared to shorter than the lane width. In the contractor's experience, the long-term temporary rumble strips are easy to install but difficult to remove, especially on asphalt pavement. The contractor often uses a hammer for removal. The contractor indicated that he believes temporary rumble strips help to slow vehicles down in some situations. The contractor has used short-term temporary rumble strips on other projects and finds their removal challenging due to the heavy weight which requires two workers.

Figure 5-3. Installation of long-term temporary rumble strips on MO 370 in St. Charles County

Figure 5-4. Long-term temporary rumble strips on MO 370 in St. Charles County

I-55 (Ste. Genevieve County)

A MoDOT maintenance crew installed long-term temporary rumble strips on northbound I-55 in Ste. Genevieve County as part of a four-day bridge repair project (Figure 5-5 and Figure 5-6). Two sets of three strips with approximate spacing of 2 feet between strips were installed in both lanes. Based on the 70-mph permanent posted speed limit, the EPG calls for a set of five rumble strips with a spacing of 10 to 12 feet between strips (Missouri DOT 2021a). A TMA was deployed for the installation. Installation steps included (1) applying primer with a brush, (2) removing the plastic backing from the strip, (3) applying the strip to the pavement, and (4) tamping the strip with a piece of wood (Figure 5-5). The MoDOT crew did not have access to the tamper cart that is recommended for use by the manufacturer (Myers Industries 2021). The research team noted the plastic backing tended to tear when being peeled from the strip. The installation took approximately 10 minutes to complete at each location.

Although the research team did not observe the removal of the long-term temporary rumble strips, a member of the MoDOT maintenance crew provided feedback after the installation and removal of the long-term temporary rumble strips on this work zone. The MoDOT employee indicated the installation and removal of the strips was not difficult. The removal was accomplished with a shovel. The installer expressed some concern about the time required for deployment in conjunction with a mobile work zone operation and suggested maybe a permanent lane closure could be used to place the strips. In addition, he thought the application of the primer would have worked better using a roller instead of a brush. He indicated the temporary rumble strips could be effective in getting the attention of distracted drivers. Finally, he thought that the rumble strips were too close together, and the strips may have been more effective in sets of five strips with greater spacing between strips.

Figure 5-5. Placement of long-term temporary rumble strips on I-55 in Ste. Genevieve County

Figure 5-6. Long-term temporary rumble strips on I-55 in Ste. Genevieve County

US 63 (Ashland)

As part of a project to install new J-turns on US 63 near Ashland, the contractor installed short-term temporary rumble strips (Figure 5-7 and Figure 5-8). The research team and MoDOT Central Office personnel observed a deployment in the morning on southbound US 63. Two sets of three strips with approximate spacing of 18 feet to 26 feet were deployed in each lane. Based on the 70-mph permanent posted speed limit, the EPG calls for a spacing of 35 feet (Missouri DOT 2021a). As shown in Figure 5-7, the contractor utilized gaps in traffic to quickly pull the strips across the lane and place them. The installation took less than five minutes per location.

In subsequent feedback provided to the research team, the contractor noted challenges with trying to install the short-term temporary rumble strips in live traffic and concerns with worker exposure to traffic. The contractor would prefer to use long-term temporary rumble strips on this project, especially due to the long duration of this work zone. The contractor believes the long-term strips would be easier to place than the short-term strips using a moving work zone operation. The contractor utilized long-term temporary rumble strips on another job and did not encounter any issues with them. The contractor also reported the tendency of the strips to move sideways and a few instances of the metal hinge breaking apart after the strips were pulled down the road by trucks. As noted in the manufacturer's guidelines, short-term temporary rumble strips become less effective when the spacing is reduced (PSS 2018). The contractor believes the temporary rumble strips help to slow down vehicles but expressed concern about the potential for fast braking when a vehicle encounters the rumble strips.

In addition, MoDOT received some motorist claims on this project involving the temporary rumble strips, including two flat tires. In another instance, a motorist reported radiator and condenser damage after hitting a temporary rumble strip that was not lying flat.

Figure 5-7. Installation of short-term temporary rumble strips on US 63 near Ashland

Figure 5-8. Short-term temporary rumble strips on US 63 near Ashland

US 63 (Columbia)

Another deployment of long-term temporary rumble strips by MoDOT maintenance personnel took place on a two-day concrete replacement project on US 63 southbound between the Brown School Road interchange and Brown Station Road interchange (Figure 5-9 and Figure 5-10). Long-term temporary rumble strips were used because short-term temporary rumble strips were not available. The research team observed the installation and obtained feedback from MoDOT maintenance personnel on both installation and removal. One set of four strips spaced at approximately 10 feet was placed in each southbound lane using a TMA. The EPG calls for five strips placed at spacing of 10 feet to 12 feet (Missouri DOT 2021a). Installation steps included (1) applying primer with a roller, (2) removing the plastic backing from the strip, (3) applying the strip to the pavement, and (4) tamping the strip by walking on it. The MoDOT crew did not have access to the tamper cart that is recommended for use by the manufacturer (Myers Industries 2021). The installation took approximately 10 to 12 minutes at each location. The air temperature was 50°F, which is the minimum temperature recommended by the manufacturer for installation (Myers Industries 2021). Some minor shifting of the strips in the driving lane was noted by the research team.

Feedback received from MoDOT maintenance personnel was very positive. MoDOT indicated both installation and removal of the strips were straightforward. Removal took approximately five minutes per side using a loader bucket and a TMA. MoDOT noted one strip shifted initially, possibly because it was set too soon. MoDOT felt they were a great tool that helped to reduce vehicle speeds and expressed interest in using them again in the future.

Figure 5-9. Installation of long-term temporary rumble strips on US 63 near Columbia

Figure 5-10. Long-term temporary rumble strips on US 63 near Columbia

6. INFORMATION FROM TEMPORARY RUMBLE STRIP MANUFACTURERS

This chapter provides an overview of manufacturer information for the two temporary rumble strip products observed during installation: Advance Traffic Markings (ATM) Rumble Strips from Myers Industries (long-term temporary rumble strips) and RoadQuake 2 from Plastic Safety Systems, Inc. (PSS) (short-term temporary rumble strips).

Advance Traffic Markings (ATM) Rumble Strips

Some product specifications and installation instructions for ATM rumble strips are available on the product website (Myers Industries 2021). The strips are composed of polymer tape with adhesive backing. The strips are 0.25 inches thick and sold in rolls of 4 inches by 96 feet (Figure 6-1). They are suitable for both asphalt and concrete pavements. For installation, the manufacturer indicates that the air temperature must be at least 50°F, and the pavement should be dry with no rain in the prior 24 hours and contaminant-free. The installation instructions indicate that the strips should be tamped with three passes of a tamper cart.

(Courtesy Myers Industries)

Figure 6-1. Advance Traffic Markings (ATM) Rumble Strips

RoadQuake 2 TPRS

PSS provides manufacturer recommendations for the use of RoadQuake 2 TPRS in its best practices guide (PSS 2018). The RoadQuake 2 strips measure 13 inches by 0.75 inches by 132 inches and weigh 105 pounds. PSS indicates they can be deployed for posted speed limits up to 80 mph and temperatures ranging from 0°F to 180°F. PSS does not recommend the use of the RoadQuake 2 TPRS on fresh seal coat, gravel roads, fresh asphalt pavement, or horizontal curves. PSS recommends the use of two TPRS sets in each direction of travel, with spacing between strips as shown in Table 6-1. For maintenance, PSS recommends repositioning when movement of the strip exceeds three feet. For transport and removal of the RoadQuake 2 TPRS, various devices are available such as a crib carrier (Figure 6-2) or handling machine (Figure 6-3).

Table 6-1. Plastic Safety Systems, Inc. (PSS) recommended spacing for RoadQuake 2 TPRS (adapted from PSS 2018)

Posted Speed Limit (mph)	Spacing (ft.)
Up to 40	10
41-55	15
56-64	20
65+	35

(PSS 2018)

Figure 6-2. Crib carrier for RoadQuake 2 TPRS

(PSS 2018)

Figure 6-3. Raptor handling machine for RoadQuake 2 TPRS

7. COLLECTION OF SPEED AND COUNT DATA

The chapter provides an overview of the methodology used to collect speed and count data in order to analyze speed effects of using temporary rumble strips, including coordination with MoDOT Districts, site selection, and data processing.

Coordination with MoDOT Districts to Collect Speed and Count Data

To maximize the number of work zone locations included in the study, vehicle speed and count data were collected by MoDOT District Traffic personnel using Armadillo units (Figure 7-1) (Houston Radar 2021). The Armadillo units use radar technology to collect data on vehicle speeds and counts. Output files generated by the Armadillo units include various types of reports and raw data with the following information for each vehicle: date and time, speed, class (Small, Medium, or Large), direction (Incoming or Outgoing), lane, and GPS location of the Armadillo unit.

The research team prepared a memorandum to request the vehicle speed and count data (Appendix H) and distributed the memorandum to MoDOT District Traffic personnel. The memorandum included information on Armadillo placement, types of data requested, and other resources. For each location, the research team requested 24 hours of speed and count data with temporary rumble strips and 24 hours of speed and count data without temporary rumble strips. Metadata for each work zone location were also requested (Table 7-1).

(Houston Radar © 2016)

Figure 7-1. Armadillo unit mounted on light pole to collect speed and count data

Table 7-1. Metadata requested from MoDOT Districts for each work zone site

Attribute
Job Number
Route
Approximate milepost for Armadillo placement
Approximate latitude and longitude for Armadillo placement
Type of work zone (Two-Lane Highway / Divided Highway)
Type of temporary rumble strips (Long-Term / Short-Term / None)
Start date and time for data collection
End date and time for data collection
Date and time for installation of temporary rumble strips
Date and time for removal of temporary rumble strips
Work zone speed limit
Permanent posted speed limit
Direction of travel for lane immediately adjacent to Armadillo (Northbound / Southbound / Eastbound / Westbound)
Picture of the rumble and the Armadillo in same frame

Site Selection

The research team worked with MoDOT to identify suitable work zone locations for the study. The research team prepared a preliminary list of suggested work zone locations based upon a list of work zone locations with temporary rumble strips provided by MoDOT. Criteria used by the research team to develop the list of suggested work zone locations include diversity with respect to type of temporary rumble strip and type of roadway (two-lane or divided) and balancing the number of locations among MoDOT's seven Districts. MoDOT Central Office personnel contacted Resident Engineers to verify construction dates and type of temporary rumble used for these projects and provided this information to the research team. Based on this information, the research team refined the list of construction projects requested for the study. The research team also worked with MoDOT Maintenance personnel to identify potential MoDOT maintenance projects for the study and coordinate with MoDOT to select some projects not using temporary rumble strips.

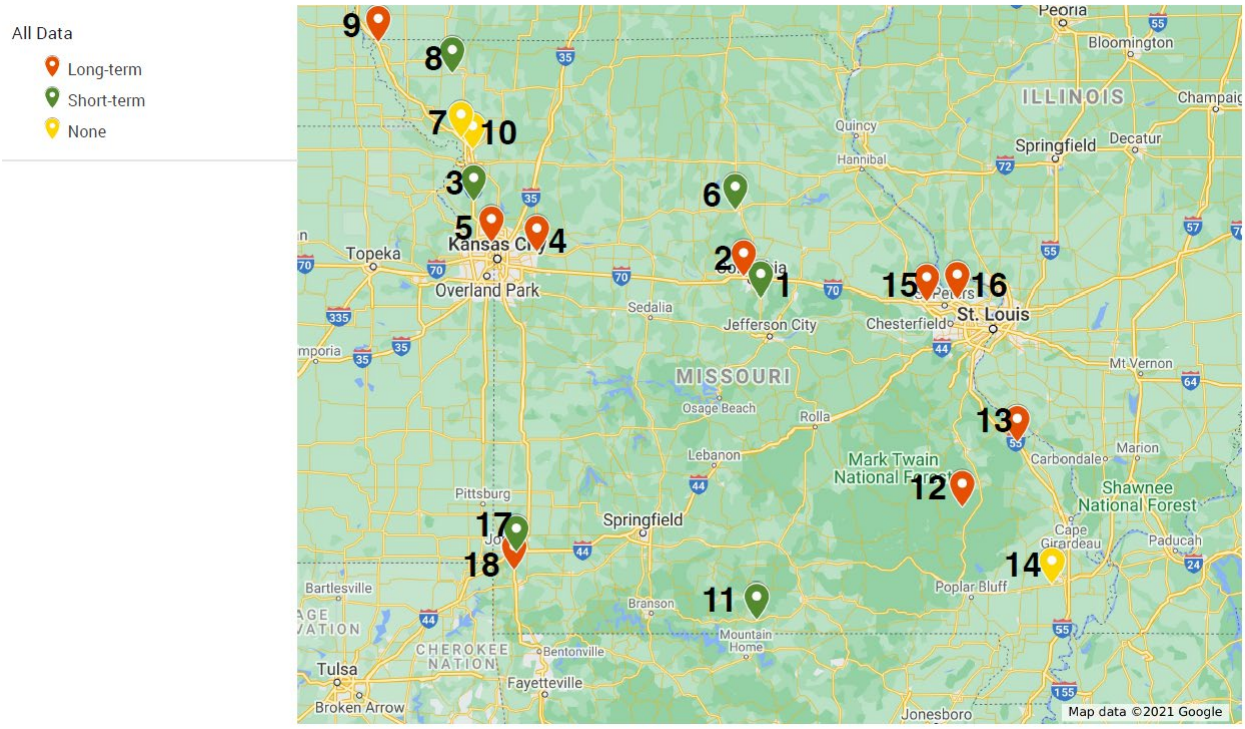
Ultimately, the research team requested speed and count data for 42 sites, including 16 sites with long-term temporary rumble strips, 18 sites with short-term temporary rumble strips, and eight

sites without temporary rumble strips. Summary statistics for these locations are shown in Table 7-2, and details on individual locations are provided in Appendix I. Information on the requested locations was sent to the MoDOT District Traffic personnel along with the memorandum requesting the collection of the speed and count data.

Table 7-2. Summary statistics for requested locations

District	Long-term	Short-term	None	Total
CD	3	3	1	**7**
KC	2	2	2	**6**
NE	2	3	1	**6**
NW	2	2	3	**7**
SE	2	3	1	**6**
SL	2	1	0	**3**
SW	3	4	0	**7**
Total	**16**	**18**	**8**	**42**

The research team received data for 18 sites, including at least one site from each of MoDOT's seven Districts. Constraints that prevented data from being collected for the other 24 sites include project schedules and completion dates and availability of District personnel and Armadillo units. A map showing the locations of the sites is shown in Figure 7-2, and summary data for the project locations are shown in Table 7-3.



(Map data © 2021 Google)

Figure 7-2. Map showing locations where speed and count data were collected

Table 7-3. Summary data for study locations

Site ID	District	JobID	Route	Direction	Two-lane or Divided	County	Temp. Rumble Type	Data for Multiple Locations
1	CD	210219-D05	US 63	SB	Divided	Boone	Short-term	
2	CD	210416-D07	I-70	WB	Divided	Boone	Long-term	
3	KC	201218-C03	I-29	NB, SB	Divided	Platte	Short-term (NB & SB), None (SB)	X (SB)
4	KC	201218-C04	US 24	EB, WB	Divided	Jackson	Long-term	
5	KC	210122-C03	I-29	SB	Divided	Platte	Long-term	
6	NE	201218-B04	US 24	EB, WB	Two-lane	Randolph	Short-term, None	
7	NW	191115-A04	I-29	SB	Divided	Andrew	None	
8	NW	201120-A02	MO 46	EB	Two-lane	Nodaway	Short-term	
9	NW	210219-A01	I-29	NB	Divided	Atchison	Long-term	
10	NW	MoDOT Maintenance	US 169	NB	Two-lane	Andrew	None	
11	SE	210122-H01	US 160	EB	Two-lane	Ozark	Short-term	
12	SE	210319-H04	ROUTE C	NB	Two-lane	Madison	Long-term	
13	SE	MoDOT Maintenance	I-55	NB	Divided	Ste. Genevieve	Long-term	
14	SE	MoDOT Maintenance	US 60	EB	Divided	New Madrid	None	
15	SL	201120-F01	I-70	EB, WB	Divided	St. Charles	Long-term	X
16	SL	210122-F02	MO 370	EB	Divided	St. Charles	Long-term	X
17	SW	201016-G02	I-44	WB	Divided	Jasper	None, Short-term	
18	SW	201120-G01	I-49	SB	Divided	Newton	None, Long-term	

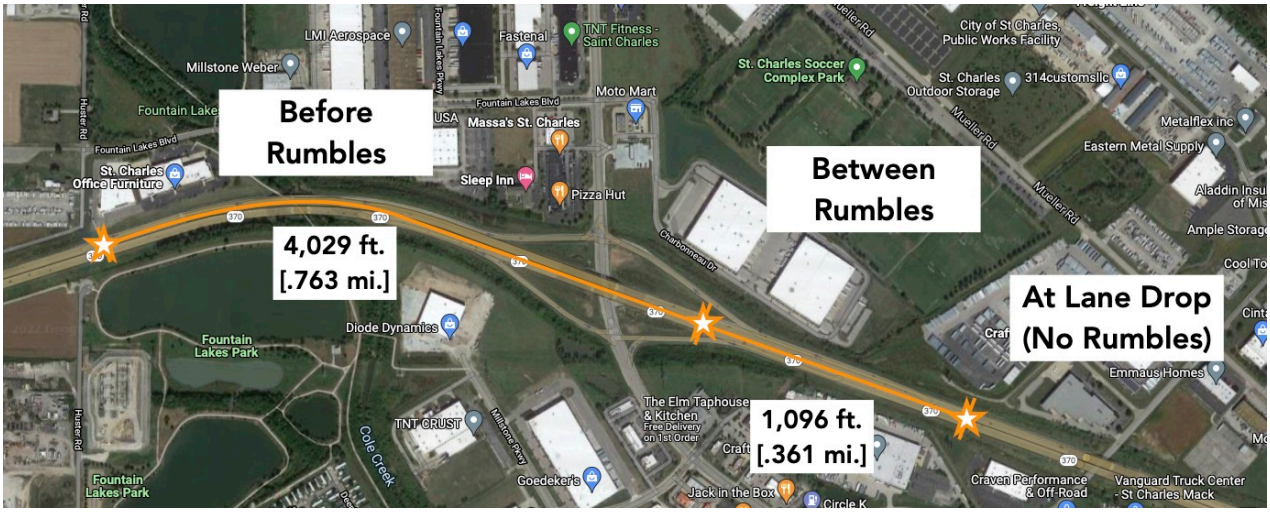
A summary of attributes for the study sites is provided in Table 7-4. Data were received for three MoDOT maintenance projects and 15 contractor projects. Half of the study sites used long-term temporary rumble strips, and the majority of sites were divided highways. The minimum work zone speed limit was 35 mph on US 160 in Ozark County (permanent posted speed limit = 55 mph), and the maximum work zone speed limit was 70 mph (also the permanent posted speed limit) on I-55 in Ste. Genevieve County.

Table 7-4. Summary of attributes for study sites

Attribute	Number
Contractor Projects	15
MoDOT Maintenance Projects	3
Long-term Temporary Rumble Strips	9
Short-term Temporary Rumble Strips	6
No Temporary Rumble Strips	3
Two-lane	5
Divided	13
Min. Work Zone Speed Limit (mph)	35
Max. Work Zone Speed Limit (mph)	70
Number of Sites with Data with and without Short-Term Rumbles	3
Number of Sites with Data with and without Long-Term Rumbles	1
Sites with Multiple Location Data (Same Direction)	2
Total Number of Vehicles	350,852

For three of the sites using short-term temporary rumble strips (I-29 southbound at Dearborn in Platte County, US 24 in Randolph County, and I-44 in Jasper County) and one site using long-term temporary rumble strips (I-49 in Newton County), data were received with and without the temporary rumble strips installed. The data collection locations with and without temporary rumble strips for I-29 southbound at Dearborn were located approximately 2.6 miles apart and took place on different days. For the projects on MO 370 and I-70 in St. Charles County, data were received for multiple locations in the same direction (Figure 7-3 and Figure 7-4). On MO 370, data were received upstream of the rumble strips, between the sets of rumble strips, and

downstream of the rumble strips. On I-70 in St. Charles County, data were received upstream of the rumble strips and between the sets of rumble strips in each direction.



(Map data © 2021 Google)

Figure 7-3. Data collection locations for MO 370 in St. Charles County

(Map data © 2021 Google)

Figure 7-4. Data collection locations for I-70 in St. Charles County

Data Processing

After receiving the speed and count data from the MoDOT Districts. the research team performed data processing prior to analysis. The data were compiled in a consistent format and organized by location and time period based on when the temporary rumble strips and work zone were in place (Appendix J). For example, data for multiple days of short-term temporary rumble strips were separated into individual time periods based on when the temporary rumble strips were actually in place. In some instances, the research team followed up with MoDOT Districts

to confirm details such as times when the temporary rumble strips and work zone were in place or work zone speed limits.

8. SAFETY ANALYSIS

Overview of the Safety Analysis

The vehicle speed data for safety analysis were collected from 18 work zones with different temporary rumble strip types, work zone speed limits, day of the week, and time from September 7, 2021 to October 19, 2021 to examine the safety effectiveness of temporary rumble strips in work zones. More than 500,000 vehicle speeds were collected. However, after removing potential duplications and reporting errors, about 350,000 vehicle speeds were analyzed to examine the safety effects of temporary rumble strips.

The safety effects of work zone rumble strips were measured via the changes in vehicle speed with and without rumble strips and the compliance with the work zone speed limit. In order to analyze the effect, both descriptive and statistical analyses were conducted. In addition, the safety analysis investigated the overall safety effects of the rumble strips with the entire data collected for the study, different periods, and before and after passing the rumble strips.

Work Zone Speed Data

After careful consideration and review of the vehicle speed data collected from 18 work zones, a total of 350,852 vehicle speeds were selected for safety analysis. Table 8-1 shows the work zone-level data. The work zones have diverse characteristics regarding the speed limit and rumble strip type. The average vehicle speed and the number of vehicle speeds observed vary by work zone. There are also work zones where the average vehicle speed limit overage is positive (overall vehicle speeds are higher than work zone speed limit) and negative (overall vehicle speeds are lower than work zone speed limit). The average vehicle speed limit overage in the data was 5.9 mph. This finding indicates that drivers tend to drive faster than the speed limits in work zones. However, it should be noted that the overage varies significantly by work zone.

Table 8-1. Observed vehicle speeds and work zone characteristics

Location	Permanent Posted Speed Limit (mph)	Work Zone Speed Limit (mph)	Type of Rumble Strips	No. of Vehicles	Mean Speed (mph)	Mean Speed Limit Overage (mph)
I-29 (56st St, KC, Platte County)	55	50	Long-term	41,387	59.3	9.3
I-29 (Andrew County)	70	55	None	9,654	70.1	15.1
I-29 (Atchison County)	70	55	Long-term	8,566	67.3	12.3
I-29 (Dearborn, Platte County)	70	60	Short-term	6,841	61.8	1.8
	70	60	None	2,023	59.0	-1.0
I-44 (Jasper County)	70	60	Short-term	9,664	67.9	7.9
	70	60	None	4,652	67.6	7.6
I-49 (Newton County)	70	60	Long-term	24,880	70.2	10.2
	70	60	None	13,187	68.9	8.9
I-55 (Ste. Genevieve County)	70	70	Long-term	12,940	69.6	-0.5
I-70 (Boone County)	70	60	Long-term	21,944	61.7	1.7
I-70 (St. Charles County)	70	60	Long-term	52,312	60.4	0.4
	70	65	Long-term	48,424	66.0	1.0
US 60 (New Madrid County)	55	55	None	26,255	66.6	11.6
US 63 (Boone County)	70	60	Short-term	21,198	67.6	7.6
US 24 (KC, Jackson County)	65	55	Long-term	19,520	60.4	5.4
US 24 Randolph County)	60	60	Short-term	268	33.5	-26.5
	60	60	None	251	41.7	-18.3
US 160 (Ozark County)	55	35	Short-term	1,685	48.0	13.0
US 169 (Andrew County)	60	55	None	1,066	52.3	-2.8
MO 46 (Nodaway County)	55	55	Short-term	113	47.7	-7.3
MO 370 (St. Charles County)	60	45	Long-term	23,931	56.4	11.4
MO Route C (Madison County)	55	55	Long-term	91	39.0	-16.0
Overall				350,852	63.7	5.9

Note: Speed limit overage is observed vehicle speed minus work zone speed limit.

As shown in Table 8-1, the levels of vehicle speed limit overage by temporary rumble strip type, including without rumble strips, are not consistent. This finding indicates that each work zone may have strong road environment characteristics specific to each work zone.

Vehicle speed and speed limit overage are associated with work zone rumble strips. As shown in Table 8-2, the average speed is higher at work zones without rumble strips and lower at work zones with rumble strips. A similar pattern is found with the average speed limit overage. The level of speed limit overage tends to be smaller or negative in work zones with rumble strips than

those without rumble strips. Long-term strips have more positive safety effects than short-term strips in terms of magnitude.

Table 8-2. Mean work zone vehicle speed and speed limit overage by type of temporary rumble strips

	Overall* (No. of Vehicles (n) =350,852)	Type of Temporary Rumble Strips		
		None (n=57,088)	Short-term* (n=39,769)	Long-term (n=253,995)
Mean Vehicle Speed (mph)	63.7 (10.0)	67.2 (8.3)	65.6 (10.3)	62.7(10.1)
Mean Speed Overage (Vehicle Speed – Work Zone Speed Limit)	5.9 (10.1)	10.4(8.6)	6.6(9.7)	4.8(10.2)

Note: Values in ( ) are standard deviations.

* US 160 WB in Ozark County (n = 1,685) had a much lower work zone speed limit (35 mph). The range of other work zone speed limits for this study was 45-70 mph. However, the effects of the US 160 WB work zone were minimal. Without the work zone, the overall mean speed and short-term rumble strip mean speed become 63.8 mph and 66.3 mph, respectively.

The associations between the type of rumble strips and vehicle speed and speed limit overage shown in Table 8-2 are also found when highway type and vehicle class are controlled. Table 8-3 (those highlighted in grey) shows that rumble strips tend to be associated with lower vehicle speed and speed limit overage than no rumble strips, and long-term rumble strips seem to be more strongly associated than short-term rumble strips. However, there are irregularities where the number of observations is low.

Table 8-3. Work zone vehicle speed and speed limit overage by highway type, vehicle class, speed limit, and rumble strip type

	Work Zone Speed Limit (mph)	Mean Vehicle Speed and Speed Limit Overage (in mph) by Rumble Strip Type								
		None			Short-term			Long-term		
		Frequency	Mean Speed	Speed Overage	Frequency	Mean Speed	Speed Overage	Frequency	Mean Speed	Speed Overage
All		57,088	67.2	10.4	39,769	65.6	6.6	253,995	62.7	4.8
Highway Type										
Multi-lane	45							23,931	56.4	11.4
	50							41,387	59.3	9.3
	55	35,909	67.6	12.6				28,086	62.5	7.5
	60	19,862	67.6	7.6	37,703	66.6	6.6	99,136	63.1	3.1
	65							48,424	66.0	1.0
	70							12,940	69.6	-0.5
Two-lane	35				1,685	48.0	13.0			
	55	1,066	52.3	-2.8	113	47.7	-7.3	91	39.0	-16.0
	60	251	41.7	-18.3	268	33.5	-26.5			
Vehicle Class										
Small	35				29	50.5	15.5			
	45							183	41.6	-3.4
	50							16	65.6	15.6
	55	708	64.5	9.5	1	28.0	-27.0	453	69.2	14.2
	60	192	68.1	8.1	370	68.5	8.5	1,012	65.5	5.5
	65							124	66.0	1.0
	70							249	69.2	-0.8
Medium	35				1,419	48.0	13.0			
	45							22,057	56.6	11.6
	50							39,352	59.3	9.3
	55	32,250	67.5	12.5	103	49.0	-6.0	26,093	62.4	7.4
	60	18,524	67.5	7.5	34,509	66.5	6.5	91,508	63.2	3.2
	65							45,777	66.1	1.1
	70							11,385	69.9	-0.1

	Work Zone Speed Limit (mph)	Mean Vehicle Speed and Speed Limit Overage (in mph) by Rumble Strip Type								
		None			Short-term			Long-term		
		Frequency	Mean Speed	Speed Overage	Frequency	Mean Speed	Speed Overage	Frequency	Mean Speed	Speed Overage
(Table 8-3 Continued)										
Large	35				237	47.4	12.4			
	45							1,691	55.7	10.7
	50							2,019	59.5	9.5
	55	4,017	64.5	9.5	9	35.8	-19.2	1,631	60.8	5.8
	60	1,397	63.6	3.6	3,092	64.6	4.6	6,616	62.1	2.1
	65							2,523	65.1	0.1
	70							1,306	66.6	-3.4

Note: Speed limit overage is observed vehicle speed minus work zone speed limit.

However, the associations between the type of rumble strips type and vehicle speed and speed limit overage in Table 8-2 and Table 8-3 were not controlled fully or simultaneously with other relevant factors. Therefore, robust statistical analyses were necessary to examine the conditional associations in depth.

Statistical Analysis Methods

Vehicle speed data from 18 work zones were compiled together and modeled to estimate the effects of temporary rumble strips on vehicle speed. In order to systematically investigate the effects, a random-effects binary logit model (Greene 2003) was employed. The dependent variable was the vehicle speed above the work zone speed limit versus the vehicle speed at or below the work zone speed limit. The model provided information about the statistical significance of observed variables associated with the work zone speed violation and the probability of the violation. The random-effects model was used since the regular binary logit model potentially violates the assumption of independence of the residuals. In this study, vehicle speed observations are more likely to be interdependent, which means that vehicle speeds nested in the same work zone are more likely to function in the same way than those nested in different work zones. The random intercepts model can allow intercepts to vary between work zones, and therefore, the dependent variable (work-zone speed violation) for each observation is predicted by the intercept that varies across work zones. This modeling approach is also appropriate since work zone sites themselves have no intrinsic meaning in this study.

The random-effects binary logit model classified work zone vehicle speeds into two binary groups: 1) over the work zone speed limit (the speed violation group) and 2) at or below the work zone speed limit (the speed compliance group).

$$y_{nj}^{*} = \mathbf{x'}_{nj}\boldsymbol{\beta} + u_j + \epsilon_{nj},\ j = 1, \dots, J;\ n = 1, \dots, N_j, \qquad (8\text{-}1)$$
$$y_{nj} = 1 \text{ if } y_{nj}^{*} > 0, \text{ and } y_{nj} = 0 \text{ otherwise,}$$

where $y_{nj} = 1$ indicates that vehicle speed n in location j belongs to the speed violation group, and $y_{nj} = 0$ indicates the individual is in the speed compliance group. The model includes a work zone-specific random effect, $u_j \sim N(0, \sigma_u^2)$, which captures the correlation of vehicle speeds from the same work zone that allows work zone-specific heterogeneity. The correlation of vehicle speeds from the same location arises from their sharing specific but unobserved properties of the respective location.

The explanatory variables of vehicle speed n in work zone j are denoted by the vector $\mathbf{x}_{nj}$, with estimable coefficients in the vector $\boldsymbol{\beta}$. There are a total of N_j vehicle speeds in work zone j. As is standard, ϵ_{nj} are assumed to be independently and identically distributed with the binary logit

regression with mean zero and variance $\sigma_\epsilon^2 = \pi^2/3$, and are independent of u_j. This leads to the log-odds-ratio:

$$\ln\left(\frac{P(y_{nj}=1|\mathbf{x}_{nj},u_j)}{P(y_{nj}=0|\mathbf{x}_{nj},u_j)}\right) = \mathbf{x'}_{nj}\boldsymbol{\beta} + u_j, \quad (8\text{-}2)$$

where a positive coefficient indicates the variable increases the probability of classifying the speed as over the speed limit, and a negative coefficient decreases the probability. The variance σ_u^2 (in natural log form) of u_j is estimated along with the coefficients. The standard deviation of the random effect, σ_u, is calculated. The proportion of the total variance captured by the work zone variance is calculated with:

$$\rho = \frac{\sigma_u^2}{\sigma_u^2+\sigma_\epsilon^2}, \quad (8\text{-}3)$$

and a likelihood-ratio test is used to test the null hypothesis of $\rho = 0$, which indicates the work zone-specific heterogeneity is not statistically significant.

The employed binary models include a limited number of covariates. Therefore, they could be misspecified and thus result in biased coefficients and residuals. In order to examine the models' potential misspecification, a link test was conducted for each model (Czado and Santner 1992, Pregibon 1980). The link test regresses the dependent variable of the original regression against the original regression's prediction and the squared prediction. The coefficient of predicted values should be statistically significant, while the coefficient of squared predicted values must be statistically insignificant to indicate a proper model specification.

Analysis of Work Zone Vehicle Speed Data

Analysis of Complete Survey Data

Speeding has been a critical work zone crash factor. Thus, in order to examine the effects of temporary rumble strips on work zone safety, this study analyzed the characteristics of vehicle speeds below or equal to the work zone speed limit ("compliance" hereafter) and the speeds above the limit ("violation" hereafter). Table 8-4 shows the characteristics.

The overall speed violation rate was 76.6 percent in the data. This means that less than one-fourth of drivers complied with the work zone speed limit. Table 8-4 shows substantial variations in the violation by various roadway, rumble strip, vehicle, temporal, and locational factors.

Table 8-4. Characteristics of non-compliance and compliance of work zone speed limit

		Vehicle Speed Above Work Zone Speed Limit		Vehicle Speed Below or Equal to Work Zone Speed Limit	
		Frequency	Pct.	Frequency	Pct.
All		268,701	76.6	82,151	23.4
Highway Type	Two-lane	1,989	57.3	1,485	42.8
	Multi-lane	266,712	76.8	80,666	23.2
Work Zone Speed Limit (mph)	35	1,581	93.8	104	6.2
	45	17,729	74.1	6,202	25.9
	50	35,404	85.5	5,983	14.5
	55	57,446	88.0	7,819	12.0
	60	122,242	77.8	34,978	22.3
	65	28,382	58.6	20,042	41.4
	70	5,917	45.7	7,023	54.3
Rumble Strip Type	None	52,020	91.1	5,068	8.9
	Short-term	33,978	85.4	5,791	14.6
	Long-term	182,703	71.9	71,292	28.1
Vehicle Class Type	Small	2,587	77.5	750	22.5
	Medium	248,263	76.9	74,714	23.1
	Large	17,851	72.8	6,687	27.3
Day and Hours: Weekday peak hours (7:00-9:00 am & 3:00-6:00 pm), Nighttime hours for weekday / weekend (7:00 pm-6:59 am)	Weekday daytime non-peak hours	95,066	76.6	28,994	23.4
	Weekday daytime peak hours	80,360	75.1	26,687	24.9
	Weekday nighttime hours	88,230	78.1	24,700	21.9
	Weekend daytime hours	3,765	75.6	1,214	24.4
	Weekend nighttime hours	1,280	69.7	556	30.3
Location	I-29 (56st St, KC-Platte)	35,404	85.5	5,983	14.5
	I-29 (Andrew)	9,456	98.0	198	2.1
	I-29 (Atchison Bridge)	8,214	95.9	352	4.1
	I-29 (Dearborn)	6,219	70.2	2,645	29.8
	I-44	12,924	90.3	1,392	9.7
	I-49	35,645	93.6	2,422	6.4
	I-55	5,917	45.7	7,023	54.3
	I-70 (Perche Creek)	16,626	75.8	5,318	24.2
	I-70 (STL)	60,193	59.8	40,543	40.3
	US 60	24,372	92.8	1,883	7.2
	US 63	18,971	89.5	2,227	10.5
	US 24 (KC-Jackson)	15,042	77.1	4,478	22.9
	US 24 (NE-Moberly)	46	8.9	473	91.1
	US 160	1,581	93.8	104	6.2
	US 169	349	32.7	717	67.3

		Vehicle Speed Above Work Zone Speed Limit		Vehicle Speed Below or Equal to Work Zone Speed Limit	
		Frequency	Pct.	Frequency	Pct.
	(Table 8-4 Continued)				
Location	MO 46	11	9.7	102	90.3
	MO 370	17,729	74.1	6,202	25.9
	MO Route C	2	2.2	89	97.8

Multi-lane highways, where traffic volume and vehicle speed limit tend to be higher, had a higher speed violation rate than two-lane highways (76.8 percent vs. 57.3 percent). However, it should be noted that the number of observations for two-lane highways was much fewer than the number of multi-lane highways. The data analyzed for this study included various work zone speed limits. Multi-lane highways had varying speed limits. Table 8-4 shows that the higher the work zone speed limit, the lower the speed violation rate. The decrease in the violation rate is evident as the speed limit increases. This may indicate that high-speed multi-lane highways had a smaller room for speed overage than relatively low-speed two-lane highways.

Temporary rumble strips (long-term rumble strips in particular) had substantially lower speed violation rates than when no rumble strips were installed in work zones. Regarding vehicle class, large class vehicles, primarily commercial vehicles, had a lower speed violation rate than medium or small class vehicles. Minor variations were found in weekday/weekend and hours of the day, even though weekend nighttime tends to have a lower violation rate. Lastly, work zone locations show substantial variations in the violation rate ranging from less than 10 percent to 98 percent. This level of variation may indicate that location-specific heterogeneity exists in the speed data collected for this study.

The random-effects binary logit model results for all work zone vehicle speed data are reported in Table 8-5. The dependent variable is binary (1=Violation of the speed limit and 0=Compliance of the speed limit). The model fit statistics show that the model fits the data well and the log-likelihood ratio (LR) test for random intercepts indicates that work zone level heterogeneity is statistically significant. Also, the link test for the model specification demonstrates that the model is properly specified (p-value of the squared prediction = 0.1803 while the p-value of the prediction = <0.0001).

Table 8-5. Random-effects binary logit model of the work zone speed limit non-compliance

		Coeff.	Std. Error	t	P>|t|	dy/dx
Intercept		-1.3820	0.571	-2.42	0.0242	
Highway Type	Multi-lane	3.9743	0.5801	6.85	<.0001	0.6136
	Two-lane (Base case)					
Work Zone Speed Limit (mph)	35 mph	4.7304	0.9957	4.75	<.0001	0.7304
	45+ mph (Base case)					
Rumble Strip Type	Short-term	-1.3736	0.5831	-2.36	0.0185	-0.2121
	Long-term	-1.1756	0.5073	-2.32	0.0205	-0.1815
	None (Base case)					
Vehicle Class Type	Large	-0.3746	0.0165	-22.69	<.0001	-0.0578
	Medium (Base case)					
	Small	-0.2056	0.0468	-4.4	<.0001	-0.0317
Day and Hours: Weekday peak hours (7:00-9:00 am & 3:00-6:00 pm), Nighttime hours for weekday/weekend (7:00 pm-6:59 am)	Weekday nighttime hours	0.1007	0.0111	9.08	<.0001	0.0155
	Weekday daytime peak hours	-0.0802	0.0106	-7.55	<.0001	-0.0124
	Weekday daytime non-peak hours (Base case)					
	Weekend daytime hours	-0.1372	0.0419	-3.28	0.0010	-0.0212
	Weekend nighttime hours	-0.4947	0.0584	-8.48	<.0001	-0.0764
Random-effects Parameter	Highway Locations with different segments and time periods (27)	Estimate	Std. Error			
		1.0521	0.3232			

Notes:

1) Fit statistics: n = 350,852; -2 LL = 331165.4; Fit Statistics for Conditional Distribution: -2 Res LL = 330971.7, Pearson ChiSq = 348873.6, Pearson ChiSq / DF = 0.99

2) LR test for random intercept: -2 LL = 363556, ChiSq = 32390.7 (1 DF), Prob > ChiSq = <0.0001

3) dy/dx indicates average marginal effect compared to the base case after taking random effects into account.

The model results show that multi-lane was positively associated with the speed violation. The work zone speed limit was significant only for the lowest observed speed limit (35 mph). When various work zone speed limits in Table 8-4 were tested conditionally in the model, the effects of varying degrees of work zone speed limits at 45 mph or above became statistically invariant.

The effects of both short-term and long-term rumble strips were statistically significant. It lowered the probability of violation by 21.2 percent and 18.2 percent, respectively. The effect of short-term rumble strips was more substantial than that of long-term rumble strips. The effect of short-term rumble strips may be associated with the presence of workers in work zones. The short-term strips usually indicate the presence of workers. The visibility of workers may instigate drivers to slow down. However, the coefficients of these two rumble strips overlapped with each other within the standard errors. This indicates that the effects of these two different types of rumble strips might be significantly different.

Large and small vehicle classes were statistically significant and had lower violation rates than medium class vehicles. Also, during weekday nighttime, vehicles were less likely to comply with the work zone speed limit, while weekday peak hours made drivers more likely to keep the speed limit, probably due to traffic. Overall, drivers were less likely to drive over the speed limit in work zones on weekends.

Analysis of Multi-day Work Zone Speed Data

The work zone speed data included four work zones where vehicle speeds were collected for more than one day. These four locations had a day with no rumble strips and a day with rumble strips installed except I-44 WB in Jasper County, where a two-day long survey was conducted with short-term strips. All four work zones had a work zone speed limit of 60 mph. Table 8-6 shows the characteristics related to the speed limit violation and compliance.

There were 42,256 vehicle speeds collected from the four work zones. The average vehicle speed was 67.4 mph. The violation rate was 88.4 percent which is more than 10 percent higher than the complete speed data in Table 8-4. Table 8-6 shows that the speed violation rate on two-lane highways was very low (8.86 percent). However, it should be noted that the rate is based on only one work zone on US 24 EB in Randolph County.

Table 8-6. Characteristics of non-compliance and compliance of work zone speed limit with multi-day survey locations

	No. of vehicles measured	Avg. veh. Speed	Above the work zone speed limit						At/Below the work zone speed limit	
			Total		Less than 10 mph		More than 10+ mph			
			Freq.	Pct.	Freq.	Pct.	Freq.	Pct.	Freq.	Pct.
All	42,256	67.43	37,360	88.41	21,374	50.58	15,986	37.83	4,896	11.59
Highway Type										
Two-lane	519	37.48	46	8.86	46	8.86	-	-	473	91.14
Multi-lane	41,737	67.80	37,314	89.40	21,328	51.10	15,986	38.30	4,423	10.60
Rumble Strip Type										
None	20,113	67.26	17,843	88.71	10,268	51.05	7,575	37.66	2,270	11.29
Short-term	13,521	66.03	11,386	84.21	7,254	53.65	4,132	30.56	2,135	15.79
Long-term	8,622	70.02	8,131	94.31	3,852	44.68	4,279	49.63	491	5.69
Vehicle Class										
Small	569	68.99	509	89.46	186	32.69	323	56.77	60	10.54
Medium	38,702	67.71	34,568	89.32	19,420	50.18	15,148	39.14	4,134	10.68
Large	2,985	63.50	2,283	76.48	1,768	59.23	515	17.25	702	23.52
Day and hour										
Weekday nighttime hours	23,953	66.72	20,727	86.53	12,843	53.62	7,884	32.91	3,226	13.47
Weekday daytime peak hours	7,681	70.38	9,314	87.69	5,315	50.04	3,999	37.65	1,308	12.31
Weekday daytime non-peak hours	10,622	66.90	7,319	95.29	3,216	41.87	4,103	53.42	362	4.71
Location										
I-29 SB in Platte w/ no strips (Day 1)	2,023	58.96	1,553	76.77	1,103	54.52	450	22.24	470	23.23
I-29 SB in Platte w/ short-term strips (Day 2)	3,589	63.37	2,637	73.47	1,685	46.95	952	26.53	952	26.53
I-44 WB in Jasper w/ no strips (Day 1)	4,652	67.57	4,175	89.75	2,776	59.67	1,399	30.07	477	10.25
I-44 WB in Jasper w/ short-term strips (Day 2 & 3)	9,664	67.92	8,749	90.53	5,569	57.63	3,180	32.91	915	9.47
I-49 SB in Newton w/ no strips (Day 1)	13,187	68.92	12,069	91.52	6,343	48.10	5,726	43.42	1,118	8.48
I-49 SB in Newton w/ long-term strips (Day 2)	8,622	70.02	8,131	94.31	3,852	44.68	4,279	49.63	491	5.69
US 24 EB in Randolph w/ short-term strips (Day 1)	268	33.50	-	-	-	-	-	-	268	100.00
US 24 EB in Randolph w/ no strips (Day 2)	251	41.73	46	18.33	46	18.33	-	-	205	81.67

Rumble strips show a mixed association with the work zone speed violation. Short-term rumble strips have a lower violation rate than no rumble strips, and long-term rumble strips have a higher violation rate. Large class vehicles show a substantially lower violation rate than small and medium class vehicles. During non-peak hours, the violation rate was higher than nighttime and peak hours. Again, the violation rates vary substantially by work zone. These locational differences may indicate significant heterogeneity in work zones.

A random-effects binary logit model was employed to conditionally measure the effects of various factors related to the speed violation in the four work zones. The model results are shown in Table 8-7. The dependent variable is binary (1=Violation of the speed limit and 0=Compliance of the speed limit). The model fit statistics show that the model fitted the data well, and the log-likelihood ratio (LR) test for random intercepts indicates that work zone level heterogeneity was statistically significant. Also, the link test for the model specification demonstrates that the binary logit model was properly specified (p-value of the squared prediction = 0.1902 while the p-value of the prediction = <0.0001).

Table 8-7. Random effect binary logit model results on work zone speed limit overage for multi-day survey locations with/without rumble strips

		Over the work zone speed limit			
		Coeff.	Std. Error	P>|t|	dy/dx
Intercept		-3.1391	0.7821	0.0159	
Highway Type	Multi-lane highways	5.1768	0.8570	<.0001	0.4619
	Two-lane highways (Base case)				
Rumble Strip Type	Short-term	-1.3120	0.7259	0.0707	-0.1171
	Long-term	0.5589	1.0008	0.5766	0.0499
	None (Base case)				
Vehicle Class Type	Small	0.2902	0.1453	0.0458	0.0259
	Medium (Base case)				
	Large	-1.0330	0.0493	<.0001	-0.0922
Day and Hours: Weekday peak hours (7:00-9:00 am & 3:00-6:00 pm), Nighttime hours (7:00 pm-6:59 am)	Weekday nighttime hours	0.4438	0.0449	<.0001	0.0396
	Weekday daytime peak hours	0.8512	0.0634	<.0001	0.0760
	Weekday daytime non-peak hours (Base case)				
Random-effects Parameter	Highway Locations with/without rumble strips each day	Estimate	Std. Error		
		0.7619	0.4996		

Notes:
1) Fit statistics: n = 42,256; -2 LL = 26570.69; Fit Statistics for Conditional Distribution: -2 Res LL = 26522.77, Pearson ChiSq = 42206.76, Pearson ChiSq / DF = 1.00
2) LR test for random intercept: -2 LL = 27396, ChiSq = 825.70 (1 DF), Prob > ChiSq = <0.0001
3) dy/dx indicates average marginal effect compared to the base case after taking random effects into account.

The model results show that multi-lane highways had a statistically significant effect and increased the probability of violation. The speed limits at four work zones were the same (60 mph), and thus the work zone speed limit was not included in the model. The effects of short-term and long-term rumble strips were statistically insignificant given the large sample size. P-values were 0.0707 and 0.5766, respectively. The surveys at four work zones were all conducted during weekdays. Weekday nighttime and daytime peak hours were positively associated with the speed violation.

Non-parametric Analysis of Multi-day Data

There were two work zones that vehicle speeds were collected for three days. They were I-44 WB in Jasper County and I-55 NB in St. Genevieve County. The I-44 work zone had a day with no rumble strips and two days with short-term rumble strips. The I-55 work zone had long-term rumble strips for all three days.

In order to examine the statistical significance of the mean vehicle speed differences between three days, the Kruskal-Wallis test (Kruskal and Wallis 1952), a nonparametric method to compare the distributions of two or more independent samples, was employed for each work zone. A descriptive analysis of vehicle speeds for each work zone showed that vehicle speeds in each day were not normally distributed, and the number of observations was unequal each day. Therefore, instead of ANOVA, the Kruskal-Wallis test was used. The Kruskal-Wallis test does not assume normal distributions and equal sample sizes. In the test, the null hypothesis is that all speed distribution functions are equal, and the alternative hypothesis is that at least one distribution function is not equal. In other words, this test examines if the mean ranks of vehicle speeds differ between three days. In order to compare pairwise vehicle speeds for each day, the Dwass, Steel, Critchlow-Fligner (DSCF) multiple comparison analysis results were reported in Table 8-8. The DSCF comparison is based on pairwise two-sample Wilcoxon comparisons (Dwass 1960, Steel 1960, Critchlow and Fligner 1991).

Table 8-8. Comparative analysis of vehicle speeds in the work zone for locations with 3-day surveys

Location	I-44 WB in Jasper County			I-55 NB in St. Genevieve County		
Day	1	2	3	1	2	3
Date & Time	09/13/21 (Mon) 7:00 pm — 09/14/21 (Tue) 5:35 am	09/15/21 (Wed) 7:00 pm — 09/16/21 (Thu) 5:35 am	09/16/21 (Thu) 7:00 pm — 09/17/21 (Fri) 5:35 am	09/13/21 (Mon) 10:21 am — 11:59 pm	09/14/21 (Tue) 00:00 am — 11:59 pm	09/13/21 (Mon) 00:00 am — 11:31 pm
n	4,652	5,091	4,573	5,517	4,355	3,068
Work zone speed limit (mph)	60	60	60	70	70	70
Type of rumble strips	None	Short-term	Short-term	Long-term	Long-term	Long-term
Mean vehicle speed	67.6	67.9	68.0	69.4	70.0	69.1
Std. dev of vehicle speeds	6.0	5.9	6.1	6.6	5.6	8.2
Median vehicle speed	68.0	68.0	68.0	70.0	70.0	70.0
Kruskal-Wallis test (Pr > ChiSq)		0.0017			0.0095	
DSCF pairwise two-sided multiple comparison	Period 1 vs. 2	Period 1 vs.3	Period 2 vs. 3	Period 1 vs. 2	Period 1 vs.3	Period 2 vs. 3
(Pr > DSCF)	0.0366	0.0015	0.4862	0.0058	0.3358	0.4892

In the I-44 work zone, the average vehicle speed with no rumble strips was 67.6 mph, and the average speeds with short-term rumble strips were 67.9 mph and 68.0 mph. For the I-55 work zone, where long-term rumble strips were installed for all three days, the average vehicle speed ranged from 69.1 mph to 70.0 mph. However, median vehicle speeds remained the same over the three days in both work zones. However, as shown in Table 8-8, both work zones had statistically significant differences in vehicle speed between days. The p-values of the Kruskal-Wallis test were smaller than 0.01. Also, the DSCF pairwise comparisons show that some pairwise comparisons were statistically significant.

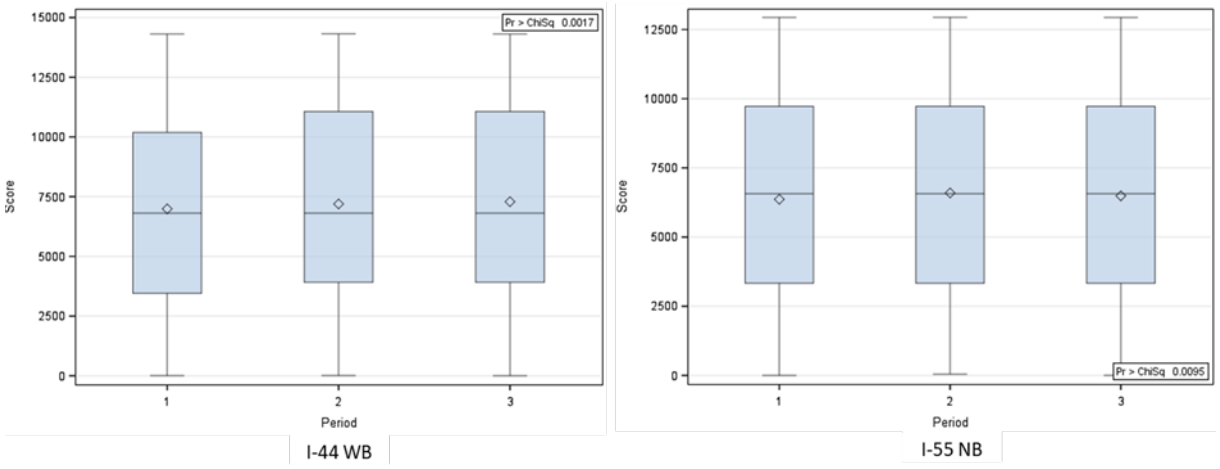


Figure 8-1. Distribution of Wilcoxon scores

The Kruskal-Wallis test results, however, require careful consideration. The statistical significance may exist due to large sample sizes, and the practical significance could be minimal. The box plots in Figure 8-1 show the mean and medians (along with the middle 50 percentile) values derived from the Kruskal-Wallis test. Across three days, in both work zones, the ranked mean and median speed values were similar despite the statistical significances reported in Table 8-8.

Analysis of Before and After Entering Rumble Strips Segments Data

The work zone speed data included two work zones where vehicle speeds were collected between two consecutive segments: one with no rumble strips and the other with long-term rumble strips. These two work zones were on MO 370 EB and I-70 EB, both multi-lane highways, in St. Charles County. Table 8-9 shows the characteristics related to speed violation and compliance.

There were 146,143 vehicle speeds collected at the two work zones. The average vehicle speed was 65.01 mph. The violation rate was 71.27 percent which is 5.3 percent lower than the complete speed data in Table 8-4. Table 8-9 shows that the speed violation rate on the lower speed limit (45 mph) highways, MO 370, was substantially lower than those with the higher speed limit (65 mph), I-70, by 23.2 percent.

Table 8-9. Descriptive analysis of work zone speed limit non-compliance and compliance before and after entering rumble strips segments

	No. of vehicles measured	Avg. vehicle speed	Above the work zone speed limit						At/Below the work zone speed limit	
			Total		Less than 10 mph		More than 10+ mph			
			Freq.	Pct.	Freq.	Pct.	Freq.	Pct.	Freq.	Pct.
All	146,143	65.01	104,160	71.27	60,920	41.69	43,240	29.59	41,983	28.73
Work Zone Speed Limit (mph)										
45 mph	47,574	61.27	41,364	86.95	2,898	6.09	38,466	80.86	6,210	13.05
65 mph	98,569	66.82	62,796	63.71	58,022	58.86	4,774	4.84	35,773	36.29
Rumble Strip										
Before entering the rumble strip segment	73,788	67.15	58,049	78.67	32,215	43.66	25,834	35.01	41,975	21.33
After entering the rumble strip segment	72,355	62.83	46,111	63.73	28,705	39.67	17,406	24.06	26,244	36.27
Vehicle Class										
Small	540	59.46	337	62.41	237	43.89	100	18.52	203	37.59
Medium	136,944	165.13	98,138	71.66	57,741	42.16	40,397	29.50	38,806	28.34
Large	8,659	63.60	5,685	65.65	2,942	33.98	2,743	31.68	2,974	34.35
Day and hour										
Weekday nighttime hours	45,041	65.25	33,509	74.40	19,378	43.02	14,131	31.37	11,532	25.60
Weekday daytime peak hours	53,492	65.18	38,680	72.31	22,056	41.23	16,624	31.08	14,812	27.69
Weekday daytime non-peak hours	47,610	64.60	31,971	67.15	19,486	40.93	12,485	26.22	15,639	32.85
Location										
MO 370 EB in St. Charles w/ no strips	23,643	66.22	23,635	99.97	505	2.14	23,130	97.83	8	0.03
MO 370 EB in St. Charles w/ long-term strips	23,931	56.38	17,729	74.08	2,393	10.00	15,336	64.08	6,202	25.92
I-70 EB in St. Charles w/ no strips	50,145	67.59	34,414	68.63	31,710	63.24	2,704	5.39	15,731	31.37
I-70 EB in St. Charles w/ long-term strips	48,424	66.02	28,382	58.61	26,312	54.34	2,070	4.27	20,042	41.39

The effect of (long-term) rumble strips on these two work zones was substantial. The violation rate was much higher in the segment with no rumble strips than with rumble strips by about 15 percent (78.67 percent versus 63.73 percent). Also, the percentage of speeding 10+ mph was smaller by about 11 percent (35.01 percent versus 24.06 percent).

Small class vehicles had a lower violation rate than medium and large vehicle classes. The vehicle speed data from the two work zones were collected on weekdays. The violation rates across different hours of the day showed that nighttime and peak hours had higher violation rates than non-peak daytime hours. Again, the compliance rates by work zone were substantially different. This also indicates substantial work zone heterogeneity.

Again, a random-effects binary logit model was employed to estimate the conditional effects of various factors related to the speed violation in two work zones. The model results are reported in Table 8-10. The dependent variable is binary (1=Violation of the speed limit and 0=Compliance of the speed limit). The model fit statistics show that the model fitted the data well and the log-likelihood ratio (LR) test for random intercepts shows that work zone level heterogeneity was statistically significant. Also, the link test for the model specification indicates that the binary logit model was properly specified (p-value of the squared prediction = 0.8004 while the p-value of the prediction = <0.0001).

Table 8-10. Random effect binary logit model results on work zone speed limit overage for before and after entering the rumble strip segment

		Over the work zone speed limit			
		Coeff.	Std. Error	P>|t|	dy/dx
Intercept		6.2050	1.4366	0.1448	
Work Zone Speed Limit (mph)	65 mph	-3.9448	1.6401	0.0162	-0.7285
	45 mph (Base case)				
Rumble Strip	After entering the rumble strip segment	-3.6802	1.6401	0.0248	-0.6796
	Before entering the rumble strip segment				
Vehicle Class Type	Small	-0.3556	0.0915	0.0001	-0.0657
	Medium (Base case)				
	Large	-0.3700	0.0251	<.0001	-0.0683
Day and Hours: Weekday peak hours (7:00-9:00 am & 3:00-6:00 pm), Nighttime hours (7:00 pm-6:59 am)	Weekday nighttime hours	0.3279	0.0153	<.0001	0.0606
	Weekday daytime peak hours	0.1960	0.0145	<.0001	0.0362
	Weekday daytime non-peak hours (Base case)				
Random-effects parameter	Locations with/without rumple strips in two consecutive segments	Estimate	Std. Error		
		2.6590	1.9043		

Notes:
1) Fit statistics: n = 146,143; -2 LL = 154939.4; Fit Statistics for Conditional Distribution: -2 Res LL = 154902.4, Pearson ChiSq = 144009.7, Pearson ChiSq / DF = 0.99
2) LR test for random intercept: -2 LL = 160883, ChiSq = 5943.34 (1 DF), Prob > ChiSq = <0.0001
3) dy/dx indicates average marginal effect compared to the base case after taking random effects into account.

The model results show that a higher speed limit had a statistically significant effect on the decrease in the speed violation. Two work zones were multi-lane highways. Thus, highway type was not included in the model. The effect of (long-term) rumble strips was statistically significant. After entering the ruble strips segment, the probability of violation decreased by 67.96. Small and large class vehicles were negatively associated with the violation, indicating that those vehicles were less likely to drive over the speed limit in these two work zones. The surveys at two work zones were conducted on weekdays. Weekday nighttime and daytime peak hours were positively associated with the violation. These associations were significant.

Key Findings of Safety Analysis

The safety analyses of work zone speed data resulted in substantive findings. The analyses involved several different analyses. Each analysis revealed different aspects of the work zone safety and the effects of temporary rumble strips, and significant heterogeneity between work

zones. However, overall, the analyses revealed the positive effects of rumble strips on the work zone speed compliance by lowering vehicle speed. More specific findings are:

1) The overall compliance rate of the work zone speed limit was very low. It was only 23.4 percent. Despite substantial variations found among work zones, this low compliance rate reflects a safety issue associated with speeding motorists in work zones.

2) Even though multi-lane highways had a higher likelihood of speed limit violation than two-lane highways, work zones with lower speed limits tended to have higher speed overages. This may indicate that the enforcement at work zones with lower speed limits needs to be strengthened.

3) The effects of temporary rumble strips were statistically significant in the analyses with the complete data and the before and after the rumble strips segment data even though the effects were insignificant in the analysis with multi-day data from four work zones. With the complete survey data, the marginal effects showed that the speed violation decreased by 21.2 and 18.2 percent for short-term and long-term rumble strips, respectively. With the data of before and after entering the rumble strips segment, long-term rumble strips decreased the speed violation by 68.0 percent. This before and after analysis result may provide a more meaningful implication on the effect of work zone rumble strips. The insignificance of the rumble strips' effects on the multi-day survey data may be due to the unbalanced data by the type of rumble strips and outliers from some work zones, including US 24, I-44, and I-49.

4) The difference between short-term and long-term rumble strips' effects on the work zone speed violation and compliance was inconclusive. The statistical significance found with the complete survey data shows that the effect of short-term rumble strips was stronger than long-term rumble strips. However, two coefficients overlapped each other within the ranges of standard errors, indicating that the more substantial effect of short-term rumble strips might not be conclusive. The analysis of before and after entering the rumble strips segment did not include short-term rumble strips.

9. ECONOMIC ANALYSIS

After reviewing previous studies that examined the effectiveness of rumble strips (Corkle et al. 2001, Meyer 2006a, Horowitz and Notbohm 2010, Chen et al. 2012, El-Rayes et al. 2013, Datta et al. 2015, Donahue 2018, Sun and Rahman 2021) and drawing upon Mackie et al. (2005) as a guide for economic evaluation, the cost-effectiveness of temporary rumble strips was evaluated by measuring the purchase, installation, maintenance, and removal costs relative to the estimated cost savings rendered from crash reduction resulting from rumble strip implementation.

Types of Rumble Strips

Short-term Rumble Strips (Portable Reusable)

Portable, short-term rumble strips do not use adhesives or other anchoring mechanisms and are ideal when daily installation and removal is required (Meyer 2000). The strips are thicker, wider, and heavier than long-term rumble strips, but can be easily moved within and removed from the work zone. A set of short-term rumble strips is defined as three strips spaced a minimum of 10 feet on center and are 10 to 12 feet in length, a minimum of 8 inches wide, ¾ to 1¼ inch thick, fabricated from a polymer material, and orange in color (Missouri DOT 2021c, Missouri DOT 2021a).

Referencing Meyer (2000), ATSSA (2013), and El-Rayes et al. (2013), the following specifications were considered in the assessment of portable reusable (short-term) rumble strips:

- Weight of approximately 110 pounds
- Shelf life of three to five years
- Removable and reusable
- Requires two workers 25 minutes to install
- Requires two workers approximately five minutes to remove
- Generates higher sound levels than long-term rumble strips

Long-term Rumble Strips

Long-term rumble strips are fabricated with an adhesive backing to prevent movement. A set of long-term rumble strips is defined as five strips spaced 10 to 12 feet on center and adhere to the following requirements (Missouri DOT 2021a; Missouri DOT 2021c):

- Fabricated from a polymer material
- Orange in color
- Ten to 12 feet in length

- Minimum width of four inches, but no greater than six inches
- Minimum thickness of 0.25 inch, but no greater than 0.50 inch
- Pre-applied adhesive backing for securing to the asphalt or concrete roadway surface

Referencing again Meyer (2000), ATSSA (2013), and El-Rayes et al. (2013), the following specifications were considered in the assessment of adhesive (long-term) rumble strips:

- Plastic strips manufactured in 50 feet rolls, 0.25 inches thick and four inches wide
- Manufactured with removable adhesive backing
- One year shelf life
- Removable and reusable
- Redressing adhesives are available and can be applied to the rumble strips up to four times (for a total of five uses)
- Requires two to five workers 30 to 40 minutes to install
- Requires one to two workers approximately five minutes to remove

Rumble Strips Costs

Purchase

The per set purchase cost of the short-term rumble strips (Roadquake 2 (RQ2) Temporary Portable Rumble Strip Color – Orange) was calculated using the expired MoDOT contract pricing of $1,705 per strip (effective June 2018 to March 2021), and a set consisting of three strips results in cost of $5,115 per set (3*$1,705).

The per set purchase cost of the long-term, adhesive backed temporary rumble strips (orange colored) was calculated using the MoDOT current contract price of $6.59 per linear foot. A set consisting of five strips, ten to 12 feet in length results in a cost of $329.50 to $395.40 per set ($6.59*5*10 feet; $6.59*5*12 feet).

Note that procurement and sourcing costs, such as administration and overhead, were not included in the purchase cost calculations, and the purchase cost calculations for the long-term, adhesive backed temporary rumble strips are based on first-time use

Installation

It was estimated that it takes two workers 25 minutes to install short-term portable rumble strips (ATSSA 2013). An average starting wage of $15.83 per hour for a full-time maintenance worker (Missouri DOT 2020) was used, and the installation costs were calculated as $15.83*2*(25/60 minutes) = $13.19 per set.

It was estimated that it takes two to five workers 30 to 40 minutes to install long-term, adhesive rumble strips (ATSSA 2013). Using an average starting wage of $15.83 per hour for a full-time maintenance worker (Missouri DOT 2020), the installation costs for long-term adhesive rumble strips were calculated to be between $15.83 and $52.77 ($15.83*2*(30/60 minutes); $15.83*5*(40/60 minutes)) per set.

Though not included in the cost estimates, environmental factors that constrain the installation process should be considered. For optimal performance, temporary rumble strips should withstand a maximum weight of 80,000 pounds, maximum speed of 80 mph, and temperatures between 0-180 degrees Fahrenheit (Dimensional Products Inc. 2013). These requirements are set to ensure that the strips remain in place and effective. While the rumble strips are manufactured to withstand cold and hot temperatures, installation of adhesive rumble strips are recommended when the air and surface temperature are between 40-50 degrees Fahrenheit. Additionally, rumble strips should not be installed earlier than 24 hours after rainfall or within 24 hours of forecasted rainfall.

It is also imperative to follow manufacturers' roadway cleaning requirements prior to installation. Surface debris can lead to the rumble strips shifting or becoming dislodged, which could potentially cause damage to the rumble strips rendering them ineffective (ATSSA 2013).

Maintenance

Significant maintenance issues have not been reported; however, strips should be checked for movement and corrected as needed (Khan and Bacchus 1995). (Though minimal movement has been reported when the rumble strips are placed perpendicular to the roadway (Sun et al. 2011)).

It is important to note that the use of temporary rumble strips is not recommended during adverse winter weather, since they may be dislodged and/or damaged by snowplow blades (Corkle et al. 2001). For example, studies have shown portable rumble strips in states such as California are more durable compared to Minnesota due to plowing activities (Corkle et al. 2001).

Additionally, costs for replacement strips could be incurred if the installed strips are damaged due to improper installation, maintenance and/or other environmental factors (ATSSA 2013). The contractor shall monitor, maintain and, if necessary, repair the long-term rumble strips until they are removed (Missouri DOT 2021c).

Removal

It was estimated that removal of short-term rumble strips requires two workers approximately five minutes (ATSSA 2013). Using an average starting wage of $15.83 per hour for a full-time

maintenance worker (Missouri DOT 2020), the removal costs were estimated to be $2.64 ($15.83*2*(5/60 minutes)) per site.

Removal costs for long-term adhesive rumble strips were estimated to be $1.32 to $2.64 per site using an average starting wage of $15.83 per hour for a full-time maintenance worker (Missouri DOT 2020) for one to two workers approximately five minutes to remove (ATSSA 2013) ($15.83*(5/60 minutes); $15.83*2*(5/60 minutes)).

Pavement Damage

Temporary rumble strips render no known significant pavement damage (Missouri DOT 2021a). In some cases, small pieces of gravel may remain on the back of the rumble strips after removal, yet it is not reported as a significant cause of road damage (Meyer and Walton 2002). In cases where all adhesive was not removed from the pavement during removal, the adhesive caused pavement discoloration. However, pavement color was naturally restored after the adhesive wore off due to normal traffic and weather conditions (Meyer and Walton 2002).

Reusability

Both short-term portable rumble strips and long-term adhesive rumble strips are reusable; however, reusability is dependent upon wear-and-tear (Meyer and Walton 2002) and is limited to the product shelf life. Short-term rumble strips have a shelf life of three to five years, while long-term adhesive rumble strips have a shelf life of one year and the adhesive may be applied up to four times for a total of five uses (FHWA 2015). Note, the MoDOT current contract price for adhesive/primer for permanent long term rumble strips is $44.18 per gallon.

Noise

Rumble strips create an audible and vibratory stimulus that produces two different noises: one inside the vehicle alerting the driver and another outside the vehicle (FHWA 2015). While the inside the vehicle noise is necessary for alerting the drivers, the outside noise is reported to be a nuisance, especially to construction workers (Meyer and Walton 2002).

There are different variables that affect the outside noise which include the type of rumble strips (short-term rumble strips generate higher sound levels than long-term, adhesive rumble strips (El-Rayes et al. 2013)), the distance between the rumble strips, type of vehicle, weight of the vehicle, speed of the vehicle and wind speed (FHWA 2015). Vehicles moving at slower speeds and carrying lighter weight tend to produce lower outside noise compared to faster moving vehicles and vehicles hauling significant weight. Since the vehicle speed determines the outside noise of the rumble strips, the noise can be reduced by alerting drivers of rumble strips ahead by using signs or flaggers to reduce their speed before getting to the rumble strips (FHWA 2015).

Table 9-1 provides a summary of the per set short-term and long-term rumble strip costs, including purchase, installation, removal, maintenance, reusability and pavement damage, which are then used in the benefit-cost analysis for benefit-cost ratio examples.

Table 9-1. Rumble strip costs (per set)

Type	Purchase	Installation (Labor)	Removal (Labor)	Maintenance	Reusability	Pavement Damage
Short-Term Portable	$5,115.00	$13.19	$2.64	No significant maintenance issues reported, but strips should be checked for movement and corrected as needed. Costs associated with replacement of damaged strips may be incurred.	Reusable 3 to 5-year shelf life	No significant road damage reported.
Long-Term Adhesive	$329.50 to $395.40	$15.83 to $52.77	$1.32 to $2.64	No significant maintenance issues reported, but strips should be checked for movement and corrected as needed. Costs associated with replacement of damaged strips may be incurred.	Reusable for a total of 5 uses. 1-year shelf life	No significant road damage reported.

Benefits

Several studies suggest that the use of temporary rumble strips in construction work zones improves driver and worker safety by effectively alerting drivers to changes in upcoming conditions, mitigating drivers from following too closely to another vehicle, making improper lane changes and driving while distracted, and serving as a countermeasure for reducing driving speeds (The Roadway Safety Consortium n.d., Roads & Bridges n.d., Morgan 2003, Savolainen et al. 2009, Sharma et al. 2017). And importantly, most traffic safety professionals conclude that excessive speeding is a contributing factor in a large percentage of work zone crashes (Sommers and McAvoy 2013).

Benefit Estimates

To quantify the benefits rendered from rumble strip implementation, Brown et al. (2018), *Safety Assessment Tool for Construction Work Zone Phasing Plans*, was used to estimate the expected number of work zone crashes and the annual crash cost in work zones without the rumble strip treatment by automatically selecting the appropriate model based on user inputs. The assessment tool was used to model two scenarios (with two examples each), and model inputs and results are presented in Table 9-2 through Table 9-5.

- Scenario 1 — Example 1: Rural two-lane facility type, no signalized intersections, duration of 180 days, annual average daily traffic (AADT) of 1,000.
- Scenario 1 — Example 2: Rural two-lane facility type, no signalized intersections, duration of 180 days, AADT of 5,000.
- Scenario 2 — Example 1: Freeway facility type, rural location, two lane traffic, one closed lane, one on-ramp, one off-ramp, duration of 180 days, AADT of 5,000.
- Scenario 2 — Example 2: Freeway facility type, rural location, two lane traffic, one closed lane, one on-ramp, one off-ramp, duration of 180 days, AADT of 15,000.

Table 9-2. Scenario 1, rural-two lane (output)

Description	Output Example 1	Output Example 2
Expected Number of PDO Crashes	0.52	2.33
Standard Error of PDO Estimation	1.124	4.153
Expected Number of Fatal and Injury Crashes	0.24	0.79
Standard Error of Fatal and Injury Estimation	0.49	0.889
Total Crash Cost; value in 2021	$122,597	$416,968
Model Used:	Rural Two-Lane	Rural Two-Lane

Table 9-3. Scenario 1, rural-two lane (input)

Description	Input Example 1	Input Example 2
Annual Average Daily Traffic	1000	5000
Duration	180	180
Length	2	2
Urban/Rural	Rural	Rural
Number of Signalized Intersections	0	0
Crash Cost Reference; Publication Year	HSM (2010)	HSM (2010)
PDO Crash Cost	$7,400	$7,400
Fatal and Injury Crash Cost	$158,200	$158,200
Facility Type	Rural Two-Lane	Rural Two-Lane

Table 9-4. Scenario 2, freeway (output)

Description	Output Example 1	Output Example 2
Expected Number of PDO Crashes	1.84	5.37
Standard Error of PDO Estimation	1.356	2.317
Expected Number of Fatal and Injury Crashes	0.59	1.73
Standard Error of Fatal and Injury Estimation	0.781	1.379
Total Crash Cost; value in 2021	$313,573	$918,913
Model Used:	Freeway 6	Freeway 6

Table 9-5. Scenario 2, freeway (input)

Description	Input Example 1	Input Example 2
Annual Average Daily Traffic	5000	15000
Duration	180	180
Length	2	2
Urban/Rural	Rural	Rural
Number of Closed Lanes	1	1
Total Number of Lanes	2	2
Number of On-ramps	1	1
Number of Off-ramps	1	1
Crash Cost Reference; Publication Year	HSM (2010)	HSM (2010)
PDO Crash Cost	$7,400	$7,400
Fatal and Injury Crash Cost	$158,200	$158,200
Facility Type	Freeway	Freeway

Using the expected number of crashes output as the base condition (as presented in Table 9-2 and Table 9-4), the crash frequency for work zones with TPRS was calculated as the crash frequency for the base condition multiplied by a crash modification factor (CMF), which represents the expected safety effect of the treatment relative to the base condition (Lawrence et al. 2018). A CMF of 0.89, derived from Ullman et al. (2018) using Texas data for work zones in which TPRS are deployed during non-queued traffic, was used to estimate the annual number of crashes when TPRS are installed.

*Estimated Crashes with Treatment = Estimated Crashes for Base Condition * CMF*

As presented in Table 9-6 through Table 9-9, the safety benefit was calculated as the difference in the estimated crash frequency with and without treatment (portable rumble strip implementation) (Lawrence et al. 2018), and the annual crash cost savings was estimated using the crash cost derived from the safety assessment tool multiplied by the crash reduction resulting from TPRS implementation (1 minus a CMF of 0.89) (FHWA 2018).

Table 9-6. Benefit estimate: scenario 1 (rural-two lane – example 1)

Crash Type	Expected Number of Crashes	CMF	Estimated Annual Crashes with TPRS	Estimated Annual Crash Reduction	Estimated Annual Crash Cost without Treatment	Estimated Annual Cost Savings with TPRS
Fatal and Injury	0.24	0.89	0.2136	0.0264	$111,315.36	$12,244.69
PDO	0.52	0.89	0.4628	0.0572	$11,281.64	$1,240.98
Total	-	-	-	-	$122,597.00	**$13,485.67**

Table 9-7. Benefit estimate: scenario 1 (rural-two lane – example 2)

Crash Type	Expected Number of Crashes	CMF	Estimated Annual Crashes with TPRS	Estimated Annual Crash Reduction	Estimated Annual Crash Cost without Treatment	Estimated Annual Cost Savings with TPRS
Fatal and Injury	0.79	0.89	0.7031	0.0869	$366,413.04	$40,305.43
PDO	2.33	0.89	0.4628	0.0572	$50,550.45	$5,560.55
Total	-	-	-	-	$416,963.49	**$45,865.98**

Table 9-8. Benefit estimate: scenario 2 (freeway, two-lane – example 1)

Crash Type	Expected Number of Crashes	CMF	Estimated Annual Crashes with TPRS	Estimated Annual Crash Reduction	Estimated Annual Crash Cost without Treatment	Estimated Annual Cost Savings with TPRS
Fatal and Injury	0.59	0.89	0.5251	0.0649	$273,652.94	$30,101.82
PDO	1.84	0.89	0.4628	0.0572	$39,920.06	$4,391.21
Total	-	-	-	-	$313,573.00	**$34,493.03**

Table 9-9. Benefit estimate: scenario 2 (freeway, two-lane – example 2)

Crash Type	Expected Number of Crashes	CMF	Estimated Annual Crashes with TPRS	Estimated Annual Crash Reduction	Estimated Annual Crash Cost without Treatment	Estimated Annual Cost Savings with TPRS
Fatal and Injury	1.73	0.89	1.5397	0.1903	$802,406.08	$88,264.67
PDO	5.37	0.89	0.4628	0.0572	$116,505.82	$12,815.64
Total	-	-	-	-	$918,911.91	**$101,080.31**

Benefit-Cost Analysis

A benefit-cost analysis is a "systematic process for calculating and comparing benefits and costs of a project" and is essential for conducting an economic appraisal (Lawrence et al 2018). The benefit-cost ratio, presented here, is calculated as the total benefits divided by the total costs (TRB n.d.). Projects with a benefit-cost ratio greater than one have greater benefits than costs, that is, positive net benefits, and the higher the ratio, the greater the benefits relative to the costs (TRB n.d.).

The cost estimates presented in Table 9-1 and the benefits estimates for the scenarios presented in Table 9-6 through Table 9-9 were used to provide example benefit-cost ratios as presented below. Specific examples are provided because the benefit-cost ratio varies depending the number and types of projects that a DOT deploys per year.

Example 1 Parameters:

Cost

- Twenty projects annually are candidates for temporary rumble strip implementation
- All 20 projects will require new strips
- Costs fall at the high end of the purchase, installation, and removal cost range
- Ten of the 20 projects will each have one set of long-term strips installed and the other 10 projects will each have one set of short-term strips installed

Following these parameters and using the cost figures presented in Table 9-1, the annual cost for temporary rumble strip implementation is estimated as $55,816.00.

Benefits

- Ten of the 20 projects are rural, two-lane, with an AADT of 1,000 (as presented in Scenario 1 – Example 1)
- Ten of the 20 projects are freeway, two-lane AADT of 5,000 (as presented in Scenario 2 – Example 1)

Following these parameters and using the information presented in Table 9-6 through Table 9-9, the annual benefits of temporary rumble strip implementation was estimated as $479,787.00.

The resulting benefit-cost ratio in this example is 8.6 ($479,787.00/$55,816.00), which indicates positive net benefits.

Example 2 Parameters:

Changing the benefits' parameters in Example 1 by increasing the AADT, with 10 projects assumed to be rural, two-lane, AADT 5,000 (as presented in Scenario 1 – Example 2) and 10 assumed to be freeway, two-lane AADT 15,000 (as presented in Scenario 2 – Example 2), the benefits were estimated to be $1,469,462.94. Following the same cost parameters as presented in Example 1 with an estimated cost of $55,816.00, the resulting benefit–cost ratio for Example 2 is 26.3 ($1,469,462.94 /$55,816.00), which illustrates that the use of temporary rumble strips in situations with greater traffic renders greater positive net benefits.

Example 3 Parameters:

Following the same parameters as Example 1, but now using two sets of rumble strips instead of one, a positive investment (benefit-cost ratio of 4.3) is still rendered, which again illustrates that the benefits of temporary rumble strip implementation outweigh the cost.

Key Takeaways

Findings suggest that temporary rumble strips improve driver and worker safety by alerting drivers of upcoming conditions, which serves as a countermeasure for reducing driving speeds. The enhanced safety was quantified by estimating work zone crash reduction and the resulting cost savings, and the benefits were compared with the costs incurred by purchasing, installation, and removal of temporary rumble strips. Positive benefit-cost ratio examples illustrate that the benefits of temporary rumble strip implementation (as measured by crash cost savings) outweigh the costs; therefore, temporary rumble strips are reported to be a positive investment that are economical and efficient for work zone implementation.

10. CONCLUSIONS

This chapter presents the conclusions from the study, including policy considerations and summary of findings.

Policy Considerations for Temporary Rumble Strips

Below are some policy considerations of temporary rumble strips MoDOT may want to examine for implementation into its current practices.

- MoDOT may want to provide greater flexibility to designers, contractors, and maintenance personnel in the type of temporary rumble strip used based on project-specific conditions (for example, work type and location) in addition to work zone duration. MoDOT maintenance personnel successfully deployed long-term temporary rumble strips on two projects with durations of four days or less. Conversely, the US 63 project in Ashland may have been a better fit for long-term temporary rumble strips instead of short-term temporary rumble strips based on the type of work (J-turn installation) and long duration.
- The research team recommends MoDOT reassess the practices for installation and removal procedures for short-term temporary rumble strips on divided highways (especially divided highways with high traffic volumes) which require direct worker exposure to traffic. Possible alternatives include the use of a TMA for installation, setting up a lane closure to install the strips, using a carriage (Figure 6-2) or handling machine (Figure 6-3) to place the strips, or only allowing the use of long-term temporary rumble strips on divided highways. The use of long-term temporary rumble strips on divided highways would limit worker exposure to traffic by providing protection with a TMA and limiting the number of installation and removals to one per location. However, extended use of long-term temporary rumble strips could potentially desensitize motorists to their use, especially during time periods when the work zone is not active.
- MoDOT may want to consider the use of a stationary work zone instead of a moving work zone to install long-term temporary rumble strips on divided highways. MoDOT maintenance personnel indicated concerns with installation time (approximately 12 to 14 minutes per set) in conjunction with a moving work zone operation. Other state DOTs have used both static and rolling lane closures with a TMA for installing long-term temporary rumble strips.
- While the selection of the type of temporary rumble strip (long-term or short-term) depends on project-specific factors, the research team recommends that short-term temporary rumble strips be used for flagging operations on two-lane highways with a minimum duration of three hours. The use of the short-term temporary rumble strips for flagging operations provides flexibility and is consistent with the practices of other states.
- Short-term temporary rumble strips may be deployed on divided highways with durations between three hours and 14 days. However, as noted previously, consideration should be given to the installation processes to minimize worker exposure to traffic (especially on high-

volume highways) by using a TMA, crib carrier, or handling machine. Short-term temporary rumble strips may be deployed at temperatures as low as 0°F and posted speed limits up to 80 mph. As noted previously, MoDOT may also want to consider only allowing long-term temporary rumble strips on divided highways.

- Consistent with the practices of other states, MoDOT may want to allow the use of short-term temporary rumble strips at night. However, consideration should be given to avoid using short-term temporary rumble strips at night in residential areas where noise is a factor. In addition, visual cues such as a "Rumble Strips Ahead" sign and speed feedback displays could help alert drivers to the temporary rumble strips at night. Finally, strip movement should be closely monitored at night.
- Long-term temporary rumble strips may also be deployed on divided highways with durations of at least two days. As noted previously, a TMA could be provided for worker protection while the long-term temporary rumble strips are installed and removed. Long-term temporary rumble strips should not be installed when the outside air temperature is less than 50°F.
- Changes in terminology regarding the type of temporary rumble strip (short-term versus long-term temporary rumble strips) may help to reduce confusion regarding their use. Examples of terminology used by other DOTs include temporary transverse rumble strips, temporary rumble strips (special), and temporary buzz strips for long-term temporary rumble strips and TPRS for short-term temporary rumble strips. Possible terms for use by MoDOT could be temporary rumble strips (portable) and temporary rumble strips (adhesive).
- The addition of a "Rumble Strips Ahead" sign to the typical traffic control plan could provide an additional cue to drivers of the upcoming work zone and may help to reduce the potential for erratic driver behavior by providing a visual alert to the upcoming temporary rumble strips. The "Rumble Strips Ahead" sign is used by several other DOTs but is not mentioned in Section 6F.87 of the MUTCD (FHWA 2009).
- While MoDOT allows for the optional use of one set of temporary rumble strips instead of two in its EPG, MoDOT may want to consider making the use of one set of temporary rumble strips standard. The use of one set instead of two could help facilitate the ease of installation, reduce installation time and worker exposure to traffic, and increase contractor compliance regarding the placement of the temporary rumble strips. Wisconsin DOT and Iowa DOT both utilize one set of rumble strips in their use of short-term temporary rumble strips for flagging and pilot car operations. However, the use of one set of strips instead of two could potentially be less effective in reducing vehicle speeds. A research study sponsored by the Iowa DOT showed the use of one set of strips with a "Rumble Strips Ahead" sign led to reductions in vehicle speeds of 3.7 mph compared to reductions in vehicle speeds of 5.5 mph with two sets of strips (Hawkins et al. 2017).
- Verification and monitoring of temporary rumble strip layout and spacing in the field will help to ensure that the temporary rumble strips are functioning properly. On four of the five temporary rumble strip installations observed by the research team, the number of strips and/or spacing between strips were not in accordance with the EPG.
- Increasing awareness of MoDOT's practices and standards (by providing training to MoDOT

staff and contractors) may help to improve compliance with the MoDOT standards for temporary rumble strips.
- Section 616.12 of the EPG limits work zone speed limit reductions to 10 mph or less unless there are special circumstances that are documented and approved by the District Work Zone Coordinator (Missouri DOT 2021d). Care should be applied when using temporary rumble strips for speed limit reductions greater than 10 mph; an awareness for the limitations of temporary rumble strips could help to guide their deployment under special circumstances.

Suggested EPG Language for Temporary Rumble Strips

This section provides some language, including Table 10-1, for consideration for possible inclusion in the MoDOT EPG regarding the use of long-term temporary rumble strips [suggested change in terminology to temporary rumble strips (adhesive)] and short-term temporary rumble strips [suggested change in terminology to temporary rumble strips (adhesive)]. The suggested language is provided below.

The decision on what type of temporary rumble strips [temporary rumble strips (portable) or temporary rumble strips (adhesive)] to deploy in a specific work zone should be based on project-specific conditions, such as duration, type of work activity, and location. General guidance for the selection of temporary rumble strip type is provided in Table 10-1 below.

Table 10-1. Guidance for use of temporary rumble strips (portable) and temporary rumble strips (adhesive)

Temporary Rumble Strip Type	Conditions for Use on Two-lane Highways	Conditions for Use on Divided Highways*

Temporary rumble strips (portable)	• Flagging operations
	  • Duration at least three hours
	  • Air temperature at least 0°F
	  • Workers present
		• Lane closure
		  • Duration at least three hours and less than 14 days
		  • Air temperature at least 0°F
		  • Workers present

Temporary rumble strips (adhesive)	• May be used if temporary rumble strips (portable) are not available.	• Lane closure
		  • Duration at least two days
		  • Air temperature at least 50°F

* TMA or other protection should be provided during installation and removal

Summary of Key Findings

Key findings from this research study are summarized below.

- Limited guidance regarding the use of temporary rumble strips, including color and conditions for placement is provided in the MUTCD (FHWA 2009). Additional guidance is available in a guide on temporary rumble strips from ATSSA which covers various topics such as advantages and disadvantages of temporary rumble strips, work zone duration, configuration, parameters, and other considerations (ATSSA 2013).
- Prior research studies have shown temporary rumble strips to be effective in reducing vehicle speeds by 4 mph to 12 mph, increasing driver braking, and alerting drivers to the presence of the work zone.
- Research has also found the use of temporary rumble strips helps to reduce the number of crashes, with CMF values ranging from 0.40 to 0.89 based on the presence of queuing and an End of Queue Warning System (EOQWS) (Ullman et al. 2018).
- The level of implementation of temporary rumble strips varies greatly between DOTs, including no current use (Delaware DOT), pilot deployment (Pennsylvania DOT and Georgia DOT), recommended use (Minnesota DOT), and required use under certain conditions (Virginia DOT and Wisconsin DOT).
- Among the 18 DOTs that provided written responses or participated in interviews, short-term temporary rumble strips appear to be used more frequently than long-term temporary rumble strips. The short-term temporary rumble strips are often used by other DOTs for flagging or pilot car operations and are sometimes also deployed on divided highways.
- DOT practices and standards for temporary rumble strips differ significantly with respect to size, color, speed, spacing, materials, installation, maintenance, removal, and other attributes.
- In general, DOTs find temporary rumble strips to be effective in reducing vehicle speeds and alerting drivers to the presence of the work zone. Concerns noted by other DOTs include the heavy weight of short-term temporary rumble strips, requirements for installation, potential for erratic driver behavior, and the need for maintenance of the temporary rumble strips.
- Field observations of driver behavior, conducted in this project after installation of temporary rumble strips at three work zones, indicated that 52.4 percent of drivers braked at one work zone on US 24 with short-term temporary rumble strips in a flagger situation during nighttime and 0.7 percent to 6.1 percent of drivers braked at work zones on MO 370 and I-55 with long-term temporary rumble strips on a divided highway during daytime. The higher percentage of braking on US 24 could potentially be due to the presence of a flagger at nighttime. Only one erratic driving maneuver, in which a motorcycle drove around short-term temporary rumble strips in a flagger work zone, was observed by the research team.
- Results from field observations of the installation of temporary rumble strips at five work zones showed that the spacing, number of rumble strips, or both in the field were not in accordance with the typical applications in the MoDOT EPG at four of the locations.
- Perceptions of the effectiveness of temporary rumble strips varied between the installers, but the installers generally thought temporary rumble strips can be effective in certain situations. Concerns noted by the installers include the heavy weight of short-term temporary rumble strips, difficulty in removing long-term temporary rumble strips on asphalt pavements, time required for installation, and worker exposure to traffic when installing short-term temporary rumble strips on a divided highway.

- Results from the safety analysis revealed positive effects of temporary rumble strips on the work zone speed compliance. With the complete survey data, the marginal effects showed the speed violation decreased by 21.2 and 18.2 percent for short-term and long-term rumble strips, respectively. However, the analyses were inconclusive on the difference between short-term and long-term rumble strips' effects on the work zone speed violation and compliance.
- Positive benefit-cost ratio examples illustrate the benefits of temporary rumble strip implementation outweigh the costs, and therefore they are reported to be a positive investment that are economical and efficient for work zone implementation.
- Modifications to existing MoDOT practices, as discussed in the previous Policy Considerations section, may potentially improve performance of temporary rumble strips and compliance with MoDOT standards.
- Worker exposure to traffic for short-term rumble strip installation and removal on multi-lane highways is a concern, and procedures for installation in this setting should be reviewed to see if the worker exposure to traffic can be reduced.

Overall, the study found temporary rumble strips can be an effective tool to lower vehicle speeds, increase braking, and reduce crashes, and such strips can produce high benefit-cost ratios. Modifications to existing MoDOT practices may potentially reduce cost, increase installation efficiency, enhance worker safety, and improve performance of temporary rumble strips. Field observations of driver behavior noted minimal erratic driver behavior. Concerns were raised by installation personnel regarding installation procedures and worker exposure to traffic. A synthesis of existing DOT practices found differences in levels of implementation and standards for temporary rumble strips among DOTs.

REFERENCES

Alabama Department of Transportation. 2019. "Design Bureau Special Drawing (2002c: Details for Traffic Control for Two Lane Highways)." Accessed November 11, 2021. https://www.dot.state.al.us/publications/Design/pdf/ETCL/2002c.pdf.

American Road and Transportation Builders Association (ARTBA). 2020. "National Estimates of Total and Injury Work Zone Crashes." Accessed December 9, 2021. https://www.workzonesafety.org/crash-information/work-zone-injuries-injury-property-damage-crashes/.

American Road and Transportation Builders Association. 2021. "Temporary Rumble Strips." Accessed December 8, 2021. https://www.workzonesafety.org/practice/temporary-rumble-strips/.

American Traffic Safety Services Association (ATSSA). 2013. *Guidance for the Use of Temporary Rumble Strips in Work Zones*. Washington, D.C.: Federal Highway Administration.

American Traffic Safety Services Association (ATSSA). 2020. *State Examples for the Application of Portable Temporary Rumble Strips (PTRS) in Work Zones*. Federal Highway Administration. U.S. Department of Transportation.

Arizona Department of Transportation. 2021. *Temporary and Portable Rumble Strips*. Phoenix, Arizona.

Brown, Henry, Carlos Sun, Praveen Edara, and Roozbeh Rahmani. 2018. *Extension of Safety Assessment Tool for Construction Work Zone Phasing Plans*. InTrans Project 18-535. Ames, Iowa: Smart Work Zone Deployment Initiative.

Caltrans. 2014. *Implementation of Portable Transverse Rumble Strips*. Memorandum. Sacramento, California.

Caltrans. 2018a. *Flagging Instruction Handbook*. Sacramento, California.

Caltrans. 2018b. *Specifications on Use of Portable Transverse Rumble Strips*. Sacramento, California.

Caltrans. 2018c. "2018 Standard Plans and Standard Specifications." Accessed November 18, 2021. https://dot.ca.gov/programs/design/ccs-standard-plans-and-standard-specifications.

Caltrans. 2021. *California Construction Manual*. Sacramento, California.

Chen, Chung, Deepak Koirala, and Tony Pane. 2012. "Road Statistical Crash Features and Adopting Optimal Rumble Strips to Save Lives and Prevent Injuries." *ITE Journal* 82, No. 8: 28-34.

Colorado Department of Transportation. 2016. "Temporary Rumble Strips Testimonial." Accessed November 11, 2021. https://www.pss-innovations.com/PSS_Innovations/media/PSS-Innovations/Products/Resources/CODOT-2016-10-25.pdf.

Colorado Department of Transportation. 2019. "Safety Standards." Accessed November 11, 2021. https://www.codot.gov/safety/traffic-safety/standard-and-specifications/s-standards.

Corkle, Jacqueline, Michael Marti, and David Montebello. 2001. *Synthesis on the Effectiveness of Rumble Strips*. Report No. MN/RC—2002-07. St. Paul, Minnesota: Minnesota Local Road Research Board.

Critchlow, Douglas, and Michael Fligner. 1991. "On Distribution-Free Multiple Comparisons in the One-Way Analysis of Variance." *Communications in Statistics—Theory and Methods* 20: 127–139. https://www.tandfonline.com/doi/abs/10.1080/03610929108830487.

Czado, Claudia, and Thomas Santner. 1992. "The Effect of Link Misspecification on Binary Regression Inference." *Journal of Statistical Planning and Inference* 33, No. 2: 213-231. https://www.sciencedirect.com/science/article/abs/pii/0378375892900695.

Datta, Tapan K., Peter T. Savolainen, Timothy J. Gates, Jonathan J. Kay, Nicholas B. Nicita, Sahadev Parajuli, and Jacob Finkelman. 2015. *Evaluation of Non-Freeway Rumble Strips-Phase II*. Report No. RC-1627. Lansing, Michigan: Michigan. Department of Transportation.

Dimensional Products, Inc. 2013. "Temporary Rumble Strips." Dimensional Products Inc., April. Accessed November 15, 2021. https://dpihighwaysystems.com/wp-content/uploads/2014/03/Specification-for-Temp-Port.pdf.

Donahue, John. 2018. *Evaluation of New Rumble Strip Designs to Reduce Roadside Noise and Promote Safety*. Olympia, Washington: Washington Department of Transportation.

Dwass, Meyer. 1960. "Some k-Sample Rank-Order Tests." In *Contributions to Probability and Statistics: Essays in Honor of Harold Hotelling*, edited by Ingram Olkin, Sudhist Ghurye, Wassily Hoeffding, William Madow, and Henry Mann, 198–202. Stanford, CA: Stanford University Press.

El-Rayes, Khaled, Liang Liu, and Tarek Elghamrawy. 2013. *Minimizing Traffic-Related Work Zone Crashes in Illinois*. Report No. FHWA-ICT-12-017. Springfield, Illinois: Illinois Department of Transportation.

Federal Highway Administration (FHWA). 2009. *Manual on Uniform Traffic Control Devices for Streets and Highways*, 2009 Edition Including Revision 1 dated May 2012 and Revision 2 dated May 2012. Washington, D.C.

Federal Highway Administration. (FHWA). 2015. "Rumble Strips and Rumble Stripes." Accessed October 15, 2021. https://safety.fhwa.dot.gov/roadway_dept/pavement/rumble_strips/faqs.cfm.

Federal Highway Administration (FHWA). 2018. "Highway Safety Benefit – Cost Analysis Guide." Accessed November 15, 2021. https://safety.fhwa.dot.gov/hsip/docs/fhwasa18001.pdf.

Federal Highway Administration (FHWA). 2020. "National Work Zone Awareness Week." Accessed December 9, 2021. https://ops.fhwa.dot.gov/wz/outreach/nwzaw_factsheet_2020/nwzaw_factsheet_2020.pdf

Florida Department of Transportation. 2021a. "Design Standards." Accessed November 11, 2021. https://www.fdot.gov/design/standardplans/DS.shtm.

Florida Department of Transportation. 2021b. "Standard Plans – FY 2022-23." Accessed November 11, 2021. https://www.fdot.gov/design/standardplans/current/default.shtm.

Florida Department of Transportation. 2022. *Standard Specifications for Road and Bridge Construction*. Tallahassee, Florida.

Fontaine, Michael D., and Paul J. Carlson. 2001. "Evaluation of Speed Displays and Rumble Strips at Rural-Maintenance Work Zones." Transportation Research Record 1745, No. 1: 27-38. https://doi.org/10.3141%2F1745-04.

Georgia Department of Transportation. 2014. *Supplemental Specification (Section 869 – Temporary Portable Rumble Strips*. Atlanta, Georgia.

Georgia Department of Transportation. 2017. *Special Construction Detail (Traffic Control Detail for Two-lane Closure on Two-lane Highway)*. Atlanta, Georgia.

Georgia Department of Transportation. 2020. *Supplemental Specification (Section 150 – Install, Maintain, and Remove Temporary Portable Rumble Strips – Department Provided*. Atlanta, Georgia.

Greene, William. 2003. *Econometric Analysis.* 5th Ed. New Jersey: Prentice Hall.

Hancock, John D. 2020. "Temporary Portable Rumble Strips." Presentation slides for AASHTO Committee on Construction.

Hawkins, Neal, and Skylar Knickerbocker. 2017. *Field Measurements on the Effect of Temporary Rumble Strips in Work Zone Flagging Operations*. Ames, Iowa: Center for Transportation Research and Education.

Horowitz, Alan, and Thomas Notbohm. 2005. *Testing Temporary Work Zone Rumble Strips*. Ames, Iowa: Smart Work Zone Deployment Initiative. 2005.

Houston Radar. 2016. *Armadillo Tracker Stats Collector*. Fact sheet. Sugar Land, Texas.

Houston Radar. 2021. "Armadillo Tracker." Accessed December 9, 2021. https://houston-radar.com/products/radar-data-collectors/armadillo-tracker-traffic-data-collector/.

Idaho Transportation Department. 2021. *Idaho 2021 Supplemental Specifications*. Boise, Idaho.

Illinois Department of Transportation. 2014. *Temporary Rumble Strips (SPECIAL)*. Springfield, Illinois.

Illinois Department of Transportation. 2017. *Detail for Temporary Rumble Strips (Special)*. Springfield, Illinois.

Illinois Department of Transportation. 2020. *2020 Illinois Highway Standards for Traffic Control*. Springfield, Illinois.

Illinois Department of Transportation. 2022. *Standard Specifications for Road and Bridge Construction*. Springfield, Illinois.

Indiana Department of Transportation. 2021a. *Indiana Design Manual*. Indianapolis, Indiana.

Indiana Department of Transportation. 2021b. "Recurring Special Provisions and Plan Details." Accessed November 11, 2021. https://www.in.gov/dot/div/contracts/standards/rsp/sep21/sep21.htm.

Indiana Department of Transportation. 2021c. "Standard Drawings." Accessed November 18, 2021. https://www.in.gov/dot/div/contracts/standards/drawings/.

Indiana Department of Transportation. 2022. *Standard Specifications*. Indianapolis, Indiana.

Iowa Department of Transportation. 2021a. "Standard Road Plans." Accessed November 18, 2021. https://iowadot.gov/erl/current/RS/Navigation/nav.htm.

Iowa Department of Transportation. 2021b. *Standard Specifications*. Des Moines, Iowa.

Kansas Department of Transportation. 2013. *STA Certification of No Suitable Alternative for the Purchase of RoadQuake 2 Rumble Strips*. Topeka, Kansas.

Kansas Department of Transportation. 2021. "2015 Special Provision." Accessed November 18, 2021. https://www.ksdot.org/bureaus/burConsMain/specprov/2015/2015-latest.asp.

Kentucky Transportation Cabinet. 2015. "Special Note for Temporary Portable Rumble Strips (Contract ID No. 212140)." Accessed December 10, 2021. https://transportation.ky.gov/Construction-Procurement/Proposals/306-ESTILL-21-2140%20Addendum%201.pdf.

Khan, A. M., and A. Bacchus. 1995. "Economic Feasibility and Related Issues of Highway Shoulder Rumble Strips." *Transportation Research Record* 1498: 92-101.

Kruskal, William, and Allen Wallis. 1952. "Use of Ranks in One-Criterion Variance Analysis." *Journal of the American Statistical Association* 47, No. 260: 583-621. https://www.jstor.org/stable/2280779.

Lawrence, Michael, Alan Hachey, Geni Brafman Bahar, and Frank B. Gross. 2018. *Highway Safety Benefit-Cost Analysis Guide*. Report No. FHWA-SA-18-001. Washington D.C: Federal Highway Administration.

Mackie, Peter, John Nellthorp, and James Laird. 2005. "Notes on the Economic Evaluation of Transport Projects. *Transport Notes Series*, No. TRN-5, Washington, DC: The World Bank."

Maine Department of Transportation. 2018. *Special Provisions (Section 652: Maintenance of Traffic).* Augusta, Maine.

Maryland Department of Transportation State Highway Administration. 2020. *Portable Rumble Strip: List of Qualified Products*. Annapolis, Maryland.

Maryland Department of Transportation State Highway Administration. 2021a. *Guidelines for Temporary Portable Rumble Strips (TPRS)*. Application Guideline No. 6-F10. Annapolis, Maryland.

Maryland Department of State Highway Administration. 2021b. *Special Provision (104.27: Temporary Portable Rumble Strips*. Annapolis, Maryland.

Massachusetts Department of Transportation. 2017. *Work Zone Safety: Temporary Traffic Control*. Boston, Massachusetts.

Massachusetts Department of Transportation. 2021. *ITEM 854.6 Temporary Portable Rumble Strips*. Boston, Massachusetts.

Meyer, Eric. 2000. "Evaluation of Orange Removable Rumble Strips for Highway Work Zones." *Transportation Research Record* 1715, No. 1: 36-42.

Meyer, Eric, and Scott Walton. 2002. *Preformed Rumble Strips*. Ames, Iowa: Smart Work Zone Deployment Initiative.

Meyer, Eric. 2006a. *Evaluation of Portable Rumble Strips—ATM*. Ames, Iowa: Smart Work Zone Deployment Initiative.

Meyer, Eric. 2006b. *Guidelines for the Application of Removable Rumble Strips*. Report No. K-TRAN: KU-02-3. Lawrence, Kansas: University of Kansas.

Michigan Department of Transportation. 2020. *Standard Specifications for Construction*. Lansing, Michigan.

Michigan Department of Transportation. 2021a. "Special Provisions – Frequently Used (2020)." Accessed November 11, 2021. https://mdotcf.state.mi.us/public/dessssp/spss/gotoview.cfm?ds=31.

Michigan Department of Transportation. 2021b. *Work Zone Safety and Mobility Manual*. Lansing, Michigan.

Minnesota Department of Transportation. 2018. *Two-Lane Two-Way Roads (Field Manual)*. St. Paul, Minnesota.

Minnesota Department of Transportation. 2020. "Special Provisions." Accessed November 11, 2021. http://www.dot.state.mn.us/pre-letting/prov/index.html.

Minnesota Department of Transportation. 2021a. "Approved/Qualified Products: Temporary Traffic Control Devices." Accessed December 10, 2021. https://www.dot.state.mn.us/products/temporarytrafficcontrol/ttcdevices.html.

Minnesota Department of Transportation. 2021b. “Long-Term Typical Applications.” Accessed November 11, 2021. http://www.dot.state.mn.us/trafficeng/workzone/twolanetwoway.html.

Minnesota Department of Transportation. 2021c. *Minnesota Manual on Uniform Traffic Control Devices*. St. Paul, Minnesota.

Mississippi Department of Transportation. 2018. *Special Provision (No. 907-619-6: Temporary Portable Rumble Strips)*. Jackson, Mississippi.

Missouri Department of Transportation. 2020. “Maintenance Workers.” Accessed October 15, 2021. https://www.modot.org/maintenance-workers.

Missouri Department of Transportation. 2021a. “616.6 Temporary Traffic Control Zone Devices (MUTCD 6F),” Engineering Policy Guide. Accessed November 11, 2021. https://epg.modot.org/index.php?title=616.6_Temporary_Traffic_Control_Zone_Devices_(MUTCD_6F)&oldid=50346.

Missouri Department of Transportation. 2021b. “General Services Specifications (MGS) by Subject.” Accessed November 11, 2021. https://www.modot.org/general-services-specifications-mgs-subject.

Missouri Department of Transportation. 2021c. “Job Special Provisions.” Accessed November 11, 2021. https://spexternal.modot.mo.gov/sites/de/JSP/Forms/JSPByTitle.aspx.

Missouri Department of Transportation. 2021d. “616.12 Work Zone Speed Limits,” Engineering Policy Guide. Accessed December 10, 2021. https://epg.modot.org/index.php/616.12_Work_Zone_Speed_Limits.

Morgan, Rick L. 2003. *Temporary Rumble Strips*. Special Report 140. Albany, NY: New York State Department of Transportation.

Myers Industries. 2021. “ATM Rumble Strips.” Accessed December 9, 2021. https://www.trafficmarkings.com/rumble-strips.html.

Nebraska Department of Transportation. 2017. *Standard Specifications for Highway Construction*. Lincoln, Nebraska.

Nebraska Department of Transportation. 2021. “Standard Plans.” Accessed November 18, 2021. https://dot.nebraska.gov/media/6645/standard.pdf.

New York State Department of Transportation. 2020. *Special Specification for Portable Temporary Rumble Strips*. Engineering Bulletin (EB) 20-047. Albany, New York.

New York State Department of Transportation. 2021. *Highway Design Manual*. Albany, New York.

North Carolina Department of Transportation. 2015. *Temporary Rumble Strips Special Provisions and Detail*. Raleigh, North Carolina.

North Dakota Department of Transportation. 2021. *General Note for Plans [704-500: Portable Rumble Strips (PRS)]*. Bismarck, North Dakota.

Ohio Department of Transportation. 2015. *Temporary Portable Rumble Strips Approved Product List*. Columbus, Ohio.

Ohio Department of Transportation. 2019. "Safety Standard Drawings: Traffic." Accessed November 11, 2021. https://www.dot.state.oh.us/SCDs/Pages/traffic.aspx?&FilterField1=Series&FilterValue1=Maintaining%20Traffic%20%28MT%29.

Oregon Department of Transportation. 2020. *Standard Guidelines for Product Review*. Salem, Oregon.

Oregon Department of Transportation. 2021a. *Standard Specifications for Construction*. Salem, Oregon.

Oregon Department of Transportation. 2021b. "Standard Details (Traffic 4000 Series)." Accessed December 10, 2021. https://www.oregon.gov/odot/Engineering/Pages/Details-Traffic.aspx.

Oregon Department of Transportation. 2021c. *Traffic Control Plans Design Manual*. Salem, Oregon.

Oregon Department of Transportation. 2021d. *Temporary Transverse Rumble Strip Request Form*. Salem, Oregon.

Pennsylvania Department of Transportation. n.d.a. *Raptor Deployment Plan for Temporary Portable Rumble Strips Freeways and Expressways*. Harrisburg, Pennsylvania.

Pennsylvania Department of Transportation. n.d.b. *Raptor Rumble Strip Handling Machine*. Harrisburg, Pennsylvania.

Pennsylvania Department of Transportation. 2021. *Temporary Traffic Control Guidelines*. Publication 213. Harrisburg, Pennsylvania.

Pregibon, Daryl, 1980. "Goodness of Link Tests for Generalized Linear Models." *Journal of the Royal Statistical Society: Series C (Applied Statistics)* 29, No. 1: 15-23. https://www.jstor.org/stable/2346405.

Plastic Safety Systems, Inc. (PSS). 2018. "Roadquake Temporary Portable Rumble Strip: Best Practices for Optimal Use." Accessed December 8, 2021. https://www.streetsmartrental.com/wp-content/uploads/RoadQuake-Best-Practices-2nd-Edition-LR-Nov-26-2018.pdf.

Plastic Safety Systems, Inc. (PSS). 2021. "Raptor." Accessed December 8, 2021. https://pss-innovations.com/safety-products/rumble-strip-systems/roadquake®-2f-temporary-portable-rumble-strip/related-products-folder/raptor.

Richards, Stephen H., Robert C. Wunderlich, and Conrad L. Dudek. 1985. "Field Evaluation of Work Zone Speed Control Techniques." *Transportation Research Record* 1035: 66–78.

Roads & Bridges. N.d. "Ohio Feels The Benefit Of Work-Zone Rumble Strips." Transportation Management. Accessed November 26, 2021. https://www.roadsbridges.com/ohio-feels-benefit-work-zone-rumble-strips.

The Roadway Safety Consortium. N.d. *Guidelines on Managing Speeds in Work Zones*. Washington, D.C.: Federal Highway Administration.

Savolainen, Peter Tarmo, Vivek Reddy, Joseph B. Santos, and Tapan K. Datta. 2009. "Evaluation of Temporary Removable Rumble Strips for Speed Reduction." In *88th Annual Meeting of the Transportation Research Board*, Paper No. 09-1970, Washington, D.C.

Schrock, Steven D., Kevin P. Heaslip, Ming-Heng Wang, Romika Jasrotia, and Robert Rescot. 2010. "Closed-Course Test and Analysis of Vibration and Sound Generated by Temporary Rumble Strips for Short-Term Work Zones." *Transportation Research Record: Journal of the Transportation Research Board* 2169, No. 1: 21-30. https://doi.org/10.3141%2F2169-03.

Schrock, Steven D., Vishal R. Sarikonda, and Eric J. Fitzsimmons. 2016. *Development of Temporary Rumble Strip Specifications*. Report No. K-TRAN: KU-14-6. Lawrence, Kansas: The University of Kansas.

Sharma, Anuj, Tingting Huang, and Peter Savolainen. 2017. *Setting Work Zone Speed Limits*. InTrans Project 15-536. Ames, Iowa: Center for Transportation Research and Education.

Sippel, Brian, and Erin Schoon. 2016. *Phase 1: Temporary Portable Rumble Strips Report*. Madison, Wisconsin: Wisconsin Department of Transportation.

Sommers, Norman M., and Deborah S. McAvoy. 2013. *Improving Work Zone Safety Through Speed Management*. Report No. FHWA/OH-2013/5. Columbus, Ohio: Ohio Department of Transportation.

South Carolina Department of Transportation. 2009. *Supplemental Specifications (Temporary Rumble Strips for Speed Control)*. Columbia, South Carolina.

South Dakota Department of Transportation. 2021. *Traffic Operations Manual*. Pierre, South Dakota.

Strassburg, Troy. 2020. "Portable Rumble Strips for Mills/Overlays." Presentation slides. St. Paul, Minnesota: Minnesota Department of Transportation.

Steel, Robert. 1960. "A Rank Sum Test for Comparing All Pairs of Treatments." *Technometrics* 2: 197–207. https://www.jstor.org/stable/1266545.

Sun, Carlos, Praveen Edara, and Kyle Ervin. 2011. "Elevated-Risk Work Zone Evaluation of Temporary Rumble Strips." *Journal of Transportation Safety and Security* 3, No. 3: 157–173. https://doi.org/10.1080/19439962.2011.594934.

Sun, Xiaoduan, and M. Ashifur Rahman. 2021. *Impact of Center Line Rumble Strips and Shoulder Rumble Strips on all Roadway Departure Crashes in Louisiana Two-lane Highways*. Report No. FHWA/LA 17/648. Washington, D.C.: Federal High Administration.

Tennessee Department of Transportation. n.d. *Specification for Temporary Portable Rumble Strips (TPRS) and Hitch Mounted Carrier System (Carrier)*. Nashville, Tennessee.

Texas Department of Transportation. n.d. "Temporary Rumble Strips." Presentation slides. Austin, Texas.

Texas Department of Transportation. 2021. "Traffic Standards (English)." Accessed December 10, 2021. http://www.dot.state.tx.us/insdtdot/orgchart/cmd/cserve/standard/toc.htm.

Transportation Research Board (TRB). N.d. "Transportation Benefit-Cost Analysis." Transportation Economics Committee. Accessed November 29, 2021. http://bca.transportationeconomics.org/types-of-measures/benefit-cost-ratio.

Ullman, Gerald L., Michael Pratt, Srinivas Geedipally, Bahar Dadashova, Richard J. Porter, Juan Medina, and Michael D. Fontaine. 2018. *Analysis of Work Zone Crash Characteristics and Countermeasures*. NCHRP Web Only Document 240. Washington, D.C.: The National Academies Press. https://doi.org/10.17226/25006.

Virginia Department of Transportation. 2018. *Portable Temporary Rumble Strips (PTRS)*. Instructional and Informational Memorandum No. IIM-TE-386.1. Richmond, Virginia.

Virginia Department of Transportation. 2020a. *Road and Bridge Specifications*. Richmond, Virginia.

Virginia Department of Transportation. 2020b. *Virginia Work Area Protection Manual*. Richmond, Virginia.

Wang, Ming-Heng, Steven D. Schrock, Yong Bai, and Robert A. Rescot. 2011. *Evaluation of Innovative Traffic Safety Devices at Short-Term Zones*. Report No. K-TRAN: KU-09-5. Lawrence, Kansas: The University of Kansas.

Wisconsin Department of Transportation. n.d. *Special Provision [Temporary Rumble Strips (Orange) in Advance of Lane Closure, SPV]*. Madison, Wisconsin.

Wisconsin Department of Transportation. 2019. *Temporary Portable Rumble Strips-One Array*. Madison, Wisconsin.

Wisconsin Department of Transportation. 2021a. "Standard Detail Drawings." Accessed December 10, 2021. https://wisconsindot.gov/rdwy/sdd/sd-00-00toc.pdf.

Wisconsin Department of Transportation. 2021b. "Work Zone Traffic Control Devices." Accessed November 11, 2021. https://wisconsindot.gov/Documents/doing-bus/eng-consultants/cnslt-rsrces/tools/appr-prod/ap-current/work-zone-tc.pdf.

Yang, Hong, Kaan Ozbay, and Bekir Bartin. 2015. “Effectiveness of Temporary Rumble Strips in Alerting Motorists in Short-Term Surveying Work Zones.” *Journal of Transportation Engineering* 141, No. 10. https://doi.org/10.1061/(asce)te.1943-5436.0000789.

APPENDIX A. SUMMARY OF EXISTING LITERATURE FOR TEMPORARY RUMBLE STRIPS

Table A-1. Summary of existing literature for temporary rumble strips

State	Title	Reference	Summary
-	Guidance for the Use of Temporary Rumble Strips in Work Zones	ATSSA 2013	Includes information on types of rumble strips and each type's advantages and disadvantages. Configurations and layouts, including signs and placements, are provided.
-	RoadQuake Best Practices for Optimal Use	PSS 2018	Provides general information regarding RoadQuake devices as well as suitable conditions and best practices. Indicates RoadQuake TPRS should not be used on surfaces with fresh seal coat, gravel roads, or fresh asphalt. Heavily rutted roads, oil bleeding asphalts, bridge decks, and scarified roads require discretion before installation of RoadQuake TPRS. Includes detail drawings for optimum layouts under various conditions and example specification.
-	Raptor	PSS 2021	Lists features and other information about the Raptor rumble strip device, including dimensions, coloring, limitations, overall layout, and more. This machine is designed for use with RoadQuake 2F TPRS.
California, Missouri, Virginia	State Examples for the Application of Portable Temporary Rumble Strips (PTRS) in Work Zones	ATSSA 2020	Details Virginia, Missouri, and California's DOT TPRS requirements, layout applications, and other specifications.
Georgia	Temporary Portable Rumble Strips	Hancock 2020	Presentation slides of example implementation of TPRS on SR 20. Results indicated that 80 percent to 90 percent of vehicles slowed down at the rumble strips. Driver survey found that TPRS caught drivers' attention and led them to reduce their speed.

State	Title	Reference	Summary
Illinois	Minimizing Traffic-Related Work Zone Crashes in Illinois	El-Rayes et al. 2013	The study conducted an evaluation for three types of rumble strips in terms of sound levels and ease of use. The study also evaluated various layouts for temporary rumble strips. Results indicated that sound levels of auditory alerts were sufficient to help get drivers' attention.
Iowa	Field Measurements on the Effect of Temporary Rumble Strips in Work Zone Flagging Operations	Hawkins and Knickerbocker 2017	Analyzed impacts to driver behavior (including braking and avoidance habits, and speeds) on three types of layouts (no rumble strips, Developmental Specification layout with two sets of TPRS, and a modified TPRS layout with one set of TPRS and "Rumble Strips Ahead" sign). Results showed an increase in braking percentage and a decrease in vehicle speed, with mean speed reductions of 5.5 mph (Developmental Specification layout with two sets of TPRS) and 3.7 mph (modified layout with one set of TPRS and "Rumble Strips Ahead" sign) compared to a 0.1 mph increase in mean speed when TPRS were not used.
Kansas	Guidelines for the Application of Removable Rumble Strips	Meyer 2006b	Assessed the viability of long-term temporary rumble strips in terms of vehicle speed, vehicle vibration, in-vehicle noise, roadside noise, cost, durability, and installation and removal processes. The removable strips required adhesives but were comparable in performance to the original asphalt temporary rumble strips, with greater ease of installation and removal. Results indicated the use of long-term temporary rumble strips led to speed reductions of 3.9 mph to 8.7 mph.
Kansas	Closed-Course Test and Analysis of Vibration and Sound Generated by Temporary Rumble Strips for Short-Term Work Zones	Schrock et al. 2010	Compared permanent rumble strips, portable plastic rumble strips, and adhesive rubberized polymer rumble strips with respect to generating vibrations of the steering wheel and roadside sound in a closed-course test. Test results indicated portable plastic rumble strips performed better on cars than trucks for creating vibrations and increasing sound levels in the vehicle.

State	Title	Reference	Summary
Kansas	Development of Temporary Rumble Strip Specifications	Schrock et al. 2016	Two different types of rumble strips were tested on a closed circuit. Data for movement, rotation, and sound generated by each full-size car and tandem-axle truck were collected. A decision matrix was developed for vendors and researchers to select the optimum temporary rumble strip type based on speed, AADT, and daily truck traffic.
Kansas	Evaluation of Innovative Traffic Safety Devices at Short-Term Work Zones	Wang et al. 2011	Conducted closed-course circuit test of portable plastic rumble strips and showed a speed reduction of between 4.6 mph and 11.4 mph for cars and between 5.0 mph and 11.7 mph for trucks. Approximately 5 percent of vehicles swerved around the strips.
Minnesota	Portable Rumble Strips for Mill/ Overlays	Strassburg 2020	Presentation that describes use of TPRS and provides standard drawing on typical section and pilot car rumble strip layout.
Missouri	Elevated-Risk Work Zone Evaluation of Temporary. Rumble Strips	Sun et al. 2011	Information on the driving behavior and vehicle speeds with TPRS (angled and perpendicular shape) was collected. Results indicated that 23 percent of drivers on angled strips and 21 percent of drivers on perpendicular strips braked. In contrast, 12 percent of drivers braked in work zones with no rumble strips. Speeds for vehicles that braked decreased by an average of 3.71 mph. Speed compliance increased by 2.9 percent with the use of TPRS. Relative to the angled strips, perpendicular strips did not deflect very much by in the impact test.
New Jersey	Effectiveness of Temporary Rumble Strips in Alerting Motorists in Short-Term Surveying Work Zones	Yang et al. 2015	Assessed the effect of temporary rumble strips at eight short-term survey work zones. Results indicated that mean operating speeds decreased by 10 percent in the right lane and 13.8 percent in the left lane. Speed compliance increased by 18.7 percent in the right lane and 29.5 percent in the left lane. In addition, the proportion of vehicles that braked increased by an average of 12 percent.

State	Title	Reference	Summary
Texas	Evaluation of Speed Displays and Rumble Strips at Rural Maintenance Work Zones	Fontaine and Carlson 2001	This study was designed to compare the effect of temporary rumble strips and speed displays on rural work zones. The speed display was shown to be more effective than temporary rumble strips, though notably only speed was examined. Furthermore, the temporary rumble strips required adhesive and were not reusable which relates to cost. The authors concluded that temporary rumble strips have a limited application due to the duration of the installation (40 minutes) compared to 10 minutes for speed display.
Texas	Field Evaluation of Work Zone Speed Control Techniques	Richards et al. 1985	Temporary rumble strips were compared with other speed control methods such as flagging, changeable message signs, patrol cars, etc. The author compared traffic mean speeds for various speed control methods, and rumble strips did not show much effect. The author concluded that the rumble strips were not as effective as some of the other treatments.
Texas	Temporary Rumble Strips	Texas DOT n.d.	Presentation slides that provide overview of Texas DOT practices for temporary rumble strips which are used to ensure drivers' awareness of upcoming work zones for flagging operations or lane closures. Temporary rumble strips are currently not allowed on freeways or roads with posted speed limits exceeding 70 mph. Texas DOT has found that proper installation is required to achieve effective operation.
Texas	Analysis of Work Zone Crash Characteristics and Countermeasures	Ullman et al. 2018	End of Queue Warning Systems (EOQWS) were tested over 4 years in conjunction with TPRS on I-35 in Texas. In queued conditions, the following CMFs were reported: 0.40 (TPRS only) and 0.47 (EOQWS and TPRS used together). For non-queued conditions, the CMFs were determined to not be statistically significant with the following values: 0.89 (TPRS only) and 0.72 (EOQWS and TPRS used together).

State	Title	Reference	Summary
Washington	Temporary Rumble Strips	American Road and Transportation Builders Association 2021	Summarizes Washington State DOT experience with temporary rumble strips. Products evaluated include tape and Type 2 buttons. Tape needed to be deployed in multiple layers to achieve a noticeable rumble effect, and some installation difficulties were noted (for example, need to heat the pavement to install). Type 2 buttons required a lot of labor to install and maintain.
Wisconsin	Phase 1: Temporary Portable Rumble Strips Report	Sippel and Schoon 2016	Data were collected from real work zones to compare advanced warning signs with TPRS or without TPRS. Results indicated that 33 percent to 39 percent of drivers braked with TPRS. In contrast only 3 percent braked without TPRS. 85th percentile speeds were reduced by 4.7 mph to 5.0 mph compared to a 1.5 mph decrease without TPRS. Bureau of Traffic Operations recommended use of TPRS on all static or slow-moving flagging operations with contractor discretion for deployment on moving operations.

APPENDIX B. SUMMARY OF DOT STANDARDS AND SPECIFICATIONS FOR TEMPORARY RUMBLE STRIPS

Table B-1. Summary of DOT standards and specifications for temporary rumble strips

State	Title	Reference	Summary
Alabama	Design Bureau Special Drawing (2002c: Details for Traffic Control for Two Lane Highways)	Alabama DOT 2019	Provides detail for a portable rumble strip set and information for incorporating rumble strips into traffic control.
Arizona	Temporary and Portable Rumble Strips	Arizona DOT 2021	Provides requirements for temporary rumble strips for materials, deployment, and use on lane closure plans. Includes layout drawings for two-lane and divided highways. Also provides requirements for TPRS Rapid Deployment and Transport Device (RDTD).
California	Implementation of Portable Transverse Rumble Strips (Memorandum)	Caltrans 2014	As indicated in this memorandum, the use of portable transverse rumble strips is required for all construction, maintenance, and encroachment permit flagging operations on two-lane conventional highways (with some exceptions). Exceptions include work zone duration of four hours or less, posted speed limit below 45 mph, work for emergency response, and snow or ice.
California	Flagging Instruction Handbook	Caltrans 2018a	Provides guidance for flaggers regarding temporary rumble strips on two-lane highways.

State	Title	Reference	Summary
California	Specifications on Use of Portable Transverse Rumble Strips	Caltrans 2018b	Approved rumble strips include RoadQuake 2 and RoadQuake 2F Folding Temporary Portable Rumble Strip. Portable rumble strips cannot be placed on sharp curves or at pedestrian crossings. Portable transverse rumble strips are not required for any one of the following conditions: roadwork durations of four hours or less, speed zones below 45 mph, emergency work, snow/icy conditions. Rumble strips should be replaced if Engineer determines they no longer give effective alerts.
California	2018 Standard Plans (T13: Traffic Control System for Lane Closure on Two-Lane Conventional Highways)	Caltrans 2018c	Includes signage and detail for portable transverse rumble strips.
California	California Construction Manual (Chapter 4: Construction Details, Section 12: Temporary Traffic Control, 4-1202B(18): Portable Transverse Rumble Strips, 4-1203B (18): Portable Transverse Rumble Strips, and 4-1206B (17): Portable Transverse Rumble Strip)	Caltrans 2021	Provides a few requirements for placing the portable transverse rumble strips. Manufacturer's instructions should be followed. Portable transverse rumble strips cannot be placed on sharp curves and must be either black or orange. They are paid for using a contract bid item.
Colorado	Temporary Rumble Strips Testimonial	Colorado DOT 2016	An employee of Colorado DOT is satisfied with the performance of TPRS at slowing traffic. Employee indicated that vehicles slowed down, and rumble strip movements could be corrected.
Colorado	Standard Plans [No. S-630-5: Portable Rumble Strips (Temporary)]	Colorado DOT 2019	Rumble strips shall be 0.75 inches in thickness, and there should be 40 feet between rumble strips in a portable rumble strip set.
Florida	Design Standards (Index 600: General Information for Traffic Control Through Work Zones)	Florida DOT 2021a	Includes detail for "Rumble Strips Ahead" sign.

State	Title	Reference	Summary
Florida	Standard Plans for Road Construction (Index: 102-603, Two-Lane, Two-Way Work within the Travel Way, Sheet 1)	Florida DOT 2021b	Provides layouts for two types of temporary rumble strip sets: removable striping tape or portable.
Florida	Standard Specifications for Road and Bridge Construction (Section 102-9.17: Temporary Raised Rumble Strip Set)	Florida DOT 2022	Temporary raised rumble strips should be installed in accordance with manufacturer's recommendations, and color and type should be uniform in the work zone.
Georgia	Supplemental Specification (Section 869: Temporary Portable Rumble Strips)	Georgia DOT 2014	Describes specifications for furnishing and installing TPRS and outlines rumble strip material requirements. TPRS must experience minimal movement at speeds up to 70 mph.
Georgia	Special Construction Detail (Traffic Control Detail for Two lane Closure on Two-lane Highway)	Georgia DOT 2017	Includes detail drawings demonstrating the use of temporary rumble strips on lane closures.
Georgia	Supplemental Specification (Section 150: Install, Maintain, and Remove Temporary Portable Rumble Strips – Department Provided)	Georgia DOT 2020	Provides information on the installation, maintenance, and removal of temporary rumble strips when provided by the Department.
Idaho	Idaho 2021 Supplemental Specifications (Section 626: Temporary Traffic Control)	Idaho Transportation Department 2021	TPRS should comply with manufacturer's instructions. They should be black, orange, or white in color and should not require adhesives or anchors for installation. They must weigh at least 100 pounds, be 0.75 inches thick or less, and be at least 10 inches wide. They should be suitable for 80 mph speed limit zones.

State	Title	Reference	Summary
Illinois	Temporary Rumble Strips (Special)	Illinois DOT 2014	Specification indicates that Temporary Rumble Strips (Special) must meet the following requirements: consist of preformed plastic pavement marking (6 layers), conform to Article 780.07, and placed at direction of Engineer. Payment based on one set of three temporary rumble strips across one lane.
Illinois	Detail for Temporary Rumble Strips (Special)	Illinois DOT 2017	Each set of rumble strips contains three strips, each spanning 11' perpendicular to the road. Spacing between each rumble is 20'.
Illinois	Highway Standards for Traffic Control (Standard 701321-13: Lane Closure, 2L, 2W, Bridge Repair, for Speeds ≥ 45 and Standard 701321-18: Lane Closure, 2L, 2W, Bridge Repair with Barrier)	Illinois DOT 2020	Provides standards for placement of temporary rumble strips and other traffic control devices during lane closures for repairs.
Illinois	Highway Standards for Traffic Control (Standard 701428: Traffic Control Setup and Removal Freeway/Expressway)	Illinois DOT 2020	Provides standard layout for placement and removal of traffic control for lane closures on freeways and expressways (ADT greater than 25,000). Includes work trucks with arrow boards and TMAs.
Illinois	Standard Specifications for Road and Bridge Construction [701.15(k): Temporary Rumble Strips and 1106.03: Temporary Rumble Strips]	Illinois DOT 2022	Specifies material requirements for temporary rumble strips. Temporary rumble strips should be black, made from high strength polycarbonate, and held in place by adhesive.

State	Title	Reference	Summary
Indiana	Indiana Design Manual 2013 [Section 503-3.05(07): Temporary Transverse Rumble Strips]	Indiana DOT 2021a	Use temporary buzz strips or TPRS on freeway bridge work zones with nearby traffic. Temporary transverse rumble strips should also be considered for possible use for situations involving flagging, non-freeway lane merge, or a long work zone with intermittent areas of no work. Temporary buzz strips may be useful for long-term stationary work zones, while TPRS could be useful for flagging operations, freeway work zones with possible queuing, or a long work zone with a moving work area.
Indiana	Special Provision (Section 801-T-209: Temporary Portable Rumble Strips)	Indiana DOT 2021b	Provides specifications for TPRS. Positioning of the rumble strips shall be corrected if any strip moves by more than 6 inches during the work period. TPRS shall be able to withstand vehicles up to 80,000 pounds with minimal movement and should be less than 1 inch in height.
Indiana	Standard Drawings (E801-TCDV-09: Temporary Buzz Strips)	Indiana DOT 2021c	Provides installation standard of temporary buzz strips in distance on traffic control. Each set (7 feet 4 inches in overall length) consists of 6 strips each 0.25 inches in height, and 8 inches in width, with 8 inches between strips. The distance between each set of temporary buzz strips decreases with the flow of traffic from 800 feet to 150 feet to 80 feet.
Indiana	Standard Specifications (Section 801.12a.4 : Temporary Buzz Strips)	Indiana DOT 2022	Defines temporary buzz strips as “a set of transverse marking constructed of removable or durable marking materials.” Materials shall conform with 808.07(b).

State	Title	Reference	Summary
Iowa	Standard Road Plans – TC Series (TC-214: Lane Closures with Flaggers for use with Pilot Car)	Iowa DOT 2021a	Provides layout drawing for temporary rumble strips to accommodate flagger signage on lane closures (for use with pilot car). Distance between signage varies by posted speed limit.
Iowa	Standard Road Plans – TC Series (TC-218: Lane Closure with Pilot Car and Flagger Operated Signals)	Iowa DOT 2021a	Provides drawing on lane closures with pilot cars and flagger operated signals. States that TPRS panels should be used for traffic control exceeding 2 hours.
Iowa	Standard Specifications (Section 2528.01L: Temporary Portable Rumble Strips)	Iowa DOT 2021b	Provides standards on placement, maintenance, and removal of TPRS. A temporary rumble strip panel consists of three individual rumble strips placed 15 to 20 feet apart from each other. TPRS alignment should be maintained.
Iowa	Standard Specifications (Section 4188.08: Temporary Portable Rumble Strips)	Iowa DOT 2021b	Provides requirements for TPRS. TPRS should be installed without nails or adhesive, usable for speeds of 70 mph or less, and installed and removed in under five minutes.
Kansas	STA Certification of No Suitable Alternative for the Purchase of RoadQuake 2 Rumble Strips	Kansas DOT 2013	Provides tabular summary of several products for temporary rumble strips product based on formal and informal evaluations. Certifies that there is no appropriate suitable alternative to RoadQuake 2 TPRS. Outlines several reasons for this conclusion including the ease of use, performance, and reliability.
Kansas	Special Provision to the Standard Specifications (15-17009: Portable Reusable Temporary Rumble Strips)	Kansas DOT 2015	Provides the required in-place performance characteristics of TPRS for different device classes based on vehicle speed. Maximum average relative longitudinal movement is 0.5 inches to 1.5 inches (based on device class which is linked to speed) while average lateral movement is restricted to edges of 12-foot lane.

State	Title	Reference	Summary
Kansas	Special Provisions to the Standard Specifications (15-08001-R03: Work Zone Traffic Control and Safety; TE730: Traffic Control; Flagger or Pilot Car)	Kansas DOT 2015	Provides traffic control plan for flaggers or pilot cars with the option of using temporary rumble strips. Temporary rumble strips can be used instead of lead-in channelizing devices when the roadway width (including paved shoulders) is less than or equal to 30 feet.
Kentucky	Special Note for Temporary Portable Rumble Strips (Contract ID No. 212140)	Kentucky Transportation Cabinet 2021	Contract Addendum that provides guidance on furnishing, installing, relocating, and maintaining and removing TPRS at the locations shown on the plans. Requires one group of TPRS in each direction when multiple work zones are within one mile and color should be distinct from pavement color. Includes layout drawing.
Maine	Special Provisions (Section 652: Maintenance of Traffic)	Maine DOT 2018	Provides standards on providing, relocating, maintaining, and removing TPRS. The use of rumble strips requires an additional work zone sign stating "Caution Rumble Strips" in the set of signs leading up to the rumble strips. Signs must meet all applicable MUTCD standards. Requires one group of TPRS in each direction when multiple work zones are within one mile.
Maryland	Portable Rumble Strips Product Lists	Maryland DOT SHA 2020	RoadQuake 2 folding and TraFix Alert High Speed Rumble Strip (8450-HS) have been approved by Maryland DOT State Highway Agency (SHA).
Maryland	Guidelines for Temporary Portable Rumble Strips (TPRS) (6-F10: Temporary Portable Rumble Strips)	Maryland DOT SHA 2021a	Specifies guidelines for implementing TPRS in work zones on Maryland roadways. TPRS are used to accommodate different types of lane closures. Includes table of spacing between TPRS based on speed limit. Typical applications for flaggers and lane closures drawing are provided.

State	Title	Reference	Summary
Maryland	Special Provision (104.27: Temporary Portable Rumble Strips)	Maryland DOT SHA 2021b	Specifies the requirements to furnish, install, maintain, adjust, and remove TPRS. Includes separate pay item to remove and relocate TPRS.
Massachusetts	Work Zone Safety: Temporary Traffic Control (Figure 24-1: Multilane Divided Roadway Placement of Temporary Portable Rumble Strips)	Massachusetts DOT 2017	Includes detail drawings for TPRS layout on multi-lane divided highway. Rumble strip separation varies based on speed. TPRS sets must include a minimum of 3 strips.
Massachusetts	Item 854.6 Temporary Portable Rumble Strips	Massachusetts DOT 2021	Specifies the requirements for TPRS including material, construction method, method of measurement, and basis of payment. TPRS should be certified for use by manufacturer for speeds of at least 70 mph.
Michigan	Michigan DOT Standard Specifications for Construction [Section 812.03.D.14: Temporary Rumble Strips (Orange)]	Michigan DOT 2020	Provides requirements for temporary rumble strips in advance of work zones. Material is polymer with pre-applied adhesive, and dimensions are 0.25 inches thick by 4 inches wide. Contractor must place 3 sets of 9 rumble strips before the lane closure in each direction when there is a lane closure or crossover shift on a freeway work zone at the same location for at least 14 consecutive days. Also provides guidance (with drawing) on placement of temporary rumble strips (orange) in advance of a stop condition.
Michigan	Special Provisions (20SP-812D-01: Temporary Portable Rumble Strips)	Michigan DOT 2021a	Provides requirements for use of TPRS on non-freeway projects. TPRS must be used “on all Trunkline Regulating projects with existing speed limits 45 mph or higher where traffic regulating will be in place longer than 4 hours.” Requires use of RoadQuake 2F. TPRS should perform at speeds up to 65 mph. Includes table for spacing based on normal speed limit. Provides separate pay items for furnishing and operating TPRS.

State	Title	Reference	Summary
Michigan	Work Zone Mobility Manual (6.01.19: Transverse Temporary Rumble Strips)	Michigan DOT 2021b	Provides guidance for fixed transverse temporary rumble strips (freeway and non-freeway) and portable transverse temporary rumble strips (non-freeway). On freeways, fixed transverse temporary rumble strips should be considered for work zones at least three days in duration with sight distance or queuing concerns. Fixed transverse temporary rumble strips are used on non-freeways when a stop condition is established or changed. TPRS may be used when speed limit is 65 mph or less for conditions such as emergency traffic control, traffic regulating operations, temporary lane closures, and traffic shifts. For long-term temporary rumble strips, special provision for maintaining traffic should include off peak times for stationary and/or mobile lane closures, with mobile attenuators included.
Minnesota	Two-Lane, Two-Way Roads (Field Manual)	Minnesota DOT 2018	Mentions TPRS set and standard spacing between strips while performing lane closures with flagging in a two-lane road. Includes layout drawing for TPRS with three strips spaced based on posted speed limit. TPRS should be white, black, or orange in color.
Minnesota	Special Provisions (S-201 (2563): Portable Rumble Strips)	Minnesota DOT 2020	Provides specifications for TPRS. One set consisting of three portable rumble strips should be placed at each active flagger station. Payment is by lump sum.
Minnesota	Special Provisions (S-203 (2563): Temporary Rumble Strips)	Minnesota DOT 2020	Provides specifications for temporary rumble strips. Temporary rumble strips should be white and 4 feet long. Payment is made per set of ten strips (five in each wheel path). Materials are in accordance with Approved Product List.

State	Title	Reference	Summary
Minnesota	Approved/Qualified Products Temporary Rumble Strips (Temporary Traffic Control Devices)	Minnesota DOT 2021a	Lists approved products for temporary rumble strips and portable rumble strips. Includes RoadQuake 2, RoadQuake 2F, TrafFix Alert, and TrafFix Alert High Speed Rumble Strip for TPRS and Rumble Strip Model 3708 from Pexco. Portable rumble strips should either be the same color as the pavement or be white, black, or orange.
Minnesota	Long Term Typical Applications (Two-Lane, Two-Way) (Drawing 06: Temporary Rumble Strips)	Minnesota DOT 2021b	Drawing that specifies temporary rumble strip placement relative to other signage based on posted speed limit. “Rumble Strips Ahead” sign is optional.
Minnesota	Long Term Typical Applications (Two-Lane, Two-Way) (Drawing 14: Portable Rumbles Strips in Advance of Flagger)	Minnesota DOT 2021b	Drawing that specifies TPRS placement in advance of flagger relative to other signage and based on posted speed limit.
Minnesota	Minnesota Manual on Uniform Traffic Control Devices (6F.87 Rumble Strips)	Minnesota DOT 2021c	Provides guidance for transverse and longitudinal rumble strips.
Mississippi	Special Provision (No. 907-619-6: Temporary Portable Rumble Strips)	Mississippi DOT 2018	Describes product, manufacturer, and construction requirements and includes a detail drawing for TPRS. One set of three strips spaced at 15 feet should be placed in each lane. Placement of the rumbles and signage varies based on speed and urban or rural classification.
Missouri	MoDOT EPG (Section 616.6.87: Temporary Rumble Strips)	Missouri DOT 2021a	Provides layout drawings for placement of temporary rumble strips for flagging operations on two-lane highways and lane closures on multi-lane highways. Spacing between rumble strips and other dimensions vary based on posted speed limit.

State	Title	Reference	Summary
Missouri	General Services Specifications (MGS 14-01: Temporary Long-Term Rumble Strips)	Missouri DOT 2021b	Defines temporary long-term rumble strips and provides instructions for materials and construction. Long-term rumble strips should consist of polymer material; be black, orange, or white; and have adhesive backing.
Missouri	General Services Specifications (MGS 14-02: Temporary Short-Term Rumble Strips)	Missouri DOT 2021b	Defines temporary short-term rumble strips and provides instruction on materials and construction. Temporary short-term rumble strips should be orange and listed on Texas DOT's Compliant Work Zone Traffic Control Devices list.
Missouri	Job Special Provisions (JSP1304: Temporary Long-Term Rumble Strips)	Missouri DOT 2021c	Long-term temporary rumble strips should be polymer material and orange in color. They should be placed based on plans or Engineer's direction in accordance with manufacturer recommendations. A set consists of five strips, and payment is made per set.
Missouri	Job Special Provisions (JSP1305: Temporary Short-Term Rumble Strips)	Missouri DOT 2021c	Short-term temporary rumble strips should be polymer material and orange in color. They should be placed based on plans or Engineer's direction in accordance with manufacturer recommendations. A set consists of three strips, and payment is made per set.
Nebraska	Standard Specifications for Highway Construction (422.03.8: Temporary Rumble Strips)	Nebraska DOT 2017	Temporary rumble strips should be placed as shown in contract, and material must be allowed to harden before opening lane to traffic.
Nebraska	Standard Plans (No. 920-R7: Traffic Control, Construction, and Maintenance)	Nebraska DOT 2021	Provides layout drawing for temporary rumble strips (10 strips per wheel path). Materials can be asphalt, epoxy and aggregate, or other material.

State	Title	Reference	Summary
New York	Engineering Bulletin [EB20-047: Special Specification for Portable Temporary Rumble Strips (PTRS)]	New York State DOT 2020	Provides special specification for TPRS, including drawings for flagger operation on two-lane highway and lane closure on multi-lane highway. Material should be thermoset cast urethane, engineered polymers, or rubber materials. TPRS should be black. Approved models include RoadQuake 2 or 2F, TrafFix Alert High Speed Rumble Strips, or equivalent. Sets include three strips. Payment is made by lump sum.
New York	Highway Design Manual [16.3.7: Portable Temporary Rumble Strips (PTRS)]	New York State DOT 2021	Provides guidance for use of TPRS. Conditions that warrant consideration of TPRS include posted speed limit of 40 mph or higher, lane drop on multi-lane highway, or flagger operation. TPRS should not be used on seal coat, sharp curves, or rutted pavement. TPRS spacing varies based on posted speed limit.
North Carolina	Temporary Rumble Strips Special Provisions and Detail	North Carolina DOT 2015	Provides specifications for use of temporary rumble strips, including detail drawing. Temporary rumble strips should be rubber and black, black and white (combination), or white and orange (combination) in color. Adhesives should not be used. Two sets of three strips per lane are placed. Spacing varies based on speed.
North Dakota	General Note for Plans [704-500: Portable Rumble Strips (PRS)]	North Dakota DOT 2021	Provides notes about installing and deploying TPRS. TPRS are to be installed when the following signs are used: “Be Prepared to Stop” and “Flagger.” Adhesives should not be used. A set of TPRS includes at least three individual strips. Payment is made for each set.
Ohio	Approved-Temporary-Portable-Rumble-Strips	Ohio DOT 2015	Provides list of approved TPRS products. There are only two products on the list: RoadQuake 2 and RoadQuake 2F, both made by Plastic Safety Systems, Inc.

State	Title	Reference	Summary
Ohio	Standard Construction Drawings (Traffic) (MT-097.20: Temporary Portable Rumble Strips for Use with 1-Lane 2-Way Operation Using Flaggers)	Ohio DOT 2019	Provides layout drawing for TPRS on flagger operations. Two sets of three strips (strip spacing 6 feet 8 inches) are used. Spacing between sets varies based on speed. Conditions for use include two-lane highways, short-term duration, work crews present, and use of one lane two-way traffic. TPRS should not be used on wet or icy pavement, rutted pavement, or on chip seals. TPRS should be removed if erratic driver behavior is observed. Placement should be done using flaggers after work zone warning signs are installed.
Oregon	Standard Guidelines for Product Review (Section 00225.13i: Transverse Rumble Strips, Temporary)	Oregon DOT 2020	Defines materials and standards for temporary rumble strips. Temporary rumble strips should be deployed by one or more people within 10 minutes without the use of adhesives. Includes instructions on how to apply for Qualified Products List (QPL).
Oregon	Oregon Standard Specifications for Construction (00225: Temporary Pavement Marking)	Oregon DOT 2021a	Provides specifications regarding installation, maintenance, reposition, and replacement of temporary transverse rumble strips. Product must be from Qualified Product List (QPL) or Conditional Use List. Payment is based on length.
Oregon	Standard Details (Traffic 4000 Series) (Detail 4710: Temporary Transverse Rumble Strips)	Oregon DOT 2021b	Provides technical details on portable transverse rumble strip clusters (for use on pavement surfaces). Options include raised transverse rumble strips (thermoplastic or removable tape) for wearing course, milled transverse rumble strips for base course, or portable transverse rumble strips for pavement surface. Includes layout drawing for location of rumble strips.

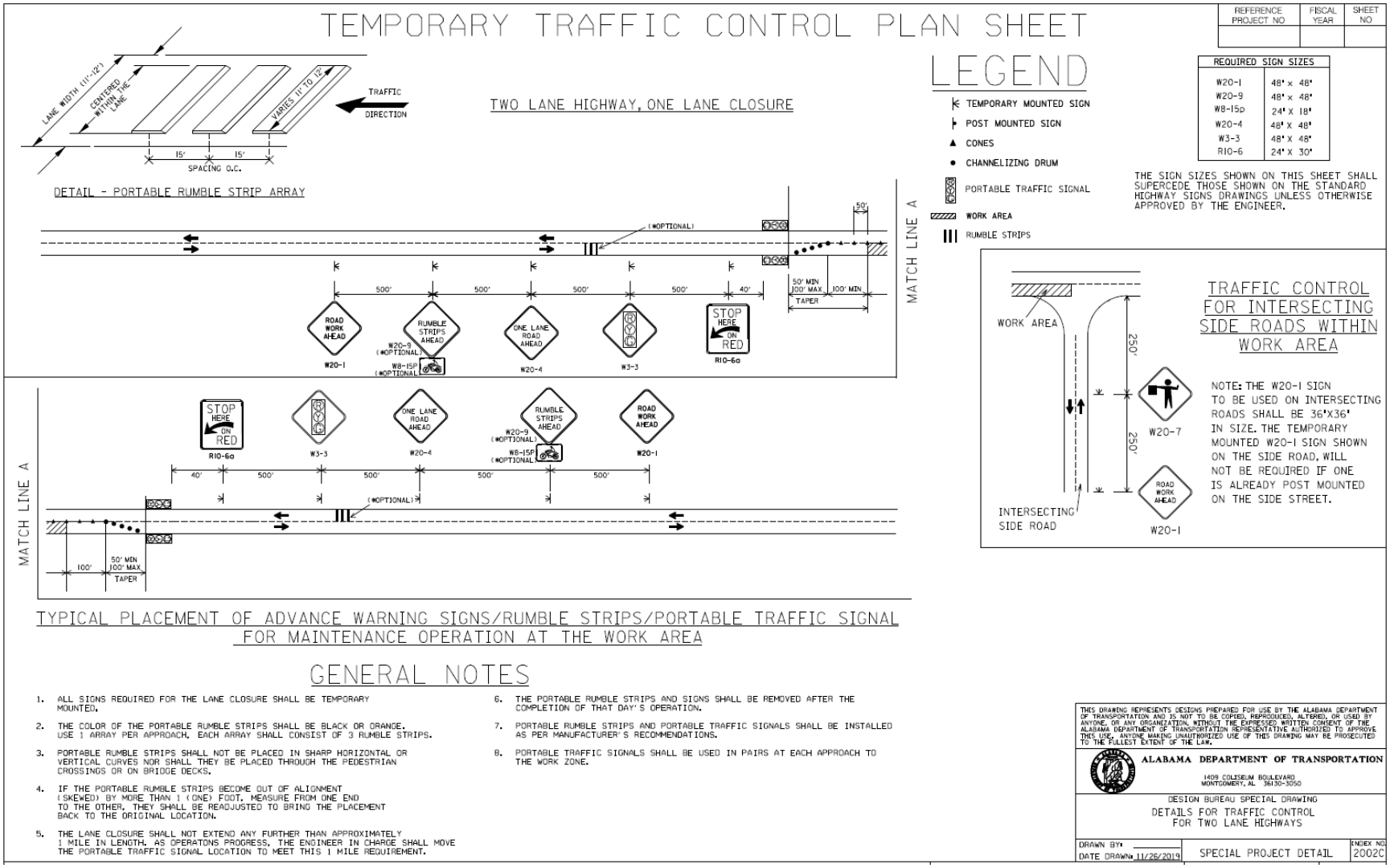
State	Title	Reference	Summary
Oregon	Standard Details (Traffic 4000 Series) (Detail 4715: 2-Lane, 2-Way Roadways One Lane Closure with Rumble Strips)	Oregon DOT 2021b	Provides layout for use of temporary rumble strips for one lane closure on 2-lane, 2-way roadways.
Oregon	Traffic Control Plans Design Manual (Section 3.4.18: Rumble Strips)	Oregon DOT 2021c	Provides designer guidance for use of Temporary Transverse Rumble Strips (TTRS). Approval for use of TTRS is required, except for short-term daylight work. States that portable strips are not intended for extended stationary use but for only daily use and should be picked up at the end of each shift.
Oregon	Temporary Transverse Rumble Strip Request Form	Oregon DOT 2021d	Form to request use of TTRS in a work zone on an Oregon State Highway. Not required for short-term daylight work. Requires approval of Region Traffic Engineer for portable TTRS during intermediate-term work and approval of State Traffic-Roadway Engineer for all other TTRS installations.
Pennsylvania	Raptor Deployment Plan for Temporary Portable Rumble Strips Freeways and Expressways	Pennsylvania DOT n.d.a.	Layout drawing for placement of TPRS using Raptor deployment device.
Pennsylvania	Raptor Rumble Strip Handling Machine	Pennsylvania DOT n.d.b.	Poster for pilot safety initiative on using Raptor machine for deploying and removing TPRS in work zones.
Pennsylvania	Temporary Traffic Control Guidelines (Publication 213) [General Application (04-A): Temporary Portable Rumble Strips Conventional Highways and General Application (04-B): Temporary Portable Rumble Strips Freeways and Expressways]	Pennsylvania DOT 2021	Provides layout drawings for TPRS on conventional highways, expressways, and freeways. TPRS should only be used on short-term lane closures when workers are present. Color may be black, white, or orange. Sign spacing varies based on speed.

State	Title	Reference	Summary
South Carolina	Supplemental Specifications (Temporary Rumble Strips for Speed Control)	South Carolina DOT 2009	Describes requirements, installation, method of measurement, and basis of payment for temporary rumble strips. Uses two layers of temporary pavement marking tape (minimum thickness 300 mils, orange in color). Three sets of ten strips are used. Payment is made per linear foot.
South Dakota	Traffic Operations Manual (Temporary Rumble Strips)	South Dakota DOT 2021	Provides guidance for the use of temporary rumble strips by staff. Only one brand of products is currently approved with two variations: RoadQuake 2 and RoadQuake 2F. Two sets of three strips are used, with spacing based on speed. “Rumble Strips Ahead” sign is used. They can be used on flagger operations and lane closures. Temporary rumble strips should not be used on seal coat or rutted pavement.
Tennessee	Specification for Temporary Portable Rumble Strips (TPRS) and Hitch Mounted Carrier System (Carrier)	Tennessee DOT n.d.	Minimum requirements for TPRS construction, maintenance, and utility operations. The temperature is limited to between 0°F and 120°F. Speed limit should not exceed 70 mph. Hitch mounted carrier should be able to carry six TPRS.
Texas	Standard Drawing (WZ(RS)-16: Temporary Rumble Strips)	Texas DOT 2021	Provides layout drawings for temporary rumble strips for one-lane two-way application and lane closure. Temporary rumble strip sets are placed in sets of three strips. Distance between sets varies based on speed. Can be used with Portable Traffic Signals and Automated Flagger Assistance Devices (AFADs).

State	Title	Reference	Summary
Virginia	Portable Rumble Strips (Traffic Engineering Division Instructional and Informational Memorandum No. IIM-TE-386.1)	Virginia DOT 2018	Guidelines and standards for the use of TPRS. Includes TPRS spacing based on speed. Use of TPRS is optional on divided four-lane roadways and during nighttime operations. Shadow vehicle should be located 80 feet to 100 feet in advance of workers. Use of TPRS is required for flagging operations during daytime with durations between three and 72 hours, existing posted speed limit of at least 35 mph, and roadways with centerline markings.
Virginia	2020 Road and Bridge Specifications [Section 512.03(w): Portable Temporary Rumble Strip (PTRS) and Section 512.04 (Measurement and Payment)]	Virginia DOT 2020a	Only one set of TPRS should be used in the work zone's advance warning area per direction. Color should be orange or black. Each set includes sets of three strips. Adhesives or fasteners should not be used. Payment is made per set of three rumble strips.
Virginia	Virginia Work Area Protection Manual (Section 6F.99: Rumble Strips and Chapter 6H: Typical Applications)	Virginia DOT 2020b	Provides guidance for temporary rumble strips. TPRS should be used for the following conditions: daytime flagging operations, work duration is between three hours and three days, existing speed limit is at least 35 mph, and centerline markings exist. Sets of three strips are used, and spacing is based on posted speed limit. Color should be black or white if not the pavement color. Long-term transverse rumble strips consisting of rough-textured or slightly raised or depressed road surface (white in color) may be used for durations greater than three consecutive days. Typical applications include detail drawings of TPRS layouts for various conditions. Tables for spacing of TPRS and long-term transverse temporary rumble strips are provided.

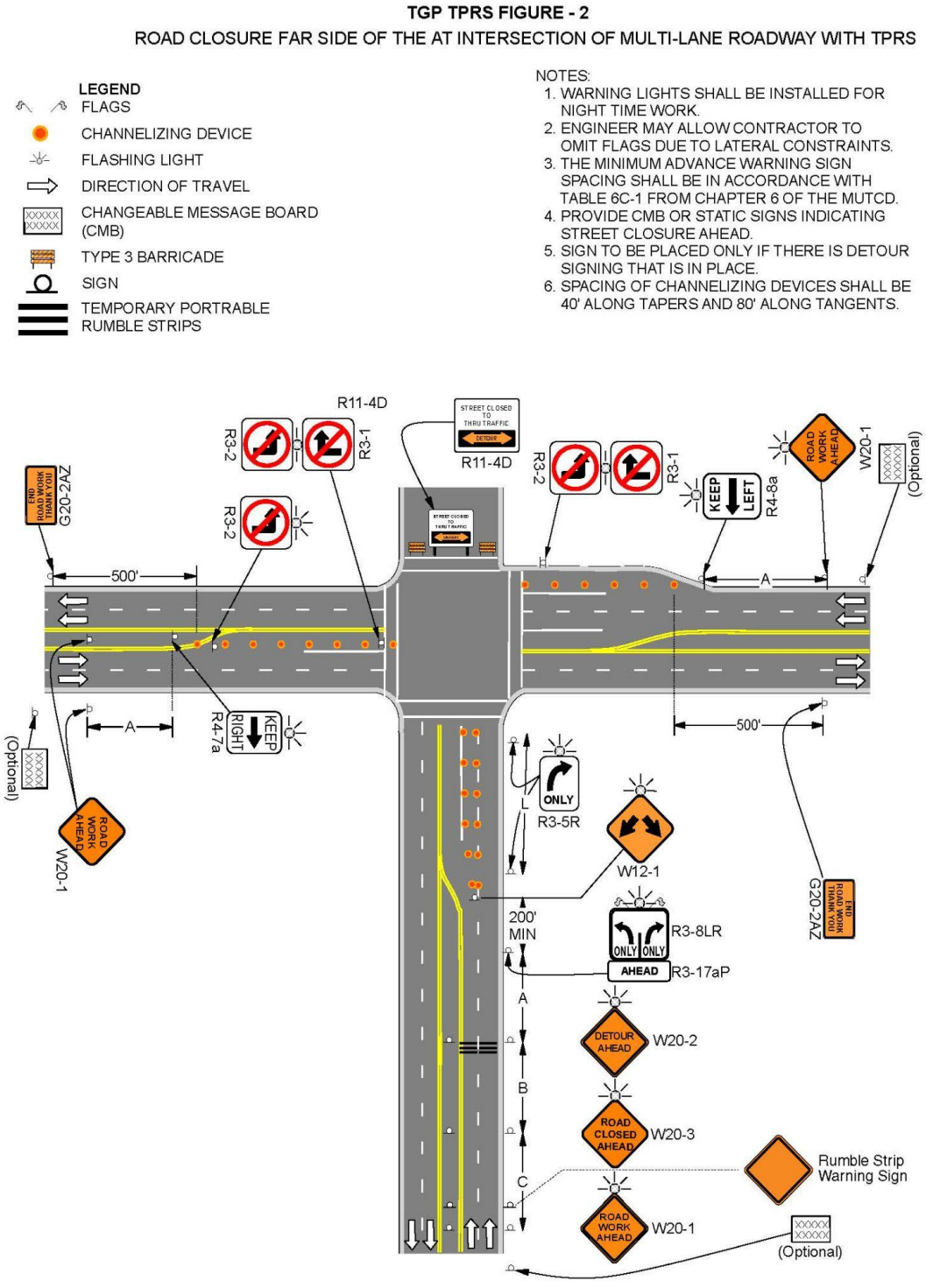
State	Title	Reference	Summary
Wisconsin	Temporary Rumble Strips (Orange) in Advance of Lane Closure, SPV	Wisconsin DOT n.d.	Special provision for installation, maintenance, and removal of temporary rumble strips (orange) in advance of lane closure. Material should be polymer with pre-applied adhesive (0.25 inches thick by 4 inches wide). Three sets of nine rumble strips should be used. Temperature and condition of the pavement limitations are noted. Payment is based on linear feet.
Wisconsin	Temporary Portable Rumble Strips – One Array	Wisconsin DOT 2019	Describes policy change that one set of TPRS should be used for all flagging operations.
Wisconsin	Standard Detail Drawings (15C12: Traffic Control for Lane Closure with Flagging Operation)	Wisconsin DOT 2021a	Layout drawing for flagger operation with TPRS. Specifies that TPRS should be used on all flagging operations. TPRS should be listed on Approved Products List (APL) and should be installed per manufacturer's recommendations. Includes table with sign and spacing of sets based on speed limit.
Wisconsin	Work Zone Traffic Control Devices (Approved Product List)	Wisconsin DOT 2021b	Includes RoadQuake 2 and 2F from PSS and TraFix Alert High Speed Rumble Strip.

APPENDIX C. EXAMPLE DOT STANDARDS AND GUIDANCE FOR TEMPORARY RUMBLE STRIPS



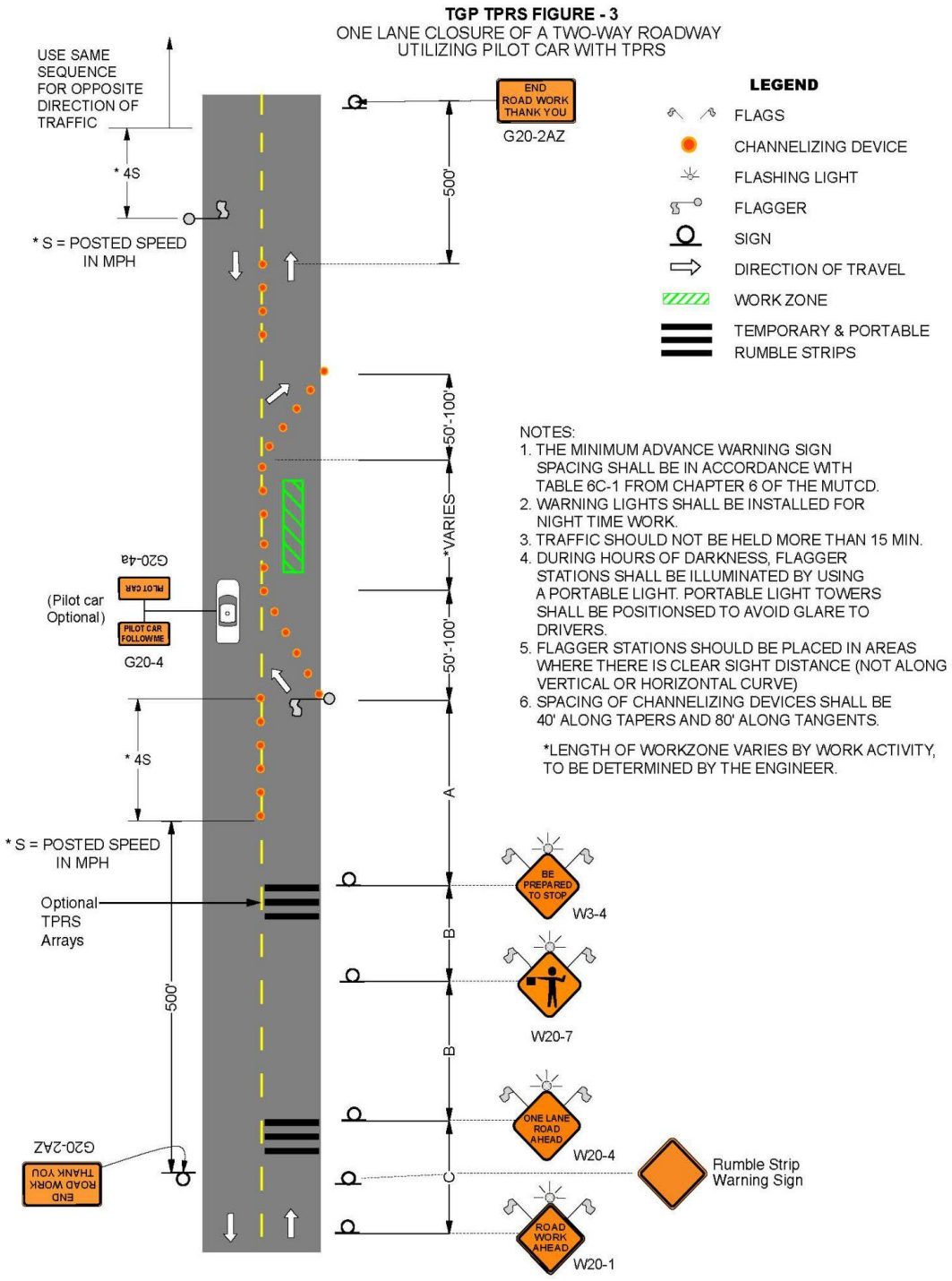
(Alabama DOT 2019)

Figure C-1. Typical placement of advance warning signs/rumble strips/portable traffic signal for maintenance operation in work area from Alabama DOT



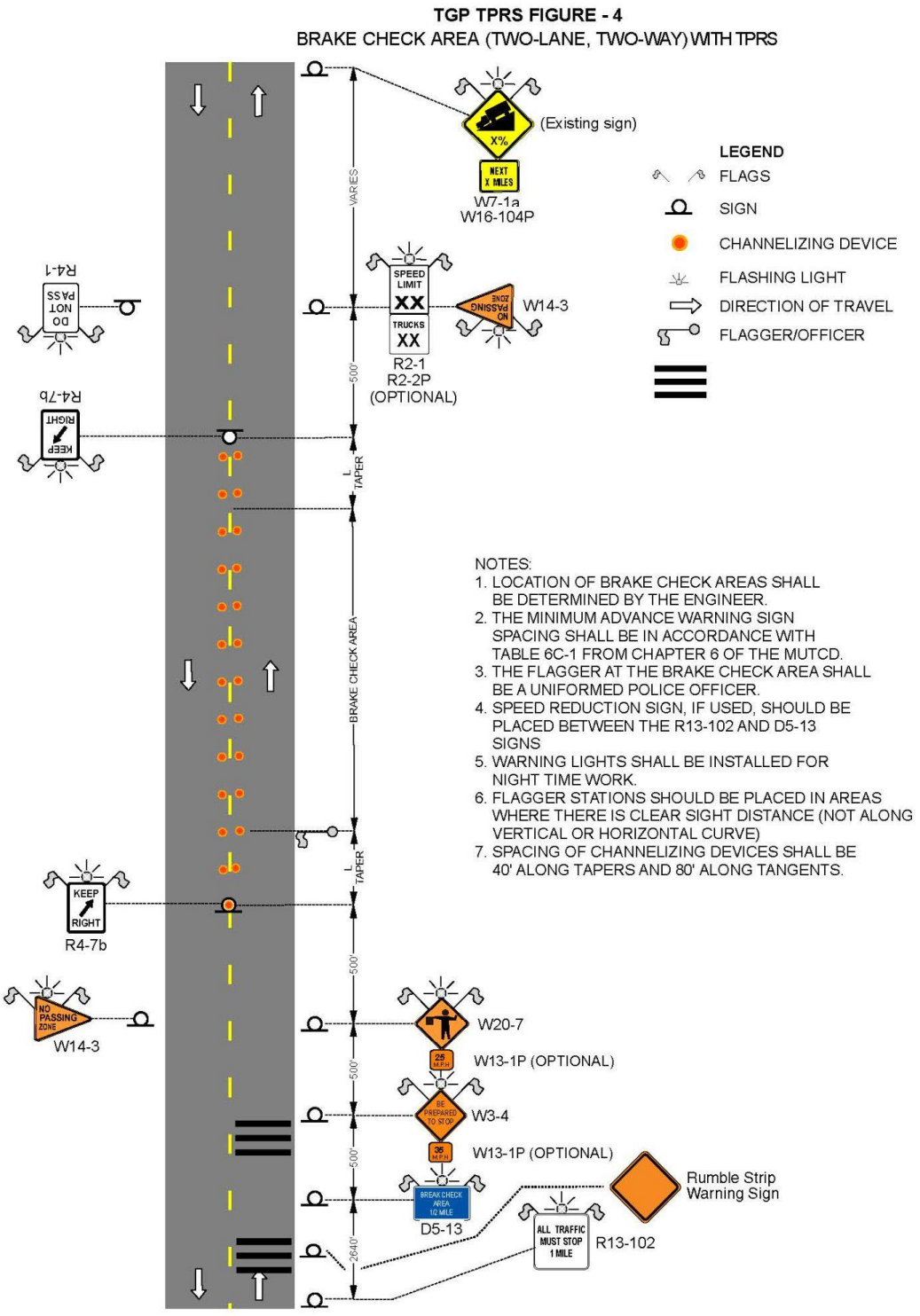
(Arizona DOT 2021)

Figure C-2. Standard layout for road closure far side of the at intersection of multi-lane roadway with TPRS from Arizona DOT



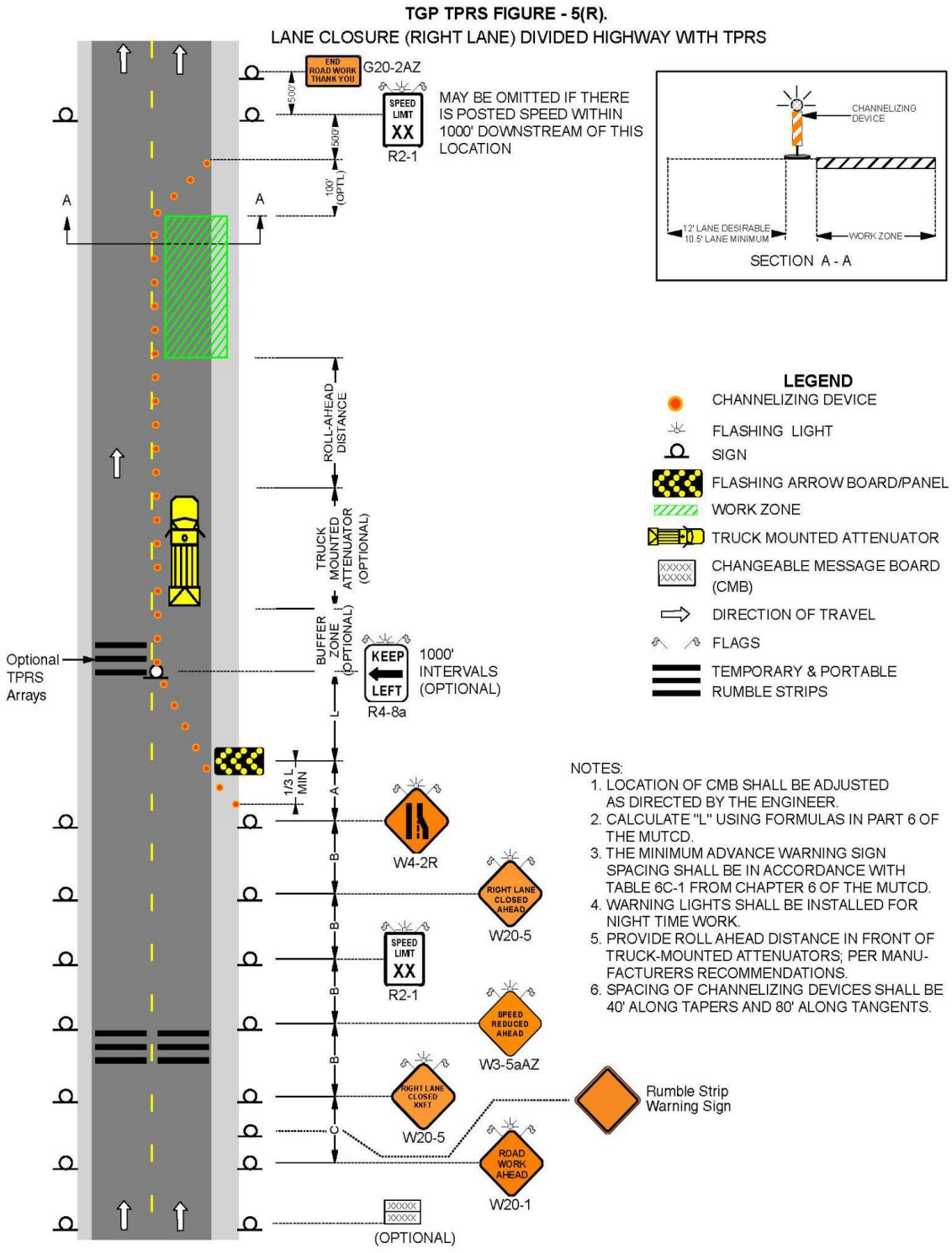
(Arizona DOT 2021)

Figure C-3. Standard layout for one lane closure of a two-way roadway utilizing pilot car with TPRS from Arizona DOT



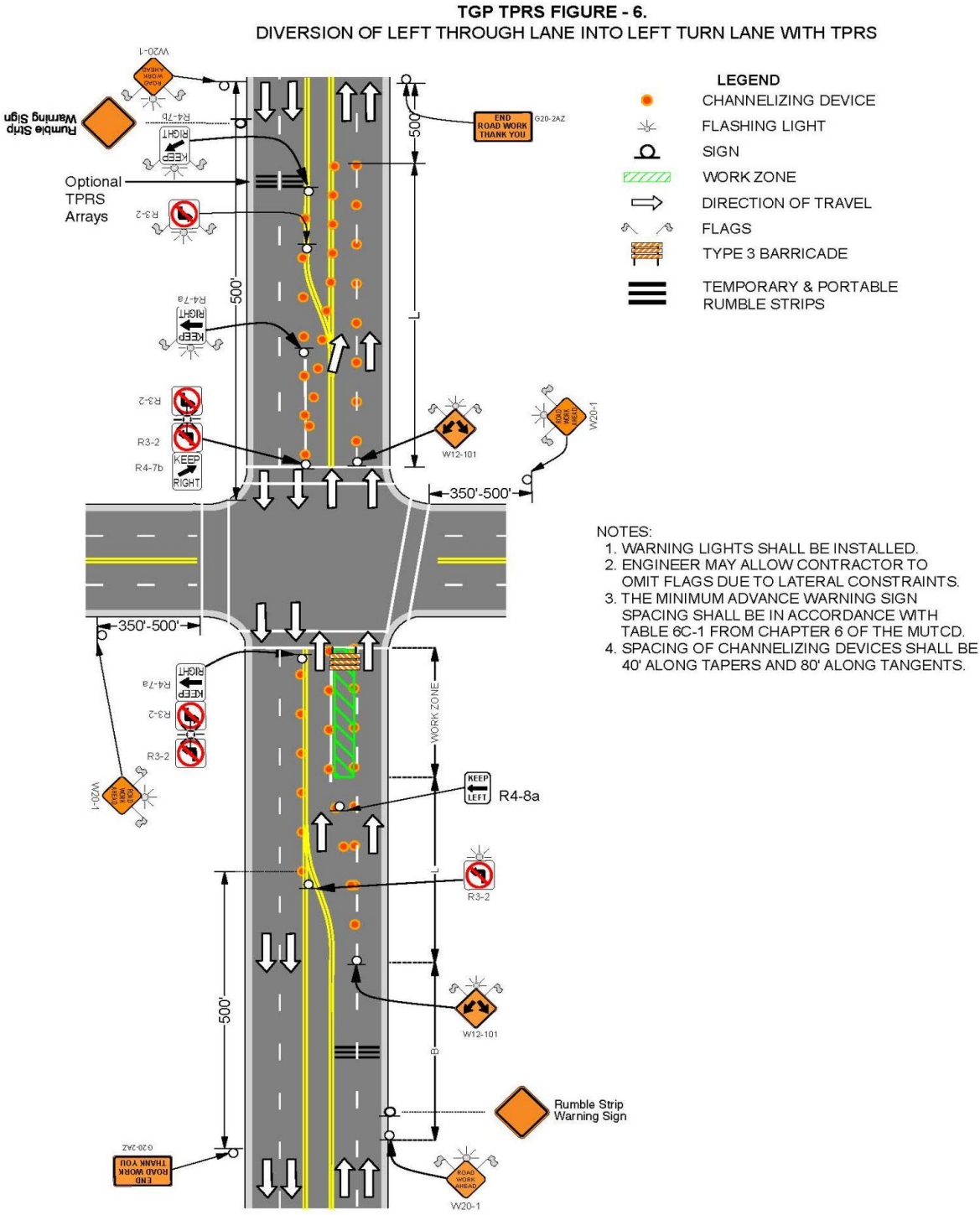
(Arizona DOT 2021)

Figure C-4. Standard layout for brake check area (two-lane, two-way) with TPRS from Arizona DOT



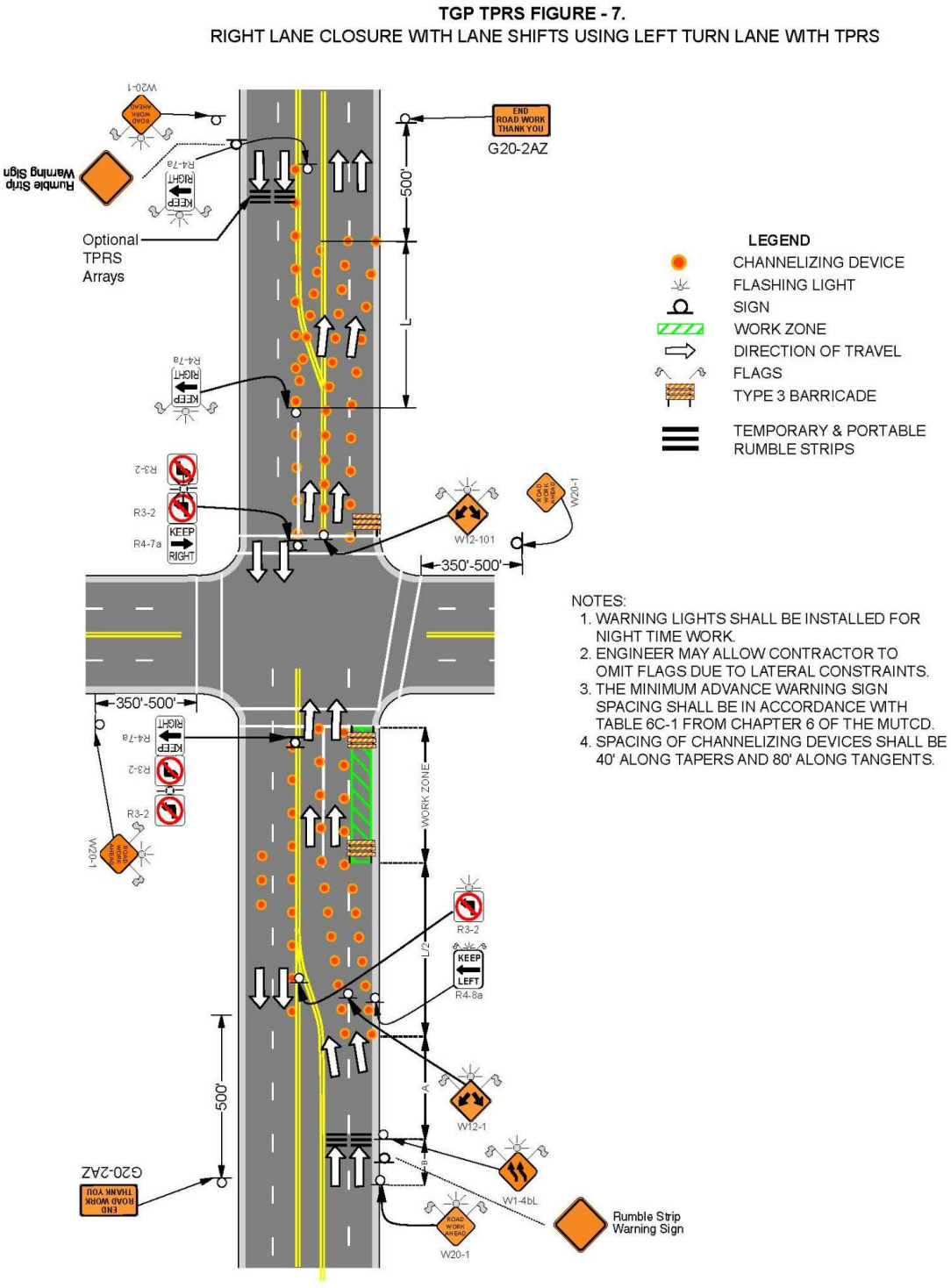
(Arizona DOT 2021)

Figure C-5. Standard layout for lane closure (right lane) divided highway with TPRS from Arizona DOT



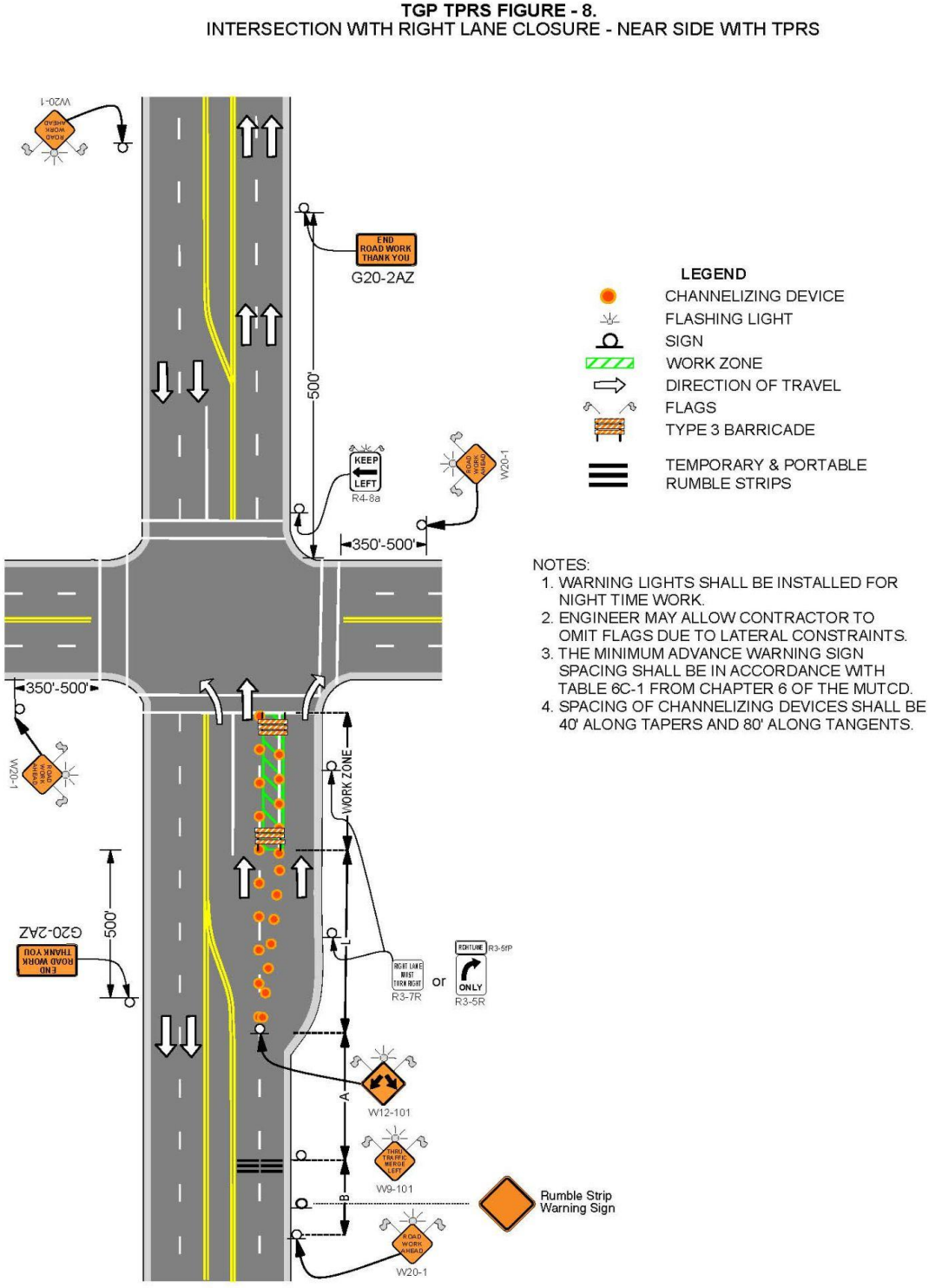
(Arizona DOT 2021)

Figure C-6. Standard layout for diversion of left through lane into left turn lane with TPRS from Arizona DOT



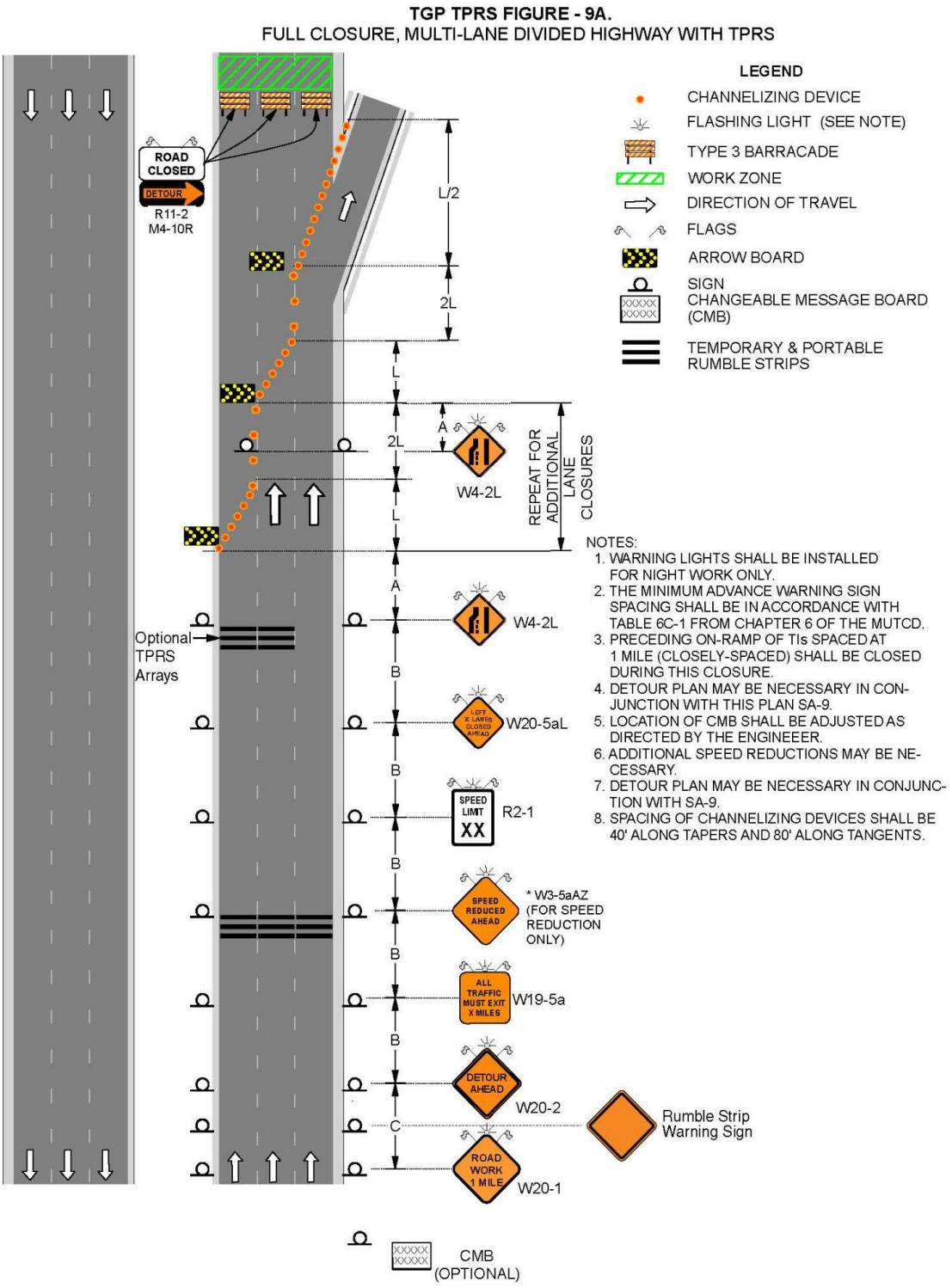
(Arizona DOT 2021)

Figure C-7. Standard layout for right lane closure with lane shifts using left turn lane with TPRS from Arizona DOT



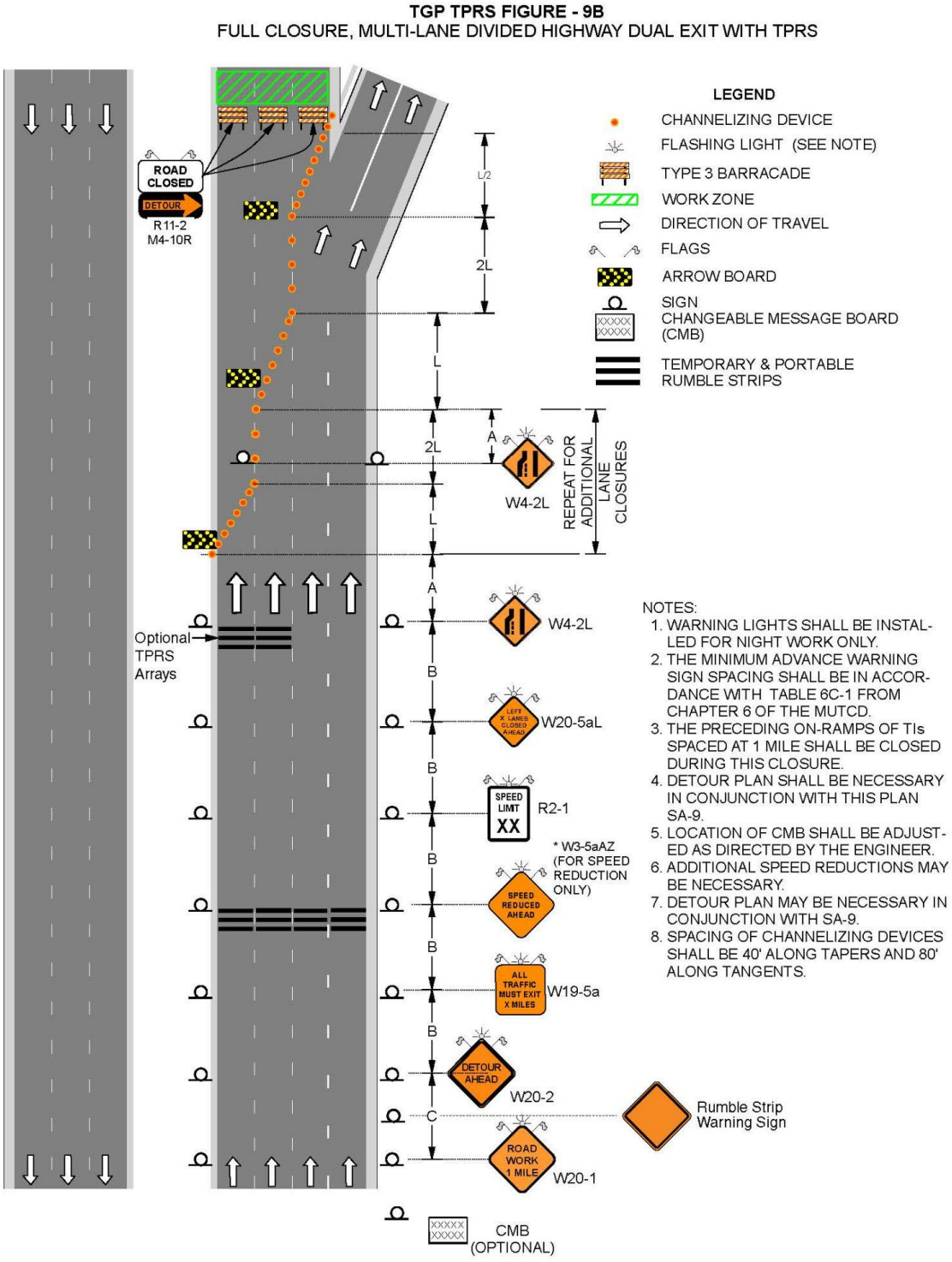
(Arizona DOT 2021)

Figure C-8. Standard layout for intersection with right lane closure – near side with TPRS from Arizona DOT



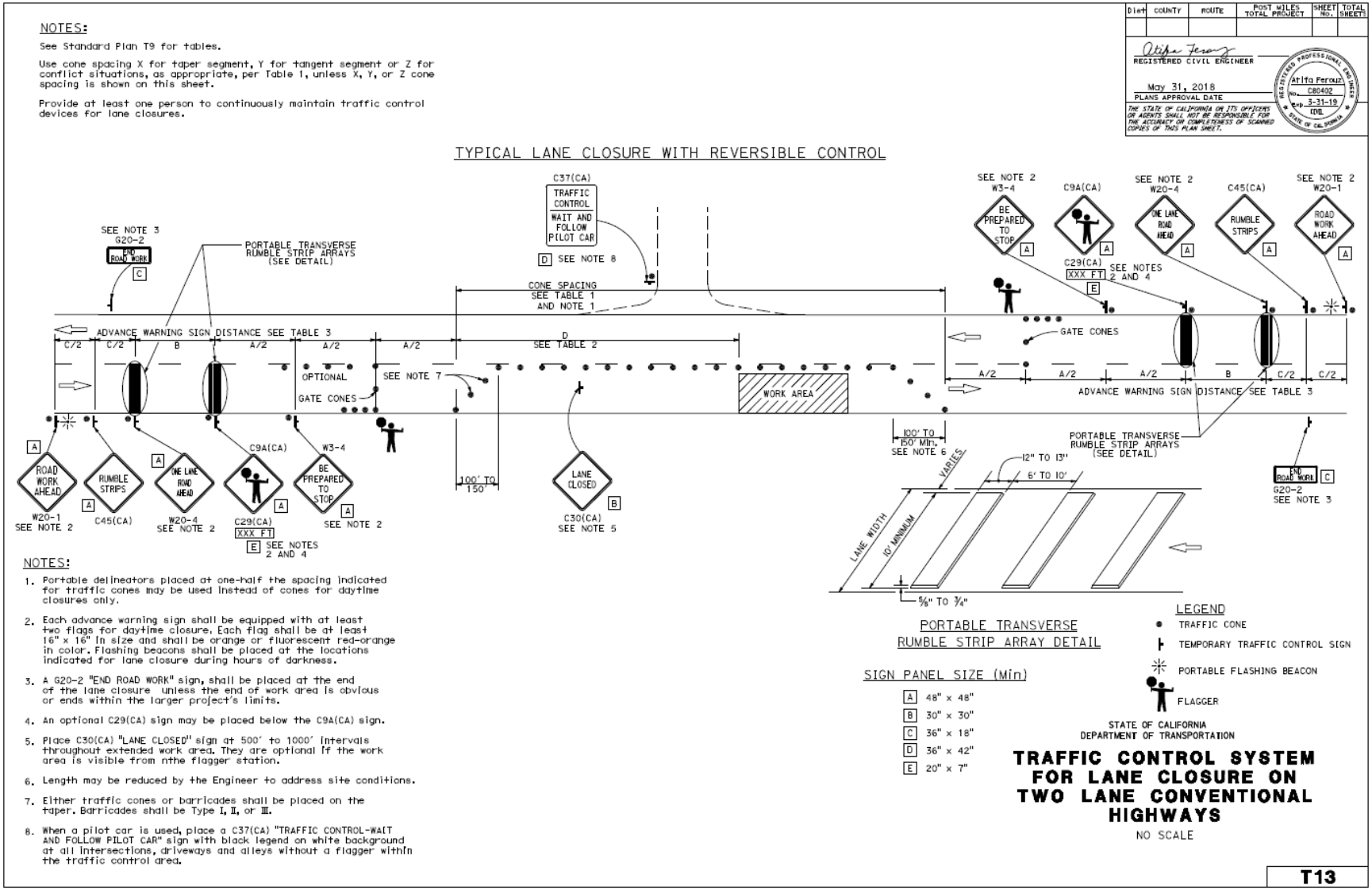
(Arizona DOT 2021)

Figure C-9. Standard layout for full closure, multi-lane divided highway with TPRS from Arizona DOT



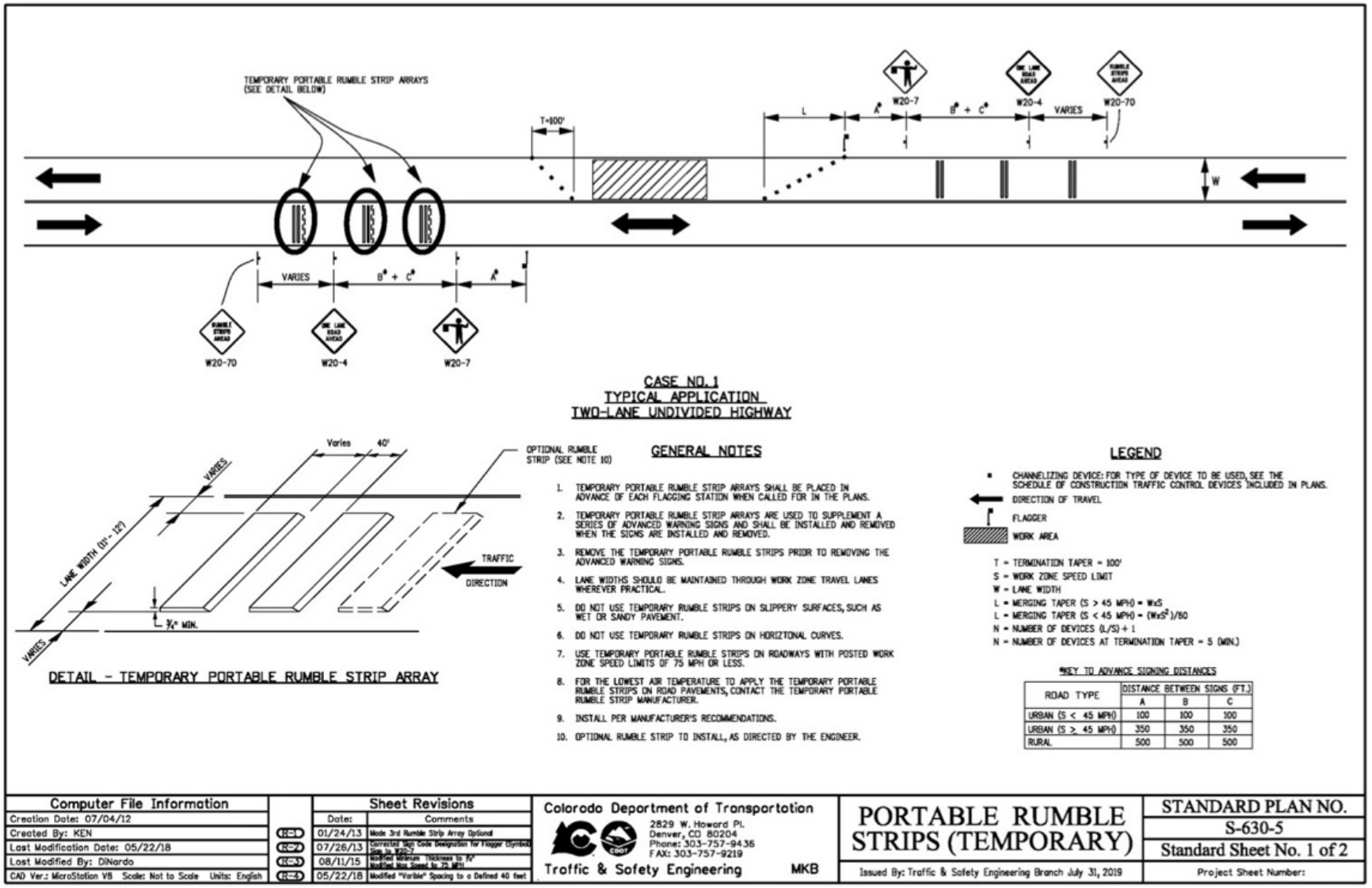
(Arizona DOT 2021)

Figure C-10. Standard layout for full closure, multi-lane divided highway dual exit with TPRS from Arizona DOT



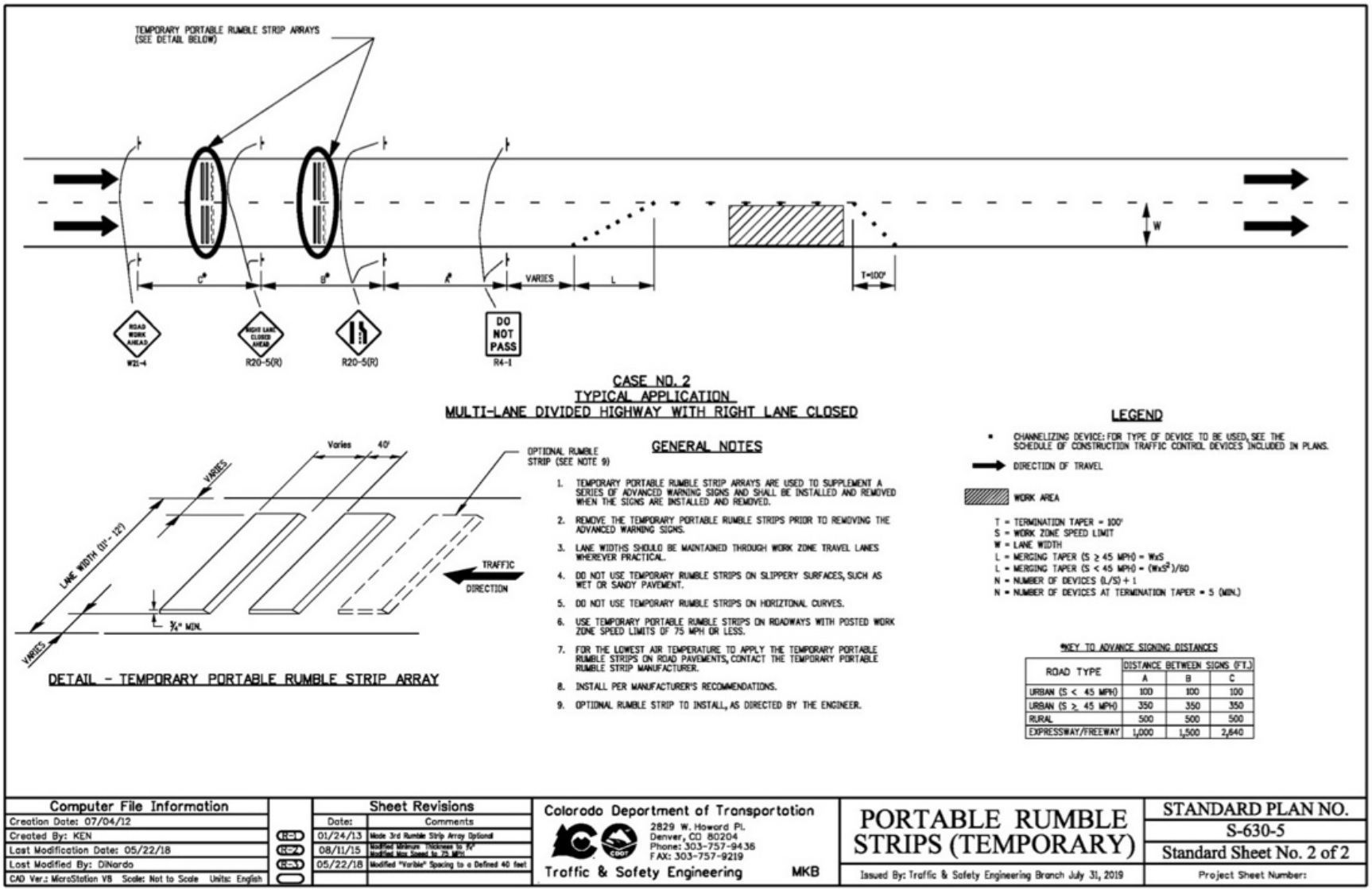
(Caltrans 2018c)

Figure C-11. Standard traffic control system for lane closure on two lane conventional highways from Caltrans



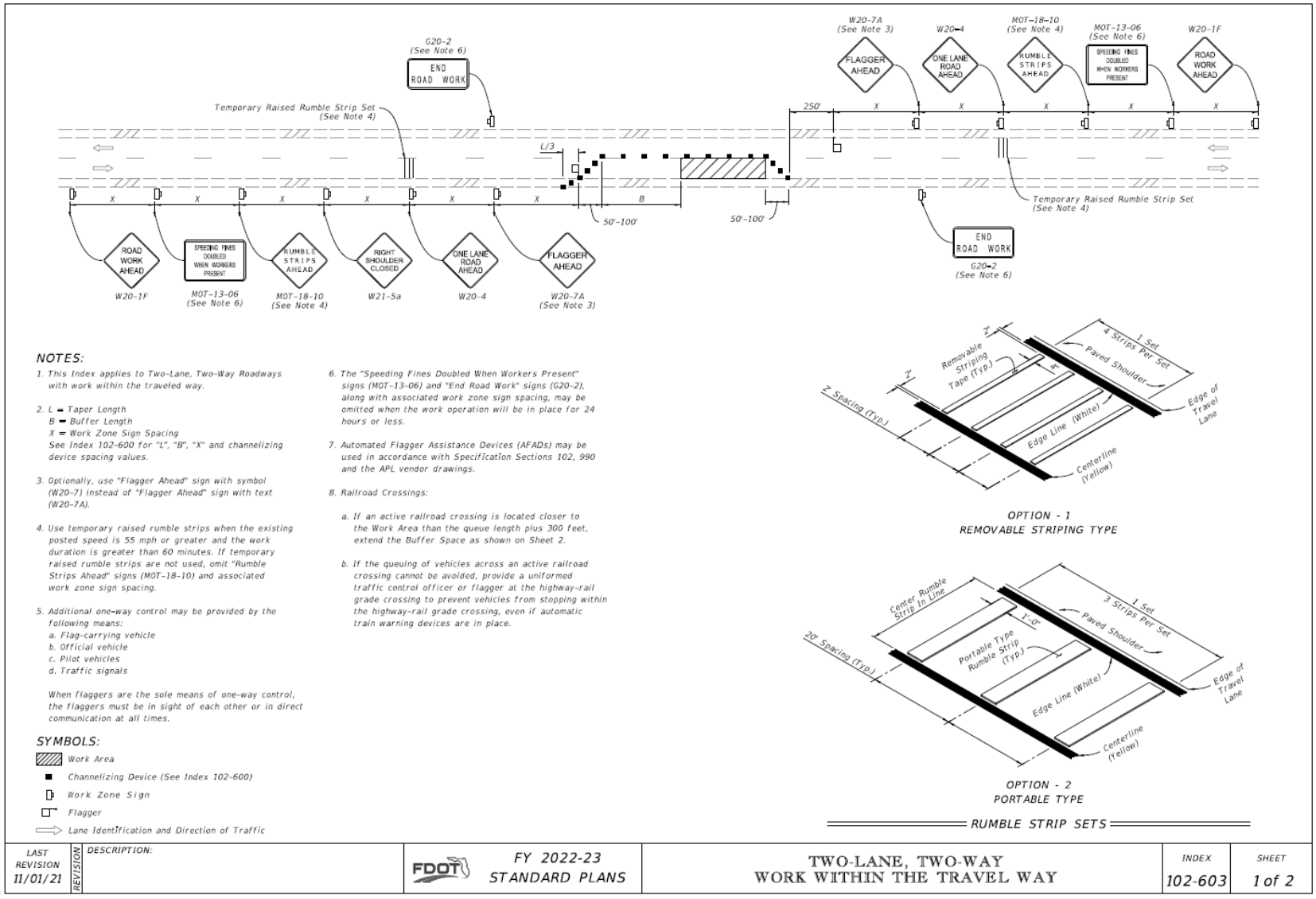
(Colorado DOT 2019)

Figure C-12. Standard layout for TPRS arrays on two-lane undivided highway from Colorado DOT



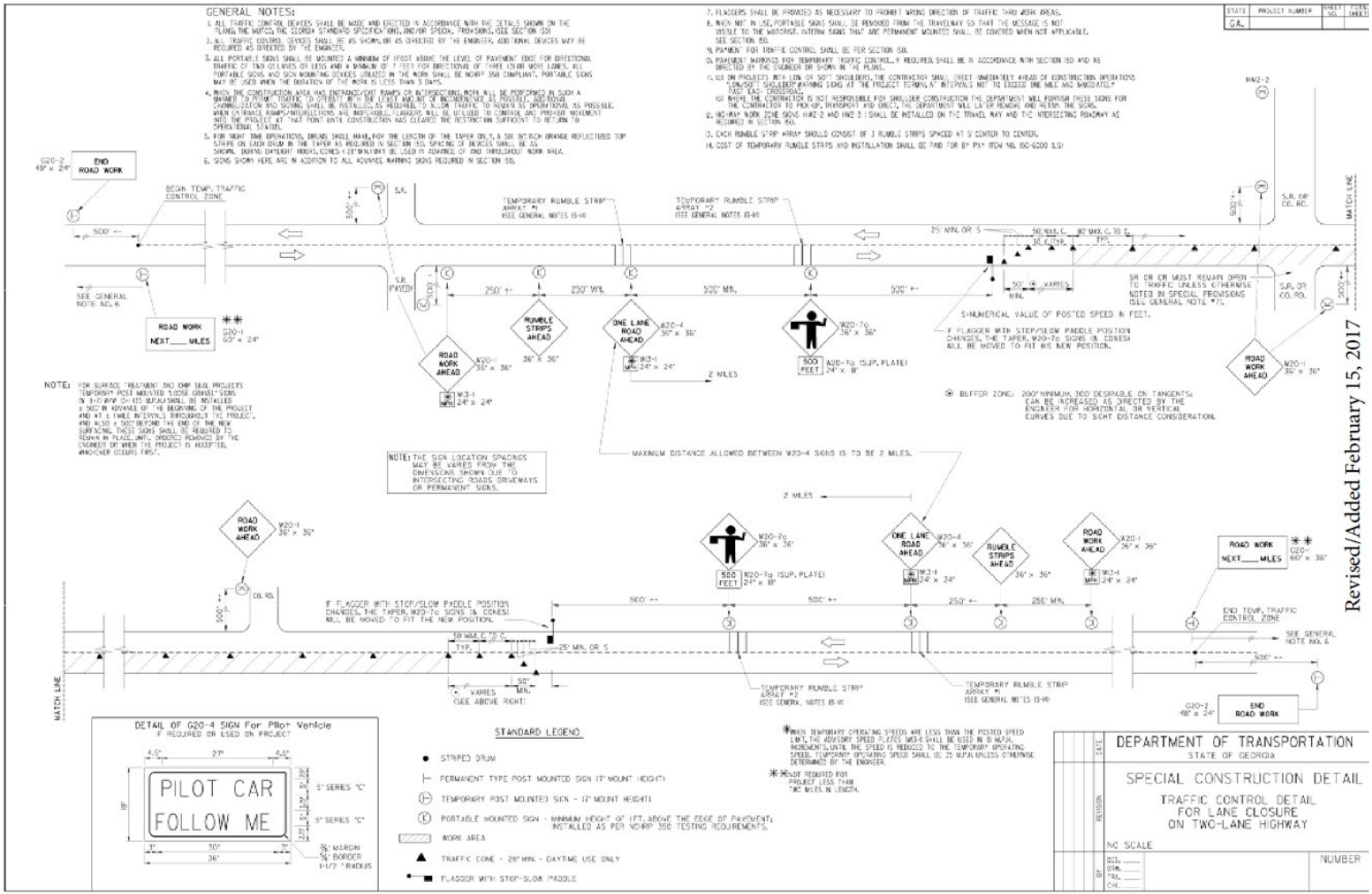
(Colorado DOT 2019)

Figure C-13. Standard layout for TPRS on multi-lane divided highway with right lane closed from Colorado DOT



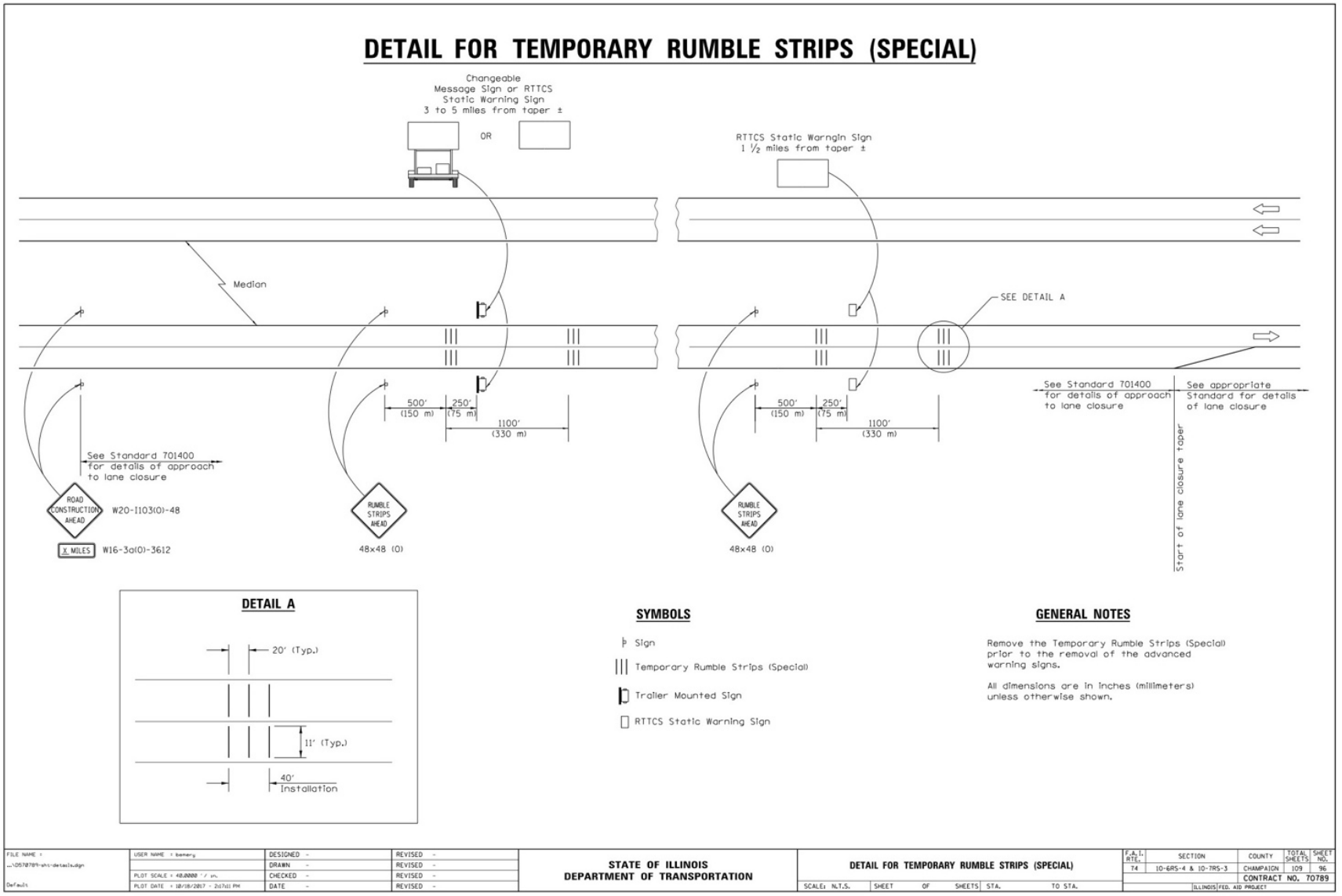
(Florida DOT 2021b)

Figure C-14. Standard layout for two-lane, two-way work within the travel way from Florida DOT



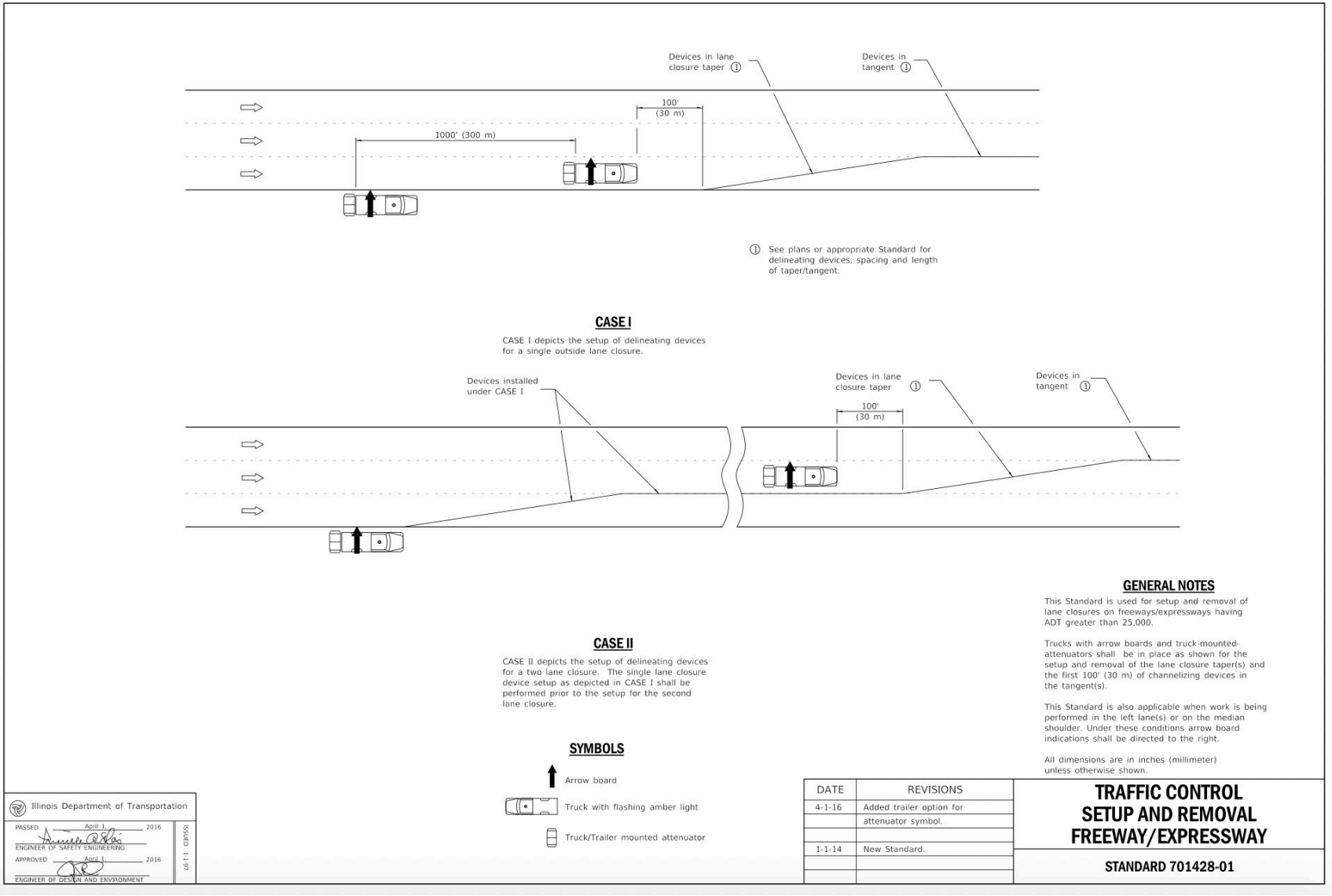
(Georgia DOT 2017)

Figure C-15. Standard traffic control detail for lane closure on two-lane highway from Georgia DOT



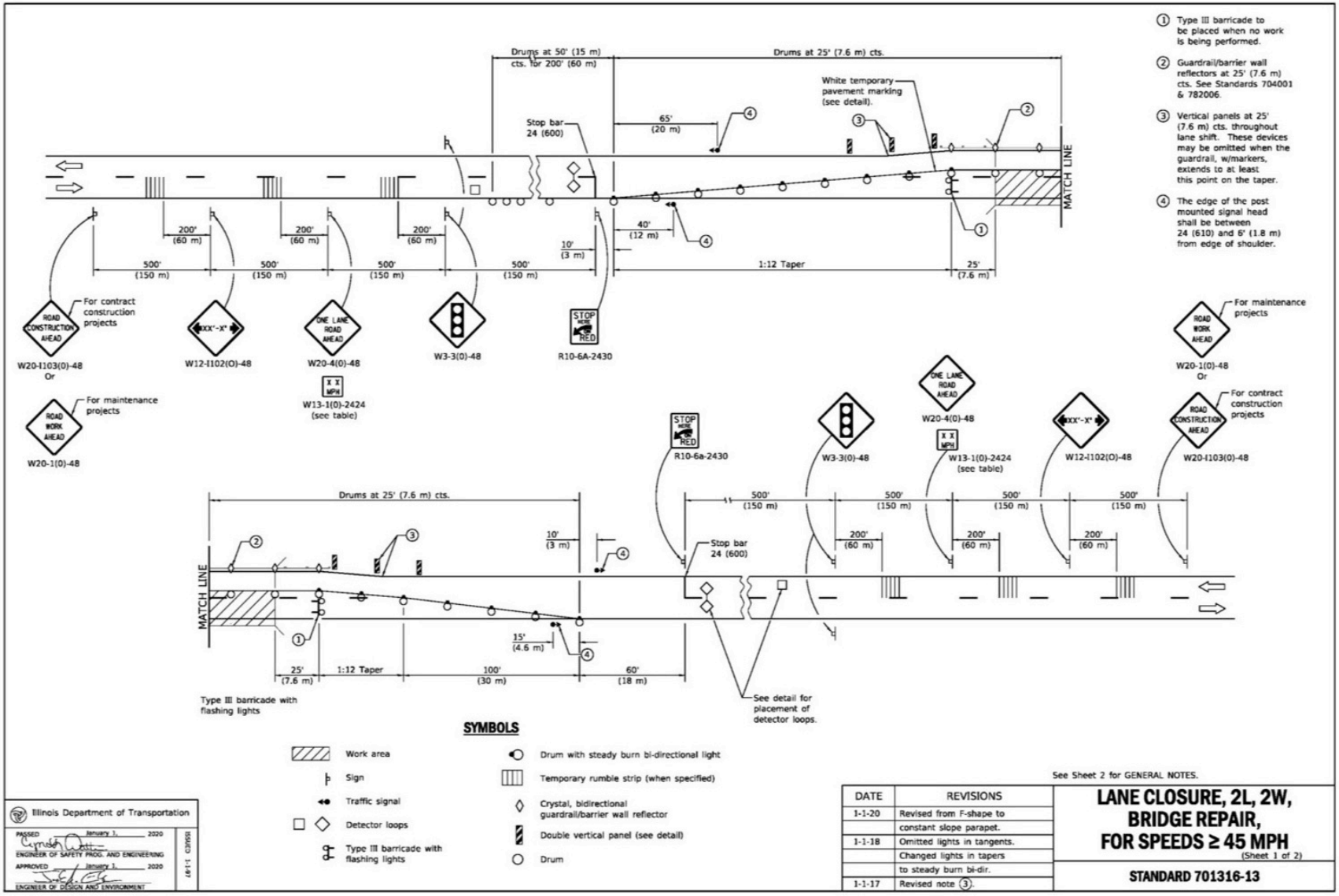
(Illinois DOT 2017)

Figure C-16. Standard detail for temporary rumble strips (special) from Illinois DOT



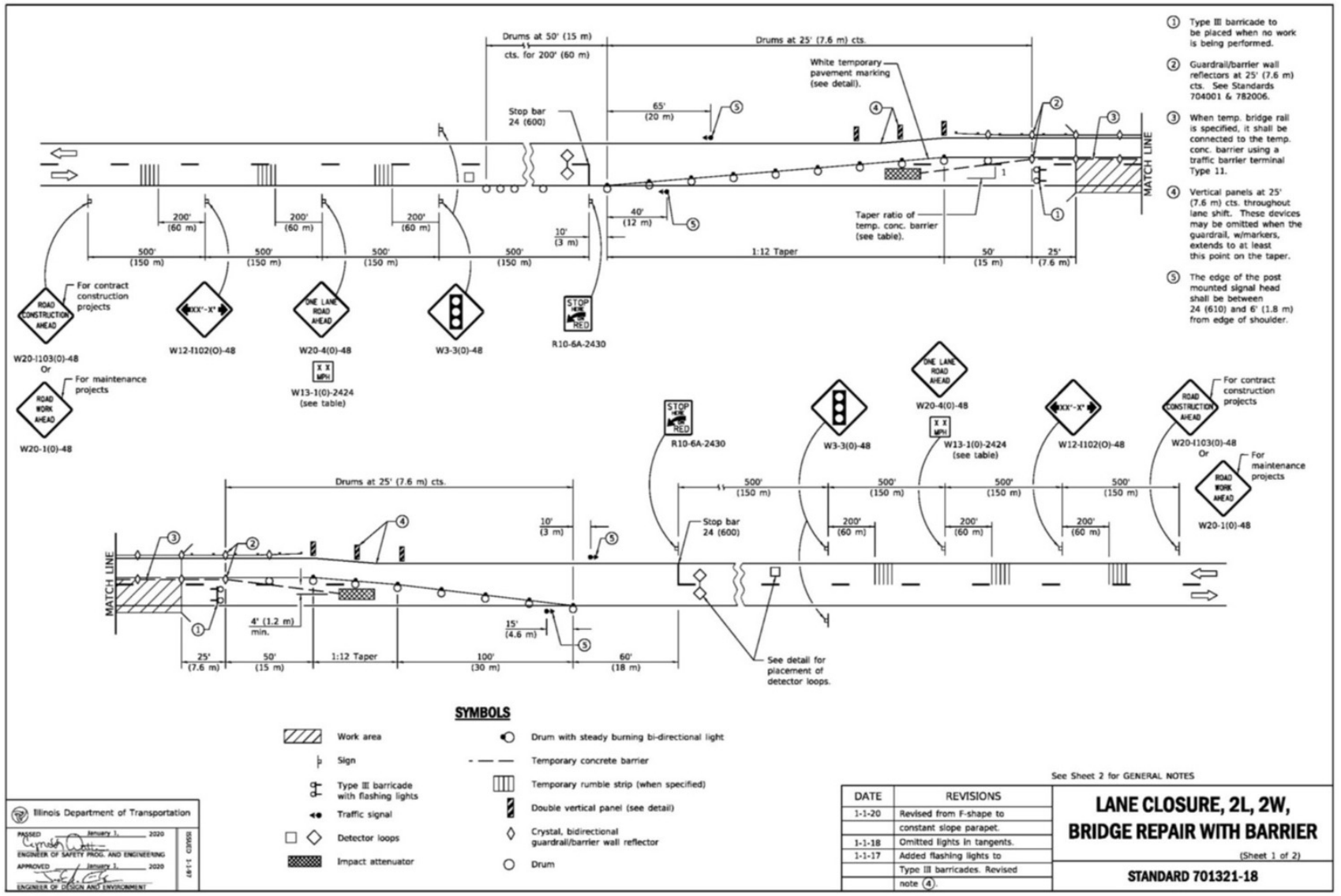
(Illinois DOT 2020)

Figure C-17. Layout for traffic control setup and removal on freeways and expressways from Illinois DOT



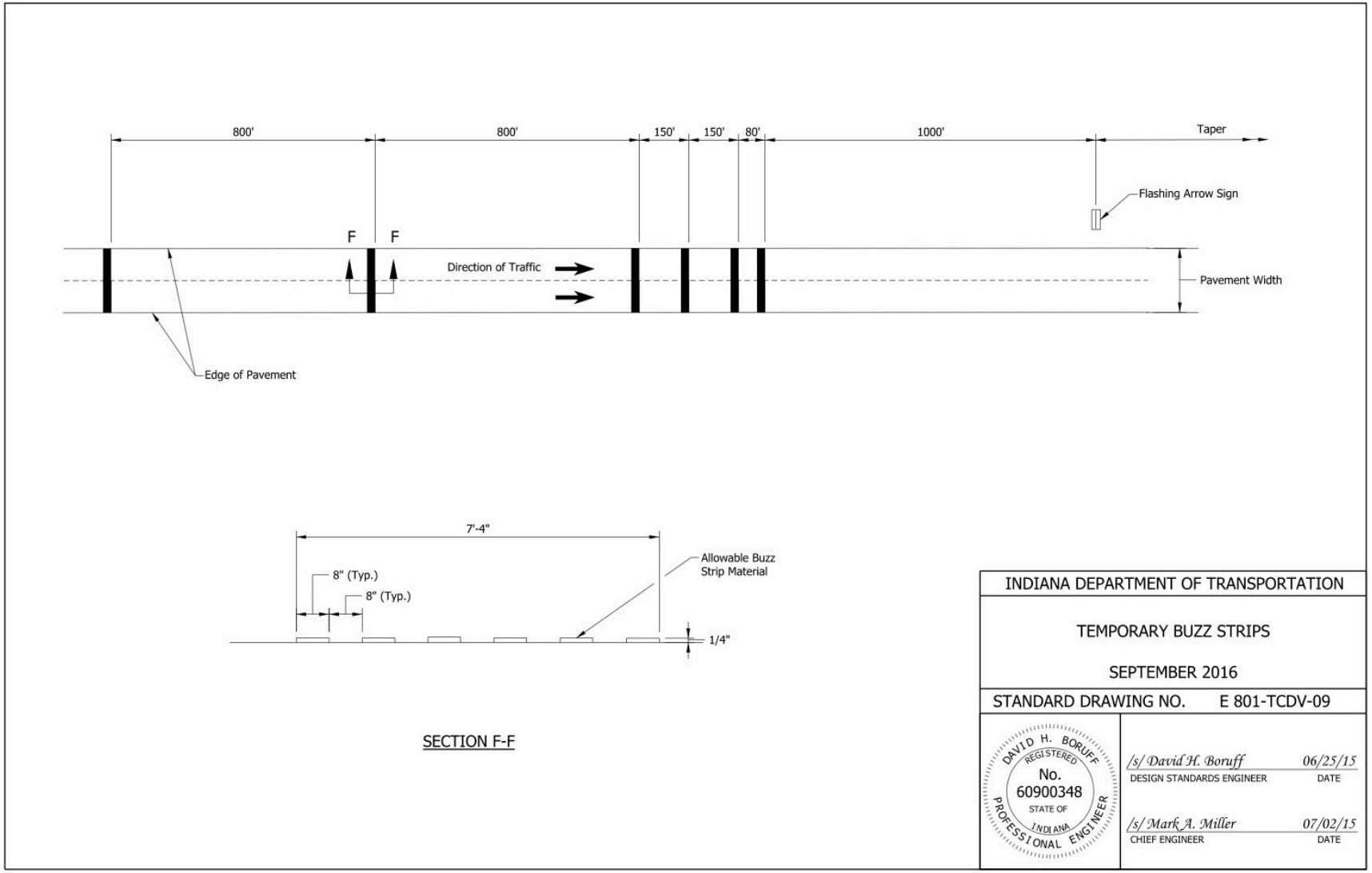
(Illinois DOT 2020)

Figure C-18. Layout for lane closure for bridge repair for speeds of 45 mph or greater from Illinois DOT



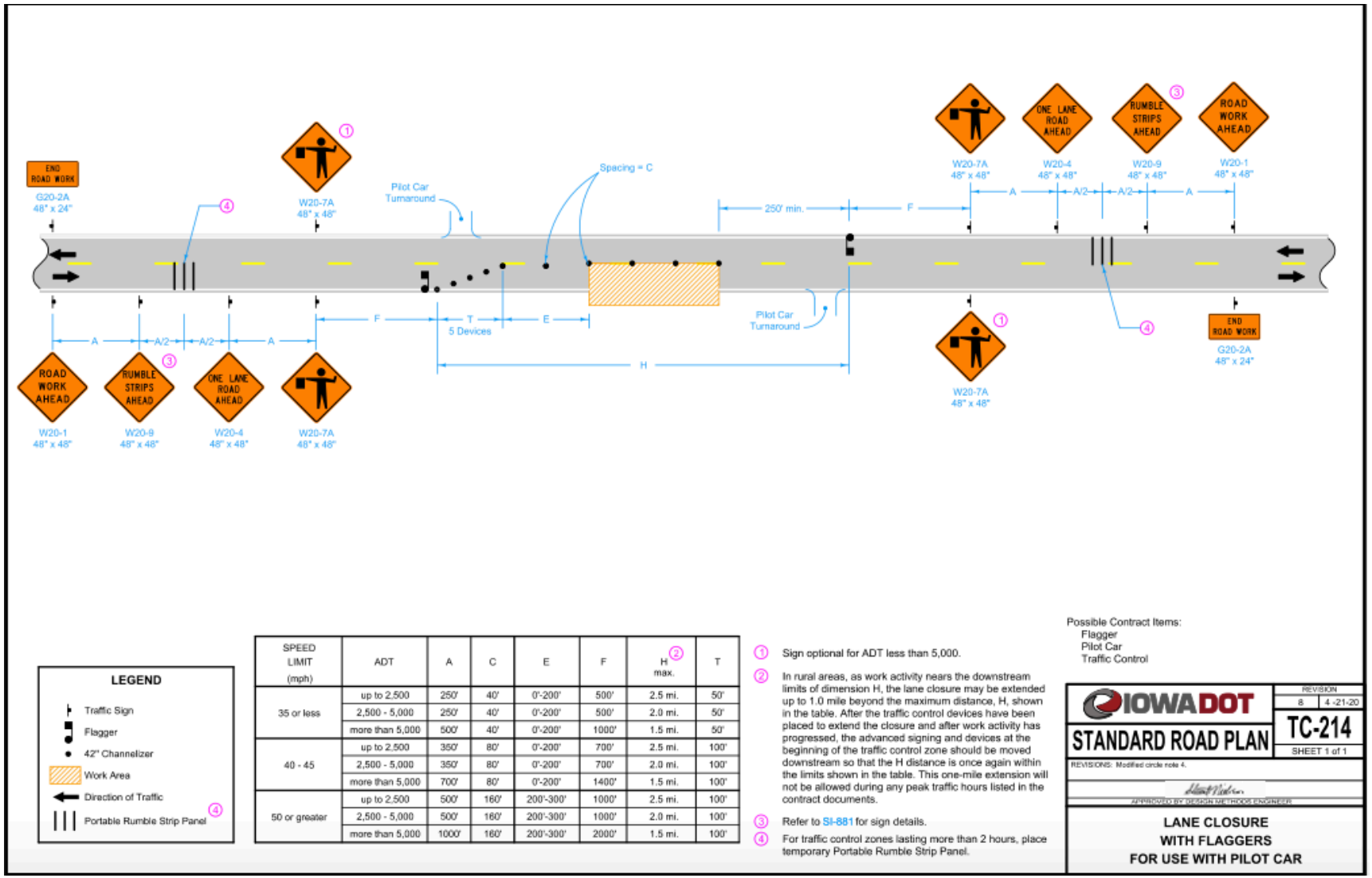
(Illinois DOT 2020)

Figure C-19. Lane closure for bridge repair with barriers from Illinois DOT



(Indiana DOT 2021c)

Figure C-20. Layout for temporary buzz strips from Indiana DOT



SPEED LIMIT (mph)	ADT	A	C	E	F	H ② max.	T
35 or less	up to 2,500	250'	40'	0'-200'	500'	2.5 mi.	50'
	2,500 - 5,000	250'	40'	0'-200'	500'	2.0 mi.	50'
	more than 5,000	500'	40'	0'-200'	1000'	1.5 mi.	50'
40 - 45	up to 2,500	350'	80'	0'-200'	700'	2.5 mi.	100'
	2,500 - 5,000	350'	80'	0'-200'	700'	2.0 mi.	100'
	more than 5,000	700'	80'	0'-200'	1400'	1.5 mi.	100'
50 or greater	up to 2,500	500'	160'	200'-300'	1000'	2.5 mi.	100'
	2,500 - 5,000	500'	160'	200'-300'	1000'	2.0 mi.	100'
	more than 5,000	1000'	160'	200'-300'	2000'	1.5 mi.	100'

① Sign optional for ADT less than 5,000.

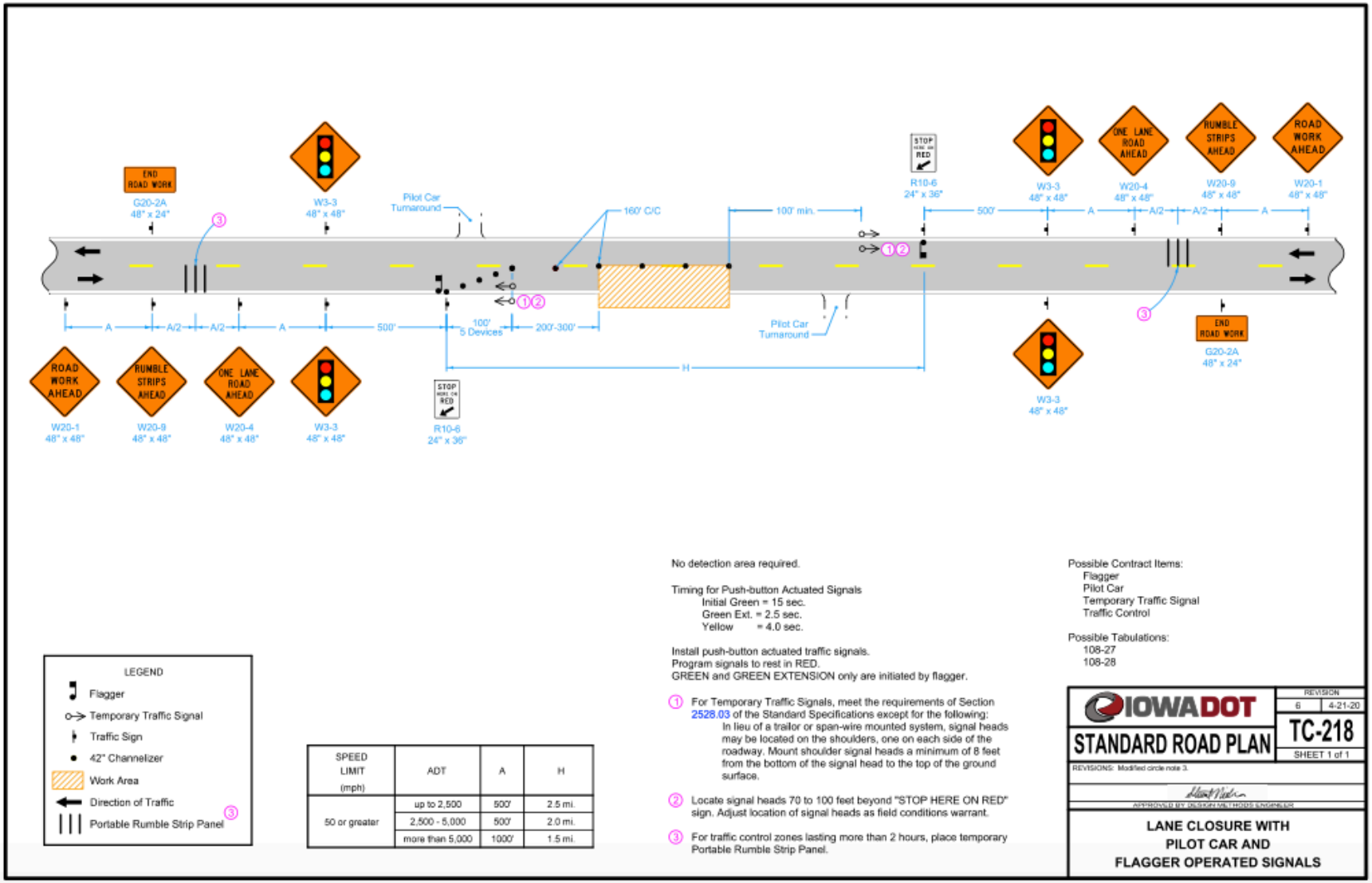
② In rural areas, as work activity nears the downstream limits of dimension H, the lane closure may be extended up to 1.0 mile beyond the maximum distance, H, shown in the table. After the traffic control devices have been placed to extend the closure and after work activity has progressed, the advanced signing and devices at the beginning of the traffic control zone should be moved downstream so that the H distance is once again within the limits shown in the table. This one-mile extension will not be allowed during any peak traffic hours listed in the contract documents.

③ Refer to SI-881 for sign details.

④ For traffic control zones lasting more than 2 hours, place temporary Portable Rumble Strip Panel.

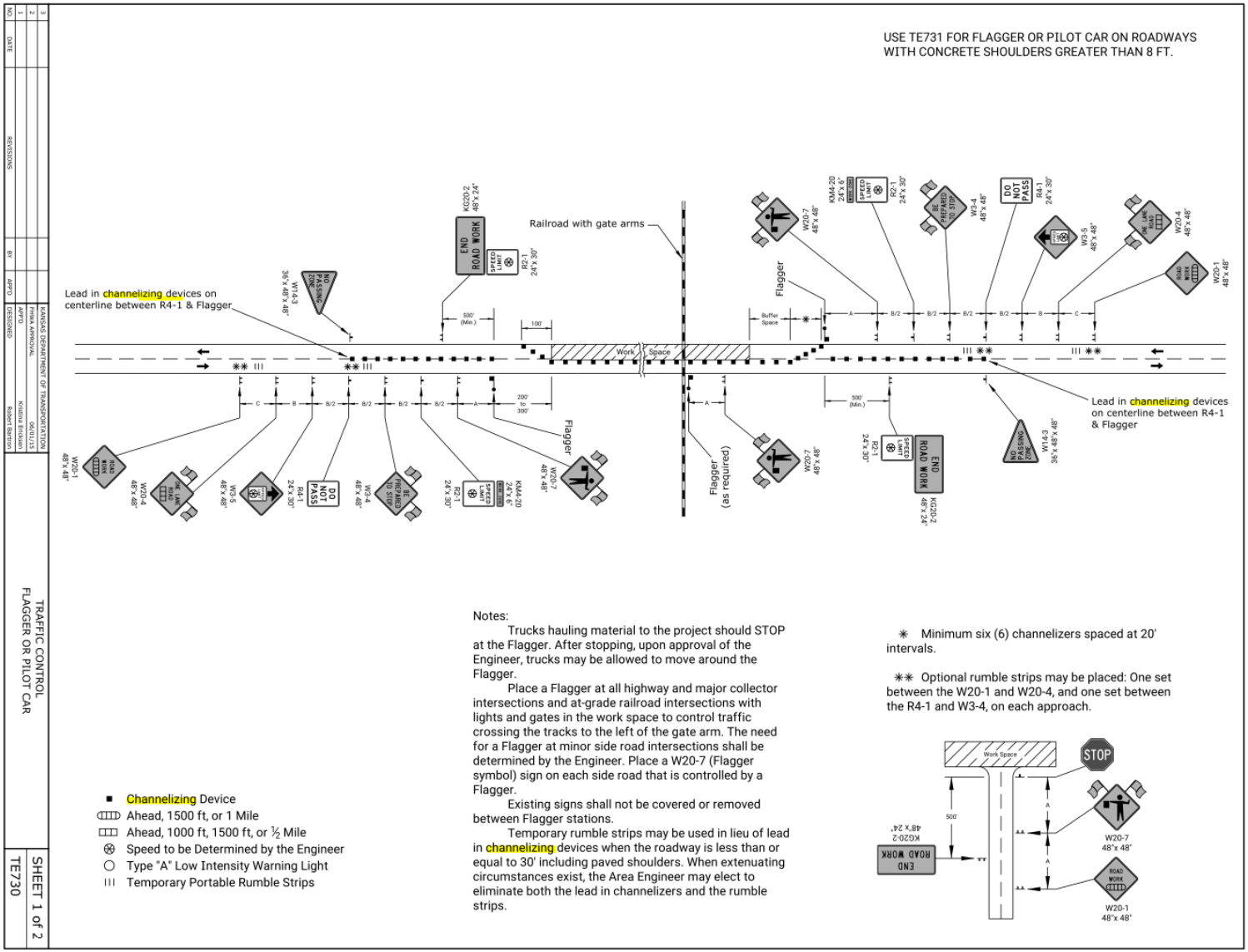
(Iowa DOT 2021a)

Figure C-21. Standard detail for lane closure with flaggers and pilot car from Iowa DOT



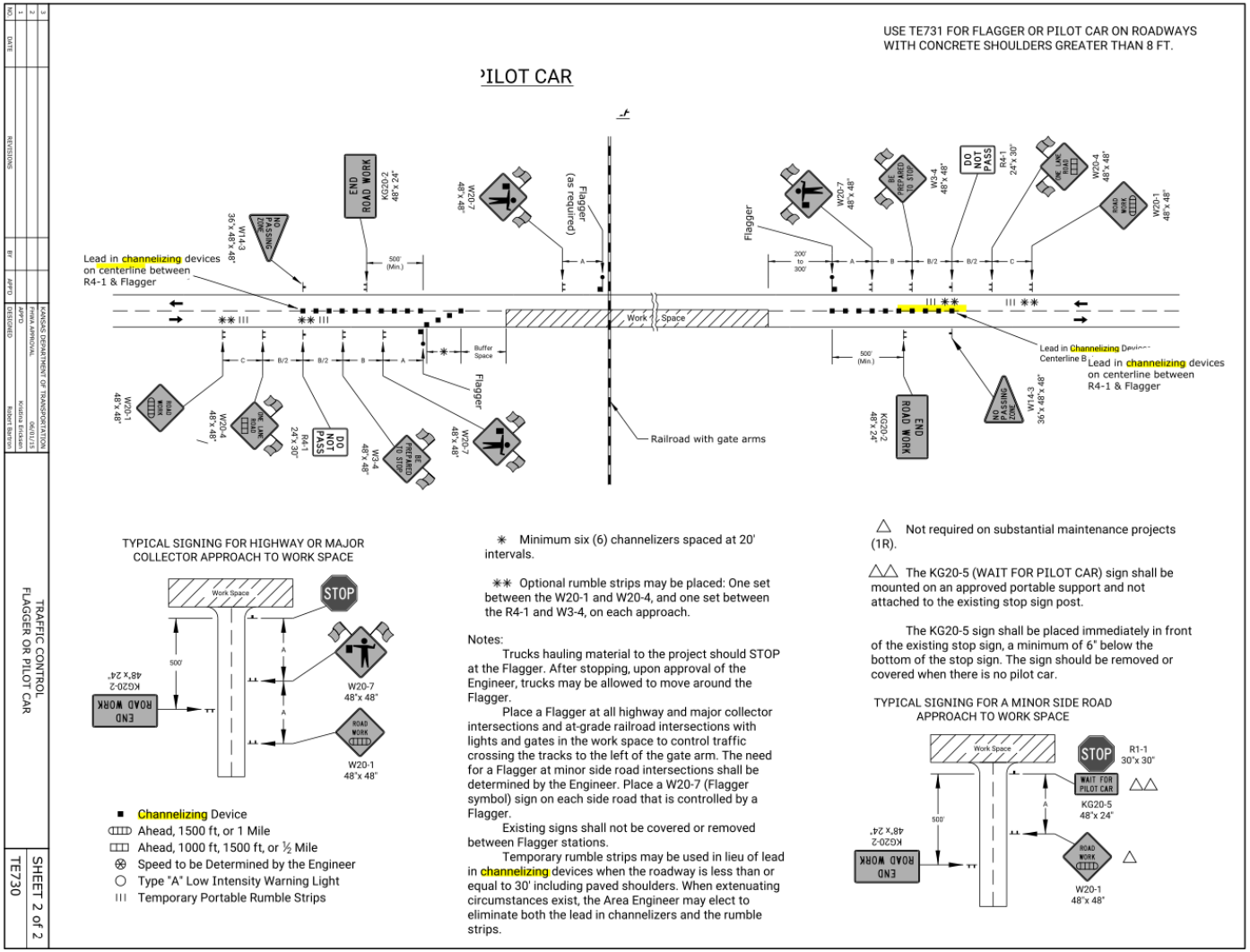
(Iowa DOT 2021a)

Figure C-22. Standard detail for lane closure with pilot car and flagger operated signals from Iowa DOT



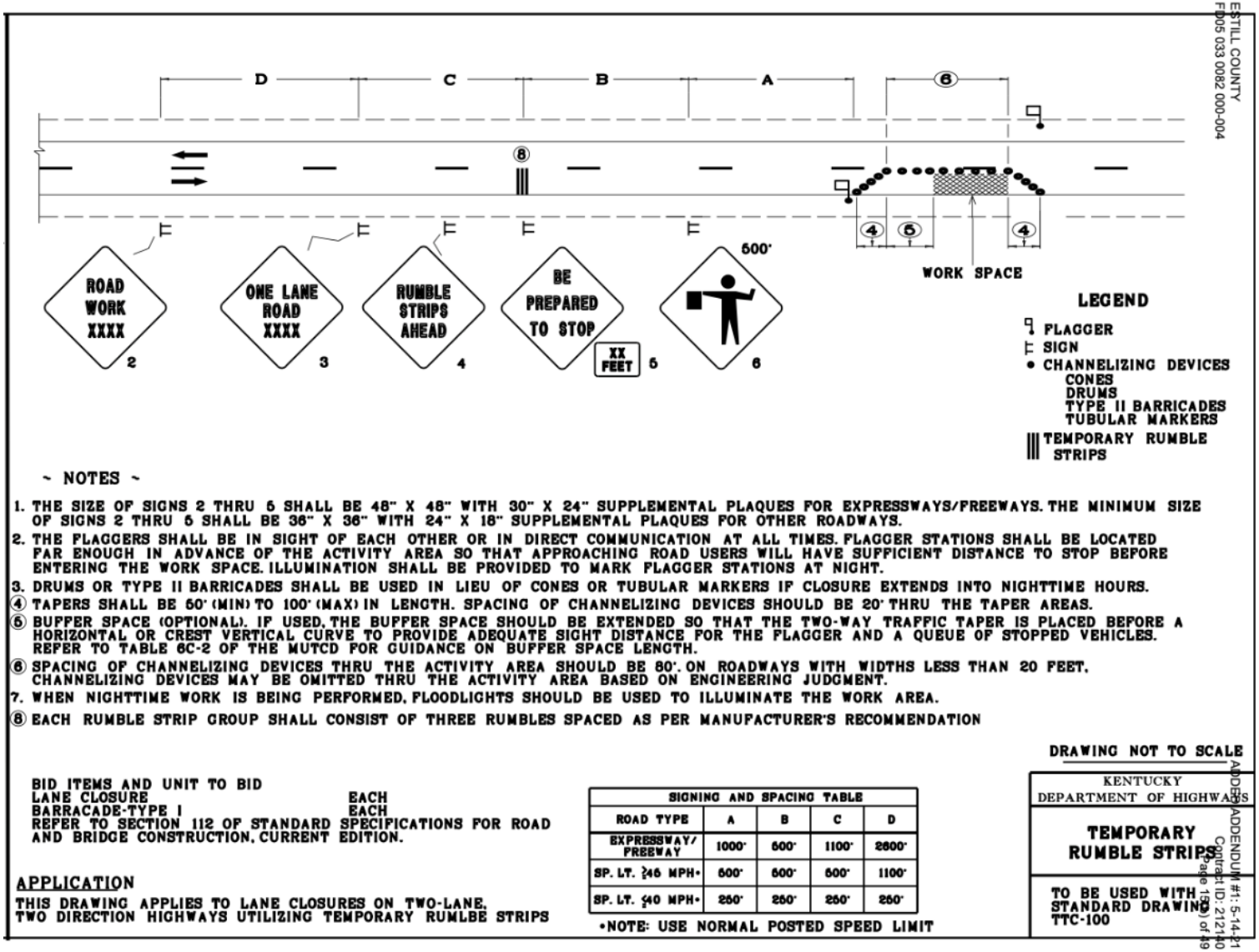
(Kansas DOT 2015)

Figure C-23. Standard detail drawing for traffic control for flagger or pilot car from Kansas DOT (1/2)



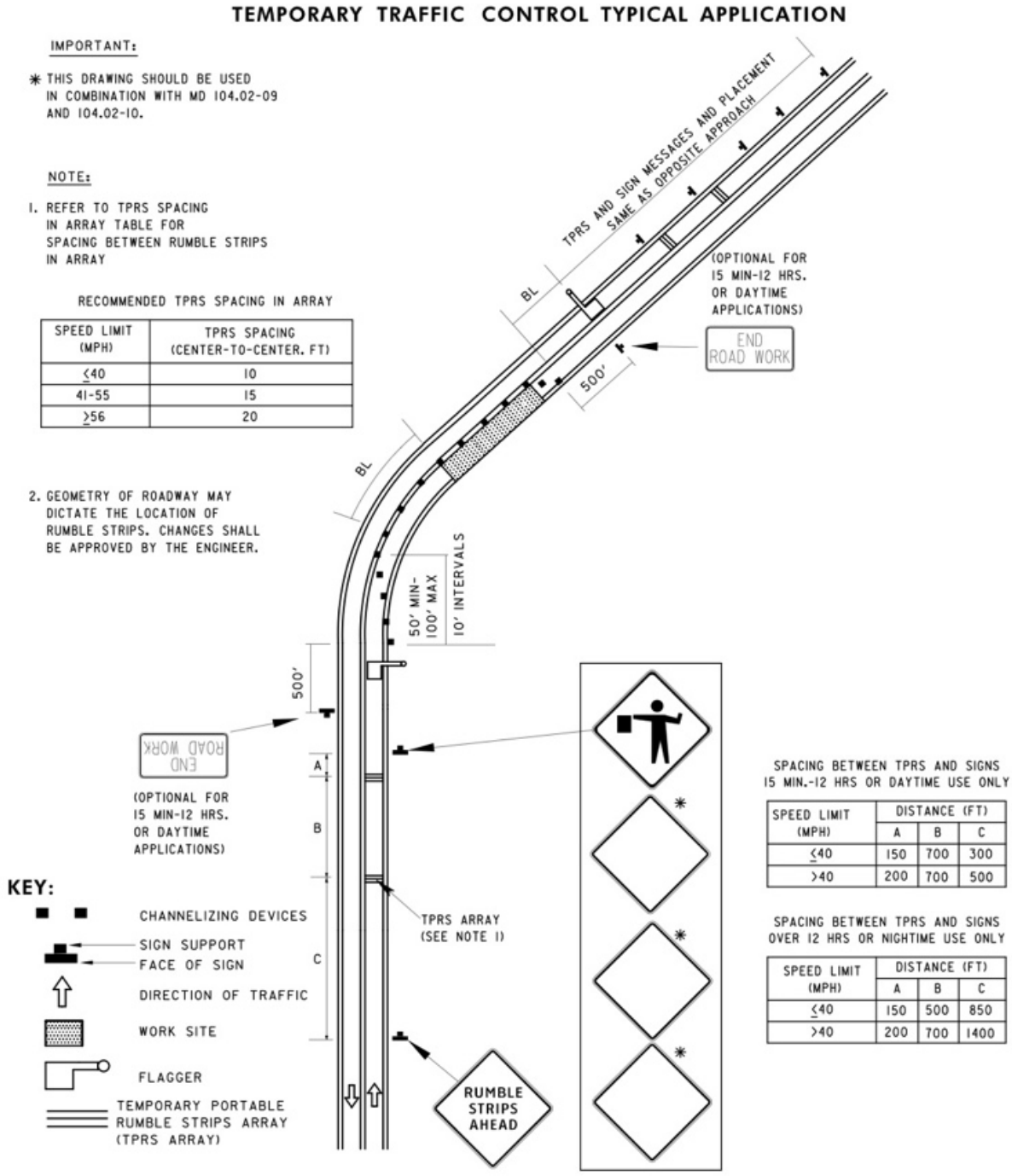
(Kansas DOT 2015)

Figure C-24. Standard detail drawing for traffic control for flagger or pilot car from Kansas DOT (2/2)



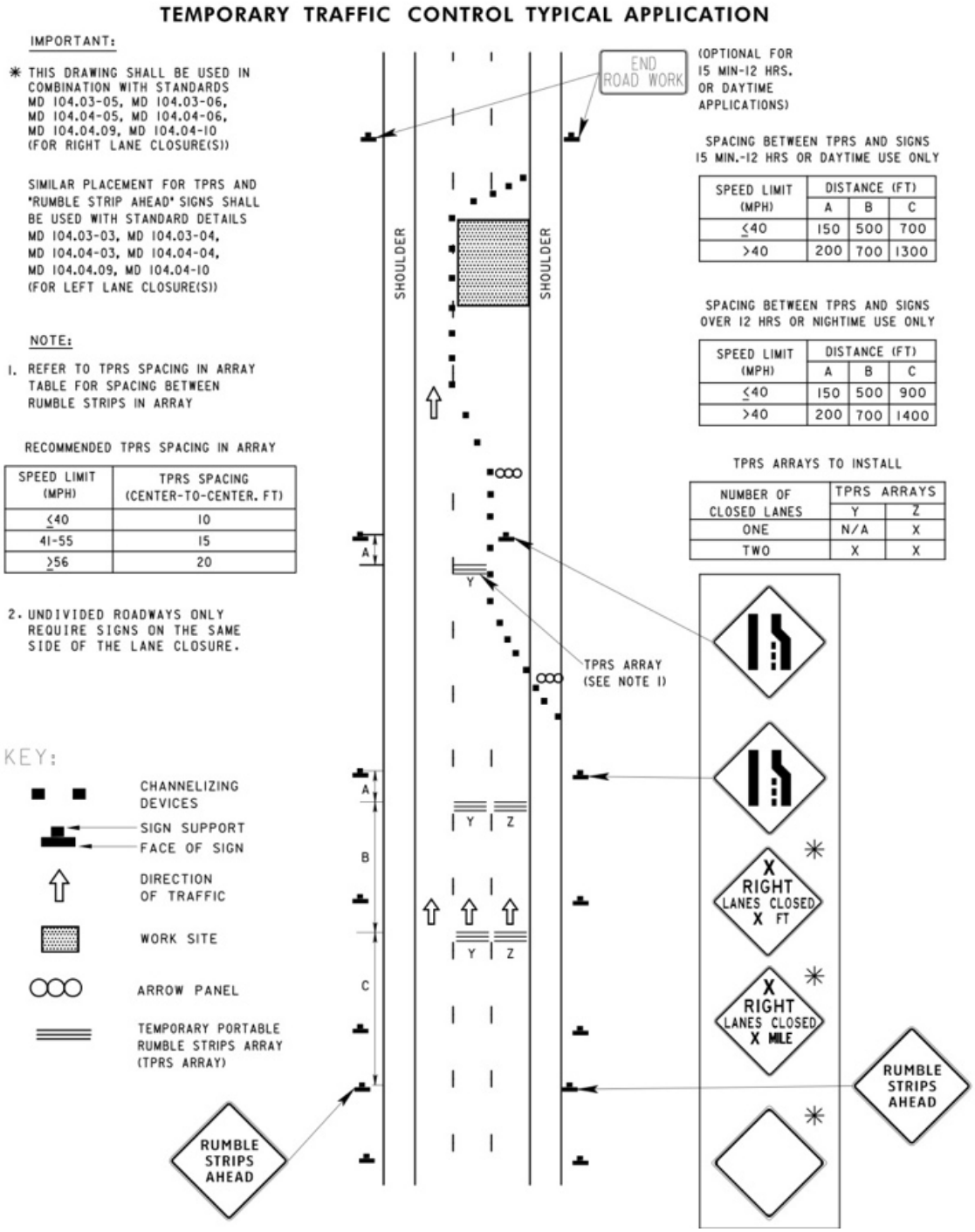
(Kentucky Transportation Cabinet 2021)

Figure C-25. Layout for temporary rumble strips from Kentucky Transportation Cabinet



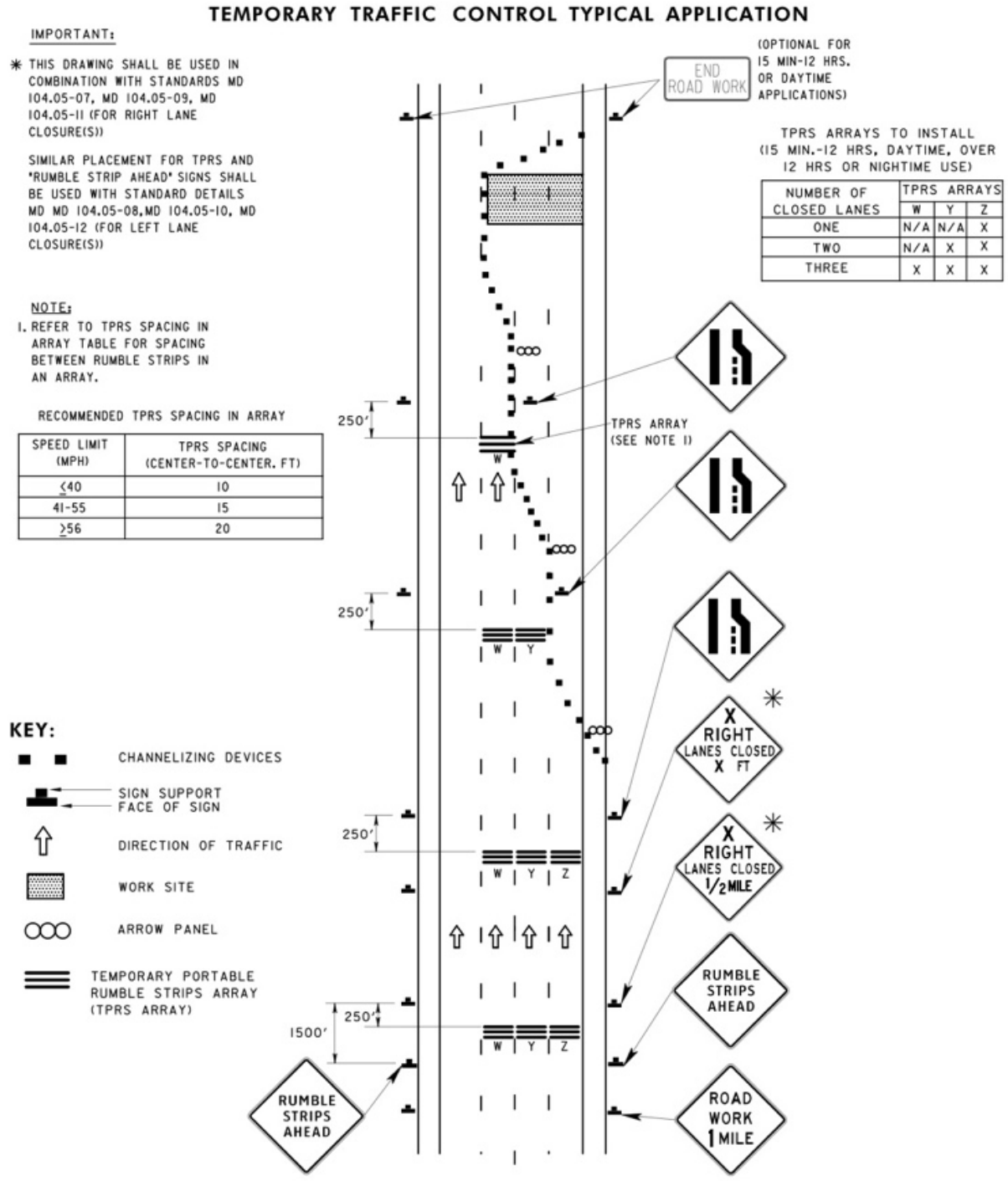
(Maryland DOT SHA 2021a)

Figure C-26. Typical application sheet for flagging operation with TPRS from Maryland DOT SHA



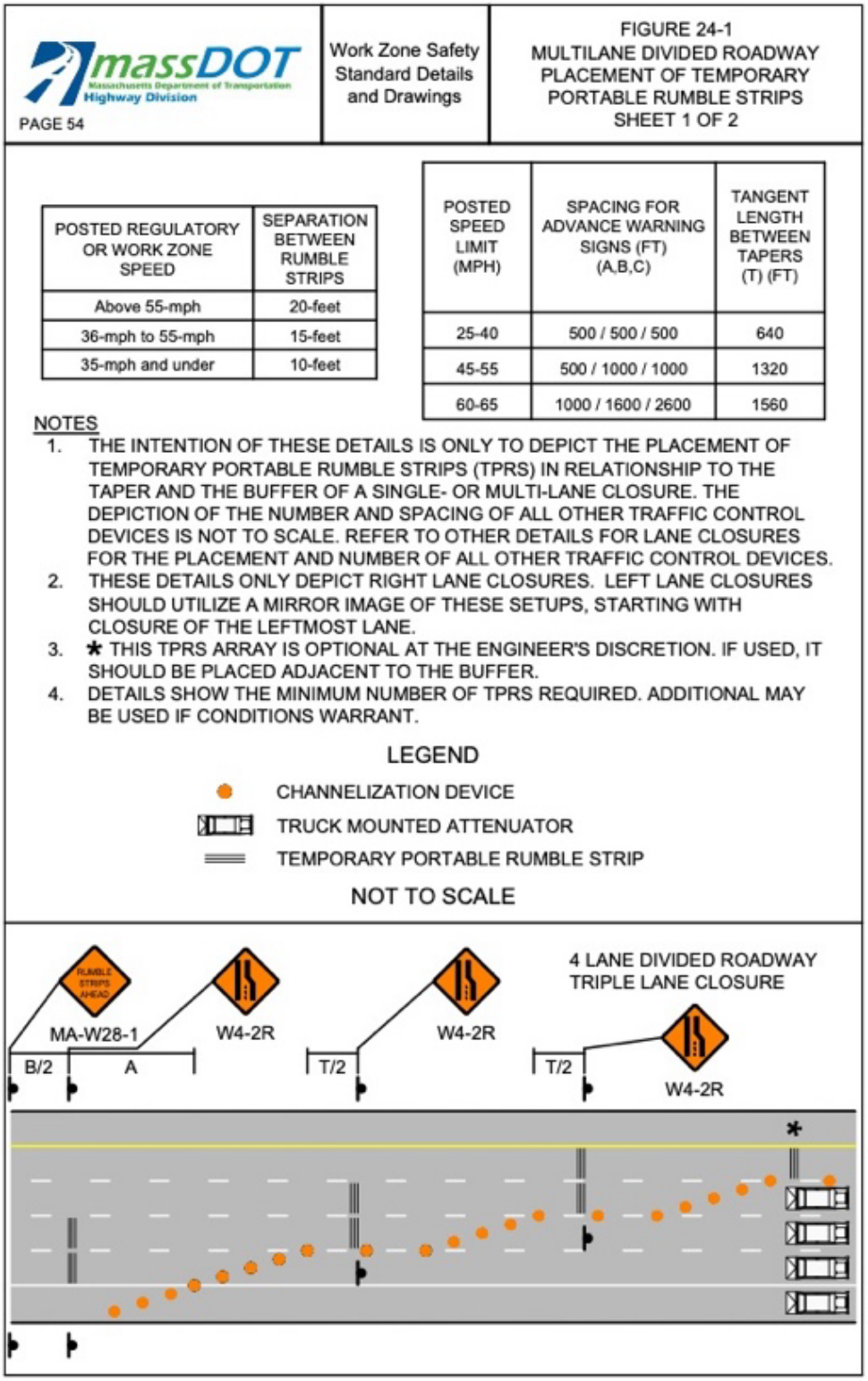
(Maryland DOT SHA 2021a)

Figure C-27. Typical application sheet for lane closure on multi-lane undivided or divided highway with TPRS from Maryland DOT SHA



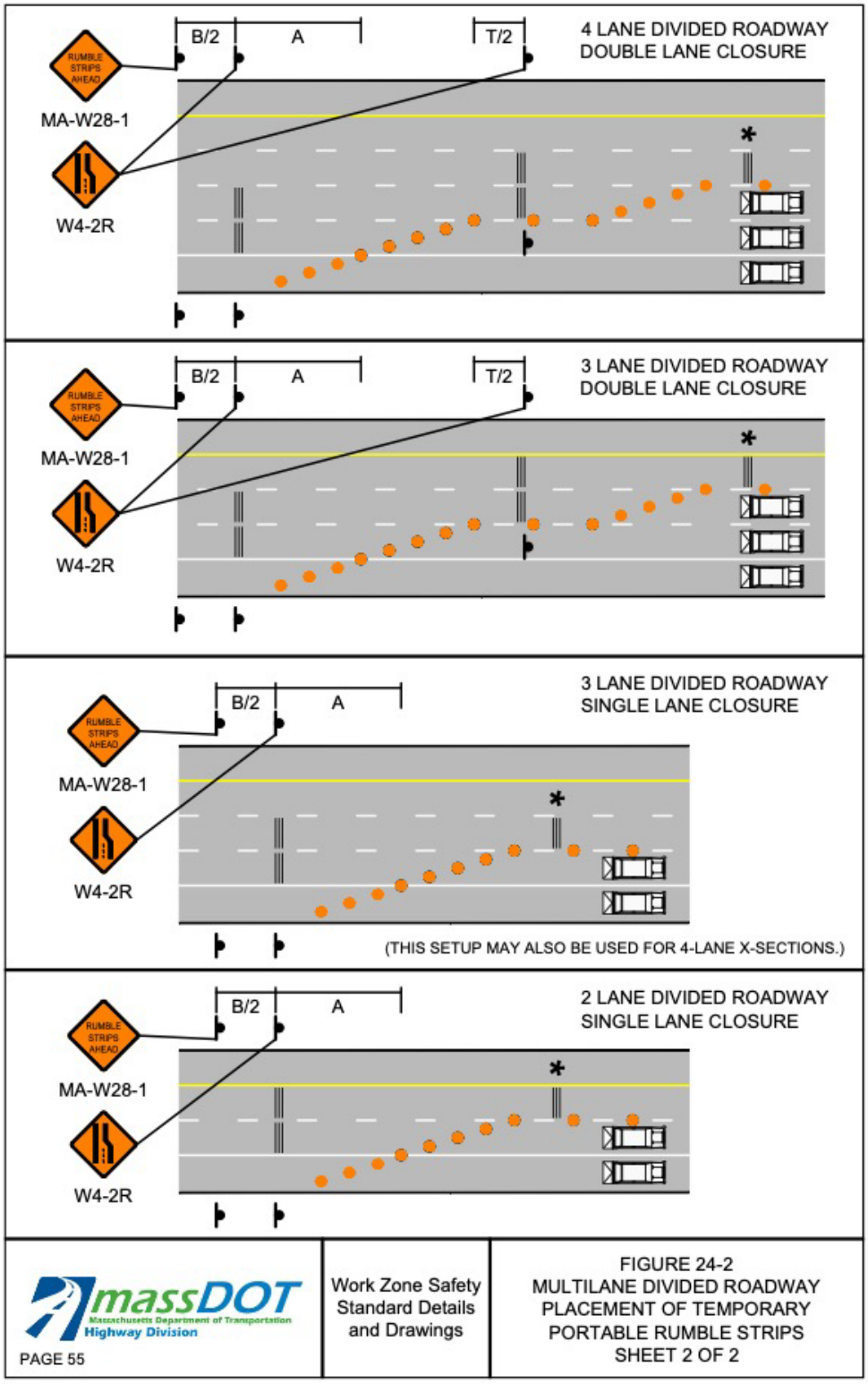
(Maryland DOT SHA 2021a)

Figure C-28. Typical detail for lane closure on expressway or freeway with TPRS from Maryland DOT SHA



(Massachusetts DOT 2017)

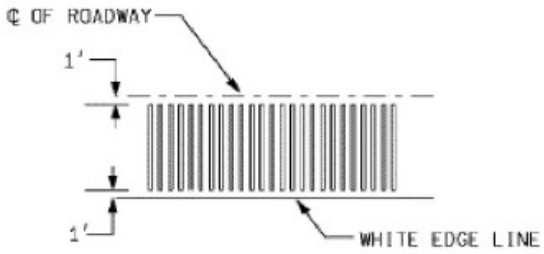
Figure C-29. Standard detail for placement of TPRS on multi-lane divided roadway from Massachusetts DOT (1/2)



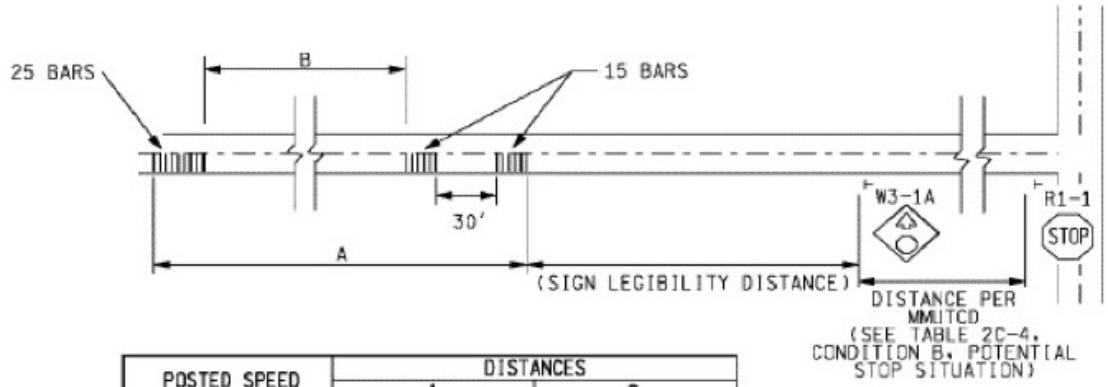
(Massachusetts DOT 2017)

Figure C-30. Standard detail for placement of TPRS on multi-lane divided roadway from Massachusetts DOT (2/2)

PROFILE VIEW



PLAN VIEW



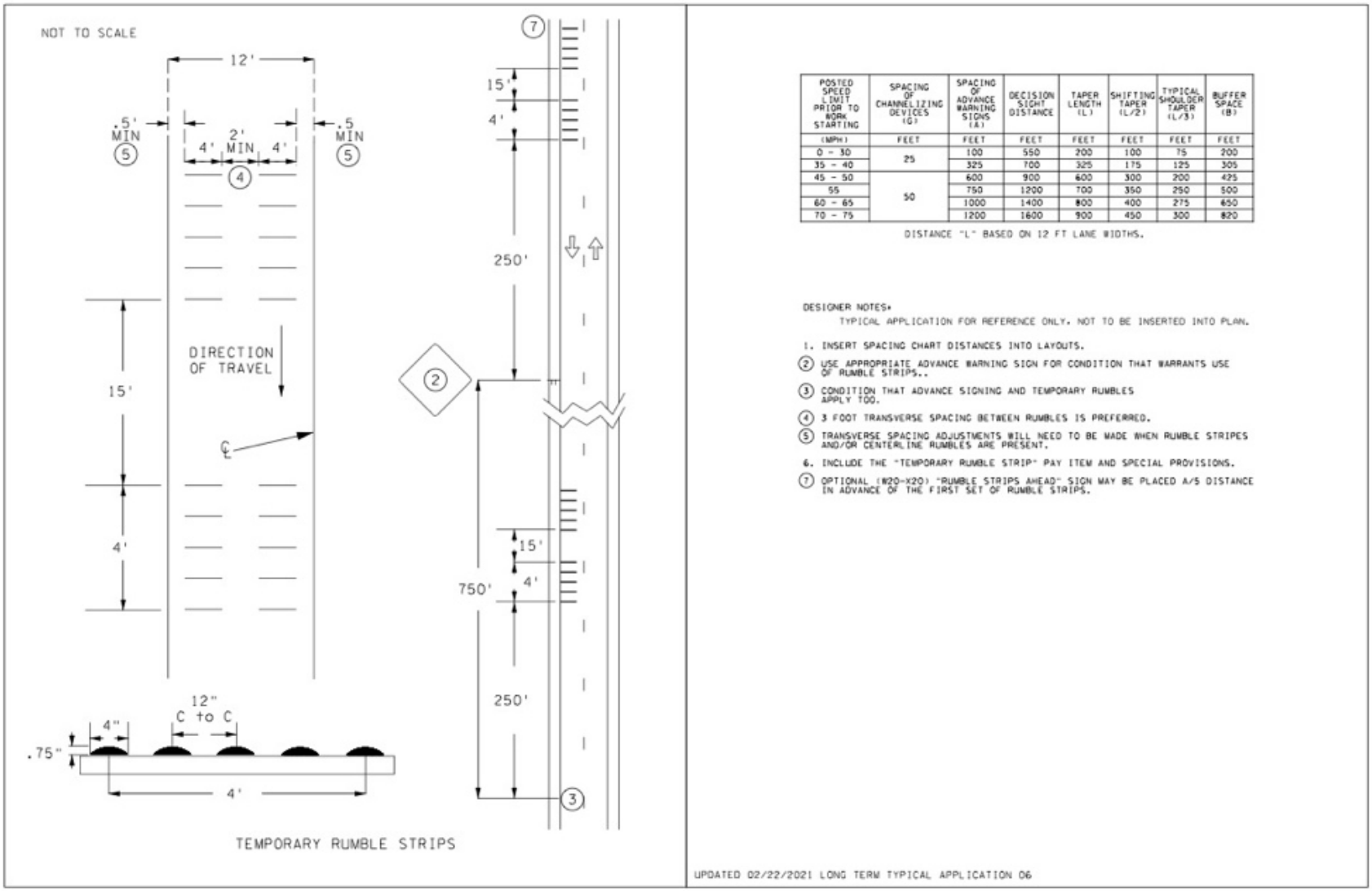
POSTED SPEED	DISTANCES	
	A	B
45 MPH	200 FT	115 FT
50 MPH	230 FT	145 FT
55 MPH	245 FT	160 FT

LOCATION

NOTE: DISTANCES GIVEN ARE MINIMUM VALUES

(Michigan DOT 2020)

Figure C-31. Temporary rumble strip layout for use in advance of a stop condition from Michigan DOT



POSTED SPEED LIMIT PRIOR TO WORK STARTING	SPACING OF CHANNELIZING DEVICES (G)	SPACING OF ADVANCE WARNING SIGNS (A)	DECISION SIGHT DISTANCE	TAPER LENGTH (L)	SHIFTING TAPER (L/2)	TYPICAL SHOULDER TAPER (L/3)	BUFFER SPACE (B)
(MPH)	FEET	FEET	FEET	FEET	FEET	FEET	FEET
0 - 30	25	100	550	200	100	75	200
35 - 40		325	700	325	175	125	305
45 - 50		600	900	600	300	200	425
55	50	750	1200	700	350	250	500
60 - 65		1000	1400	800	400	275	650
70 - 75		1200	1600	900	450	300	820

DISTANCE "L" BASED ON 12 FT LANE WIDTHS.

DESIGNER NOTES:

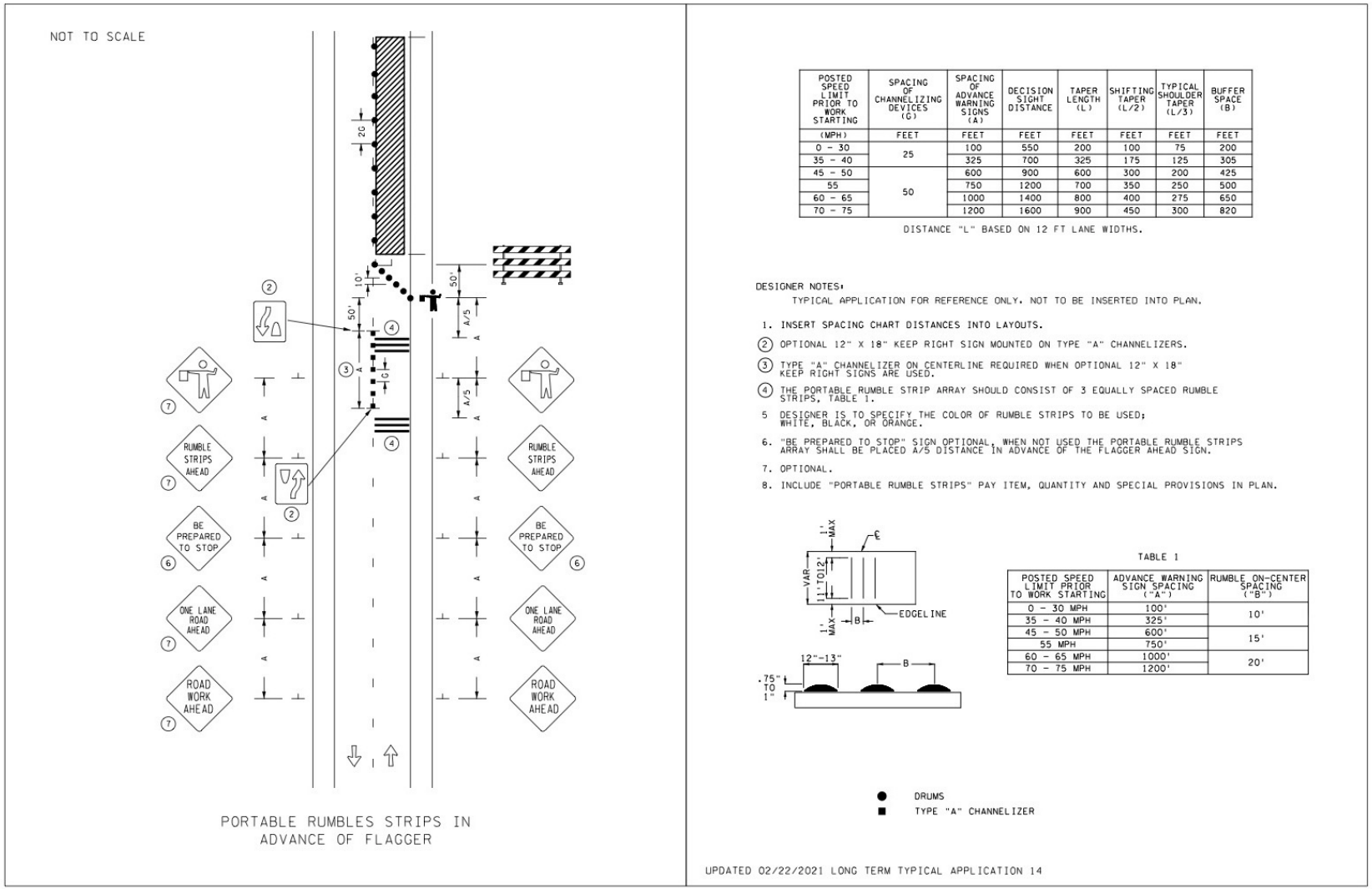
TYPICAL APPLICATION FOR REFERENCE ONLY. NOT TO BE INSERTED INTO PLAN.

1. INSERT SPACING CHART DISTANCES INTO LAYOUTS.
2. USE APPROPRIATE ADVANCE WARNING SIGN FOR CONDITION THAT WARRANTS USE OF RUMBLE STRIPS..
3. CONDITION THAT ADVANCE SIGNING AND TEMPORARY RUMBLES APPLY TOO.
4. 3 FOOT TRANSVERSE SPACING BETWEEN RUMBLES IS PREFERRED.
5. TRANSVERSE SPACING ADJUSTMENTS WILL NEED TO BE MADE WHEN RUMBLE STRIPES AND/OR CENTERLINE RUMBLES ARE PRESENT.
6. INCLUDE THE "TEMPORARY RUMBLE STRIP" PAY ITEM AND SPECIAL PROVISIONS.
7. OPTIONAL (W20-X20) "RUMBLE STRIPS AHEAD" SIGN MAY BE PLACED A/S DISTANCE IN ADVANCE OF THE FIRST SET OF RUMBLE STRIPS.

UPDATED 02/22/2021 LONG TERM TYPICAL APPLICATION 06

(Minnesota DOT 2021b)

Figure C-32. Long-term typical application sheet for temporary rumble strips from Minnesota DOT

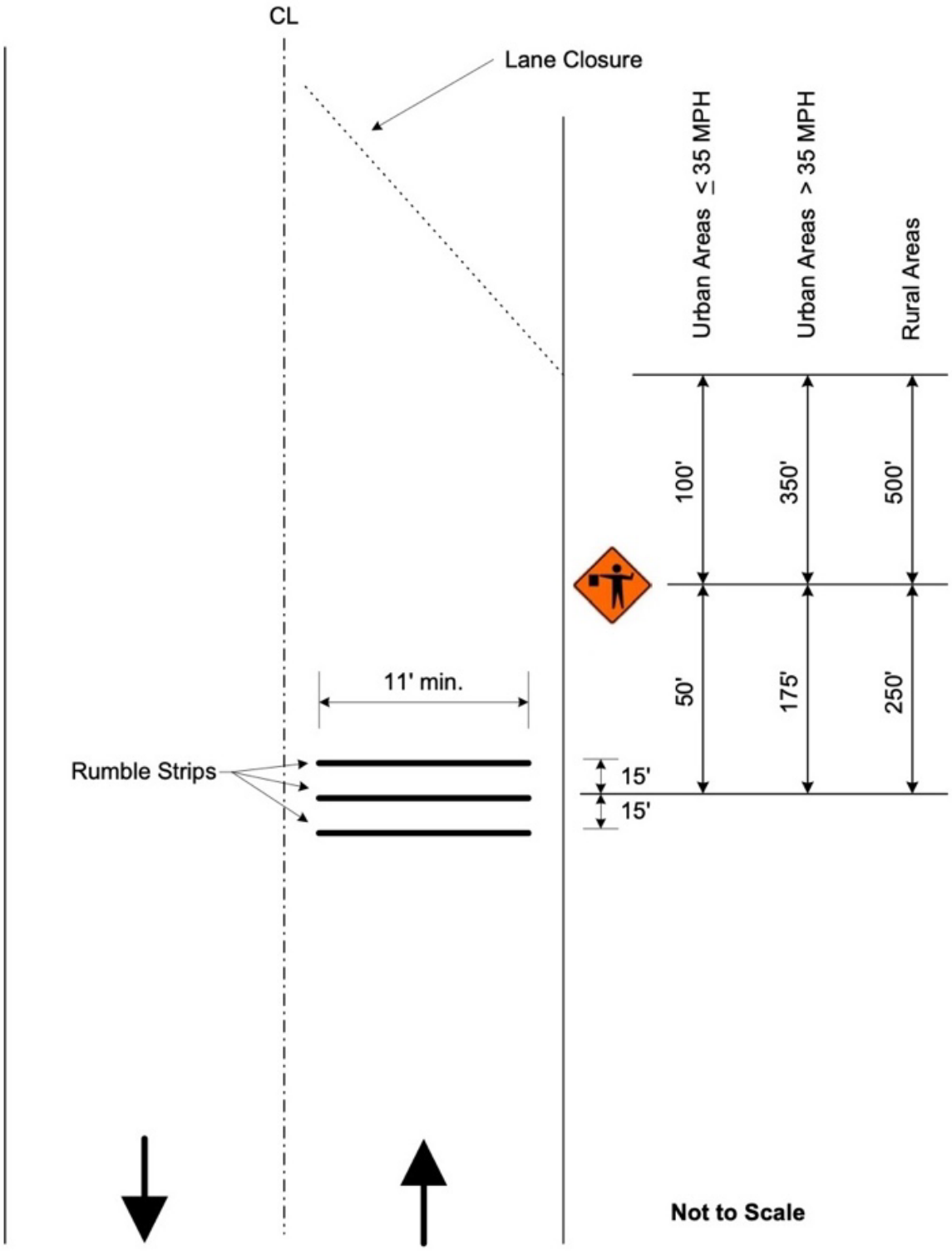


POSTED SPEED LIMIT PRIOR TO WORK STARTING	SPACING OF CHANNELIZING DEVICES (G)	SPACING OF ADVANCE WARNING SIGNS (A)	DECISION SIGHT DISTANCE	TAPER LENGTH (L)	SHIFTING TAPER (L/2)	TYPICAL SHOULDER TAPER (L/3)	BUFFER SPACE (B)
(MPH)	FEET	FEET	FEET	FEET	FEET	FEET	FEET
0 - 30	25	100	550	200	100	75	200
35 - 40		325	700	325	175	125	305
45 - 50	50	600	900	600	300	200	425
55		750	1200	700	350	250	500
60 - 65		1000	1400	800	400	275	650
70 - 75		1200	1600	900	450	300	820

POSTED SPEED LIMIT PRIOR TO WORK STARTING	ADVANCE WARNING SIGN SPACING ("A")	RUMBLE ON-CENTER SPACING ("B")
0 - 30 MPH	100'	10'
35 - 40 MPH	325'	
45 - 50 MPH	600'	15'
55 MPH	750'	
60 - 65 MPH	1000'	20'
70 - 75 MPH	1200'	

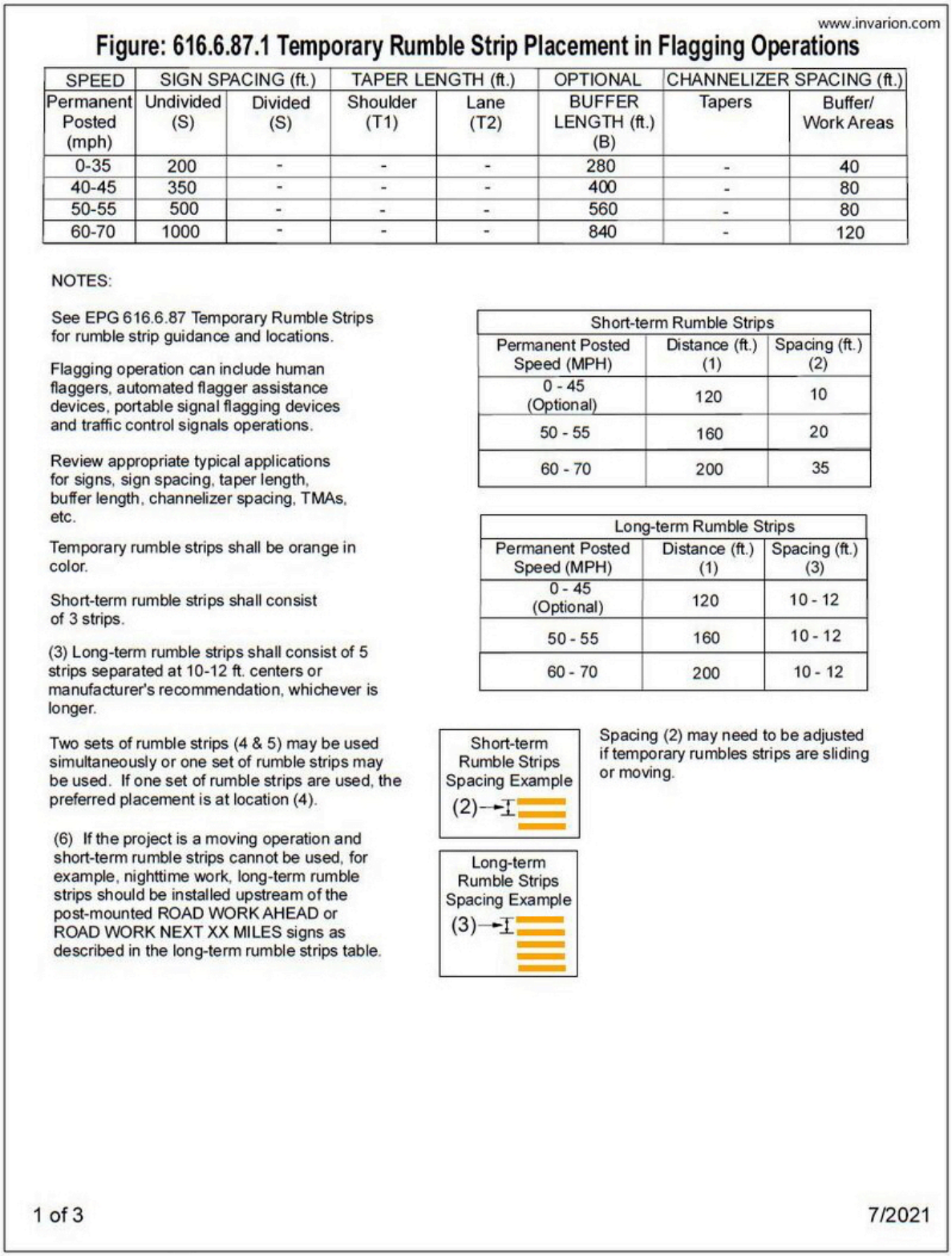
(Minnesota DOT 2021b)

Figure C-33. Long term typical application sheet for TPRS in advance of flagger from Minnesota DOT



(Mississippi DOT 2018)

Figure C-34. Layout of TPRS from Mississippi DOT



www.invarion.com

Figure: 616.6.87.1 Temporary Rumble Strip Placement in Flagging Operations

SPEED	SIGN SPACING (ft.)		TAPER LENGTH (ft.)		OPTIONAL	CHANNELIZER SPACING (ft.)	
Permanent Posted (mph)	Undivided (S)	Divided (S)	Shoulder (T1)	Lane (T2)	BUFFER LENGTH (ft.) (B)	Tapers	Buffer/ Work Areas
0-35	200	-	-	-	280	-	40
40-45	350	-	-	-	400	-	80
50-55	500	-	-	-	560	-	80
60-70	1000	-	-	-	840	-	120

NOTES:

See EPG 616.6.87 Temporary Rumble Strips for rumble strip guidance and locations.

Flagging operation can include human flaggers, automated flagger assistance devices, portable signal flagging devices and traffic control signals operations.

Review appropriate typical applications for signs, sign spacing, taper length, buffer length, channelizer spacing, TMAs, etc.

Temporary rumble strips shall be orange in color.

Short-term rumble strips shall consist of 3 strips.

(3) Long-term rumble strips shall consist of 5 strips separated at 10-12 ft. centers or manufacturer's recommendation, whichever is longer.

Two sets of rumble strips (4 & 5) may be used simultaneously or one set of rumble strips may be used. If one set of rumble strips are used, the preferred placement is at location (4).

(6) If the project is a moving operation and short-term rumble strips cannot be used, for example, nighttime work, long-term rumble strips should be installed upstream of the post-mounted ROAD WORK AHEAD or ROAD WORK NEXT XX MILES signs as described in the long-term rumble strips table.

Short-term Rumble Strips		
Permanent Posted Speed (MPH)	Distance (ft.) (1)	Spacing (ft.) (2)
0 - 45 (Optional)	120	10
50 - 55	160	20
60 - 70	200	35

Long-term Rumble Strips		
Permanent Posted Speed (MPH)	Distance (ft.) (1)	Spacing (ft.) (3)
0 - 45 (Optional)	120	10 - 12
50 - 55	160	10 - 12
60 - 70	200	10 - 12

Short-term Rumble Strips Spacing Example

(2)

Long-term Rumble Strips Spacing Example

(3)

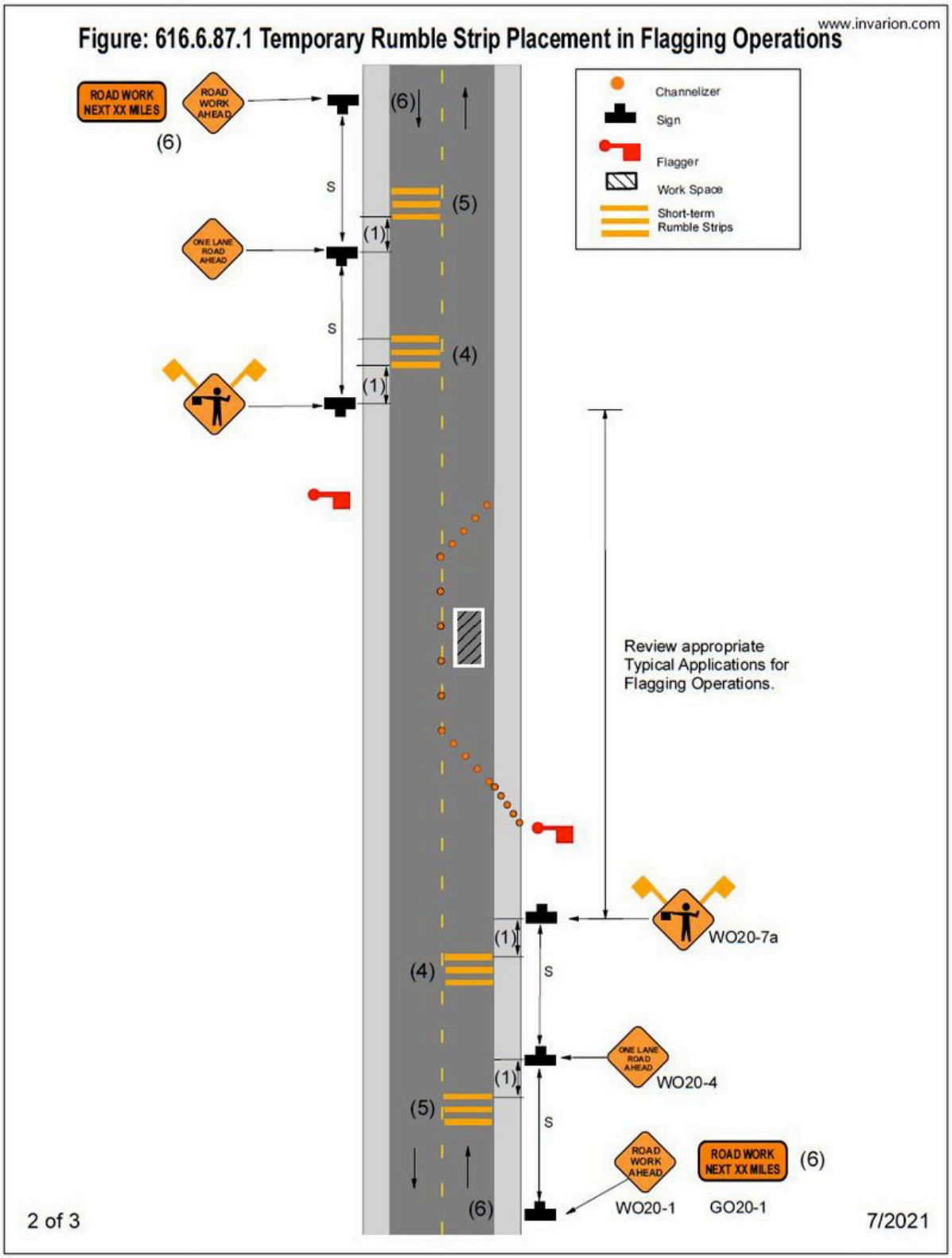
Spacing (2) may need to be adjusted if temporary rumbles strips are sliding or moving.

1 of 3

7/2021

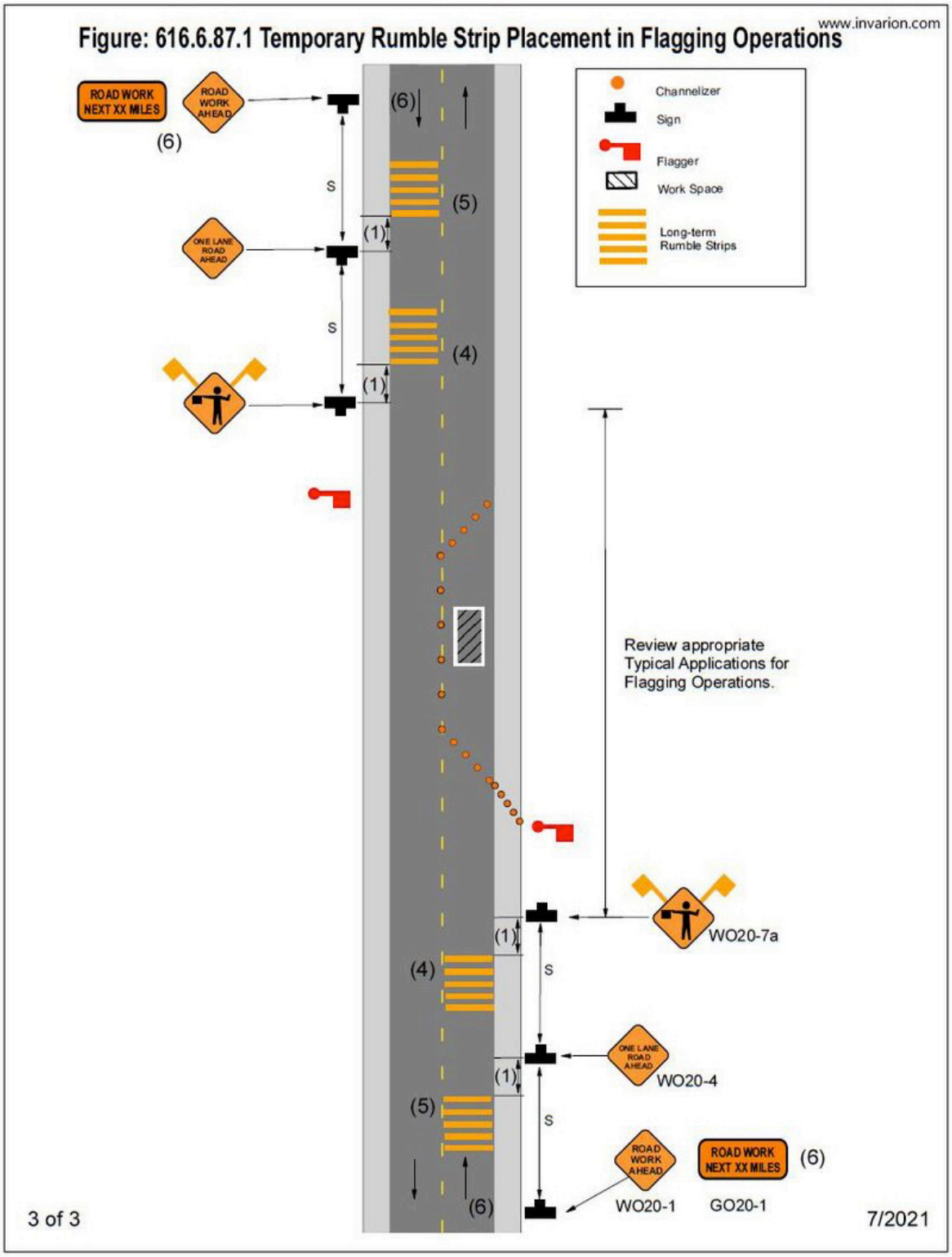
(Missouri DOT 2021a)

Figure C-35. Guidelines for temporary rumble strip placement in flagging operation from Missouri DOT (1/3)



(Missouri DOT 2021a)

Figure C-36. Standard detail for placement of short-term temporary rumble strips in flagging operation from Missouri DOT (2/3)



(Missouri DOT 2021a)

Figure C-37. Standard detail for placement of long-term temporary rumble strips placement in flagging operation from Missouri DOT (3/3)

Figure: 616.6.87.2 Rumble Strip Placement on a Divided Highway

SPEED	SIGN SPACING (ft.)		TAPER LENGTH (ft.)		OPTIONAL	CHANNELIZER SPACING (ft.)	
Permanent Posted (mph)	Undivided (S)	Divided (S)	Shoulder (1) (T1)	Lane (2) (T2)	BUFFER LENGTH (ft.) (B)	Tapers	Buffer/ Work Areas
0-35	-	200	70	245	280	35	40
40-45	-	500	150	540	400	40	80
50-55	-	1000	185	660	560	50	80
60-70	-	SA - 1000 SB - 1500 SC - 2640	235	840	840	60	120

1 Shoulder taper length based on 10 ft. (standard shoulder width) offset. 2. Lane taper length based on 12 ft. (standard lane width) offset.

Notes:

See EPG 616.6.87 Temporary Rumble Strips for rumble strip guidance and locations.

Review appropriate typical applications for signs, sign spacing, taper length, buffer length, channelizer spacing, TMAs, AWRS, flags, etc.

Temporary rumble strips shall be orange, in color.

Short-term rumble strips shall consist of 3 strips.

(3) Long-term rumble strips shall consist of 5 strips separated at 10-12 ft. centers or manufacturer's recommendation, whichever is longer.

Two sets of rumble strips (4 & 5) may be used simultaneously or one set of rumble strips may be used. If one set of rumble strips are used, the preferred placement is at location (4).

(6) If the project is a moving operation and short-term rumble strips cannot be used, for example, nighttime work, long-term rumble strips should be installed upstream of the post-mounted ROAD WORK AHEAD or ROAD WORK NEXT XX MILES signs as described in the long-term rumble strips table.

Short-term Rumble Strips		
Permanent Posted Speed (MPH)	Distance (ft.) (1)	Spacing (ft.) (2)
0 - 45 (Optional)	120	10
50 - 55	160	20
60 - 70	200	35

Long-term Rumble Strips		
Permanent Posted Speed (MPH)	Distance (ft.) (1)	Spacing (ft.) (3)
0 - 45 (Optional)	120	10 - 12
50 - 55	160	10 - 12
60 - 70	200	10 - 12

Short-term Rumble Strips Spacing Example

Spacing (2) may need to be adjusted if temporary rumbles strips are sliding or moving.

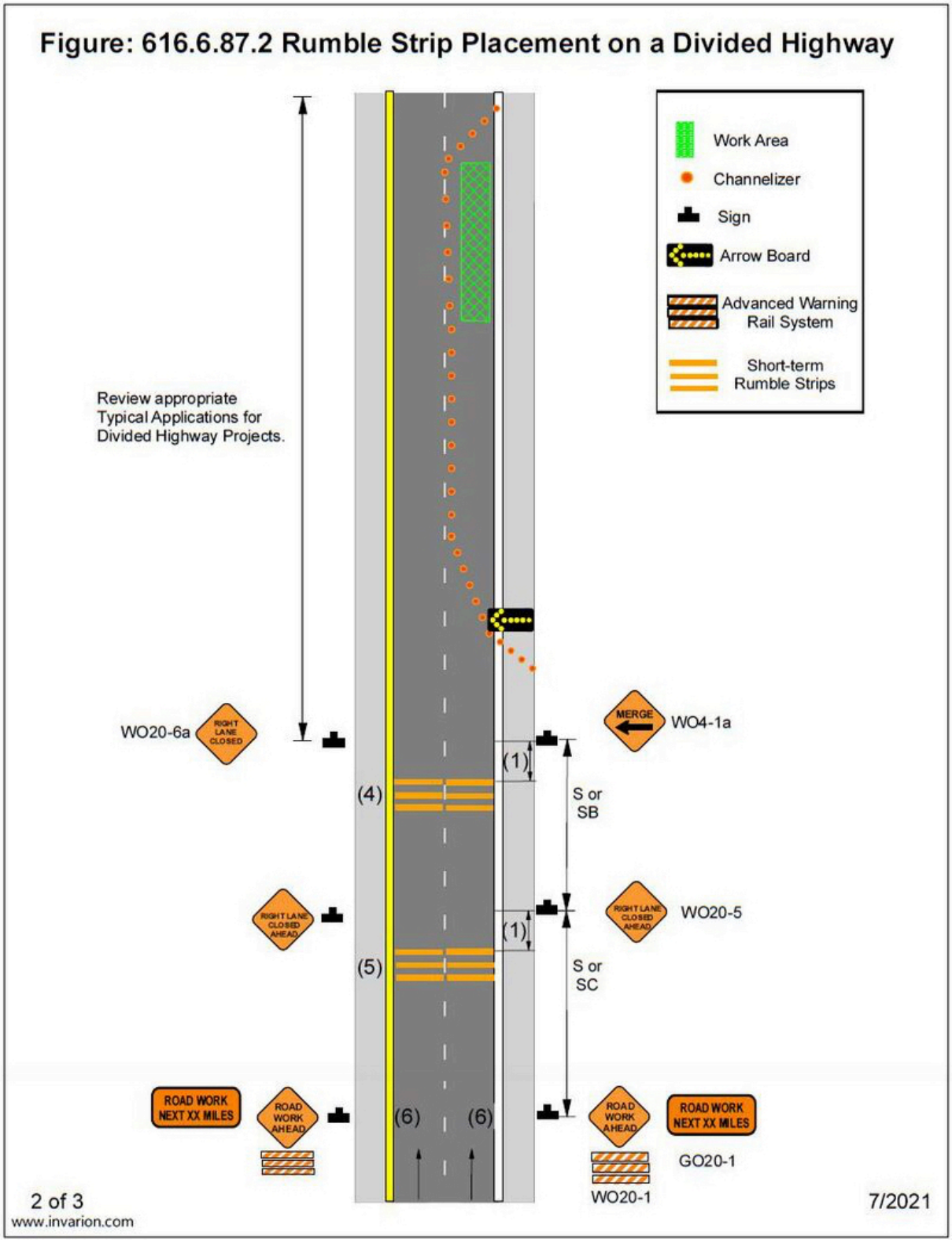
Long-term Rumble Strips Spacing Example

1 of 3

7/2021

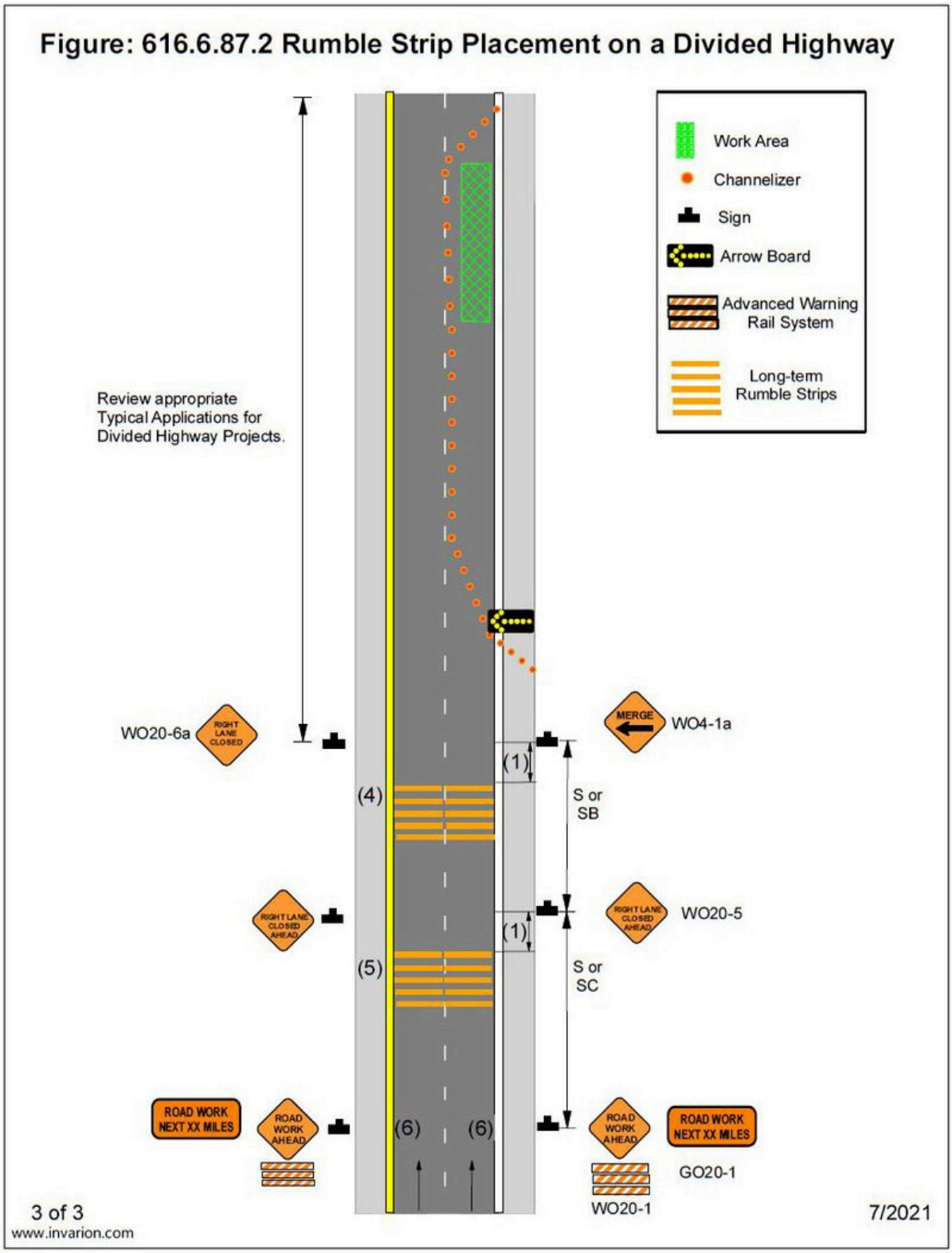
(Missouri DOT 2021a)

Figure C-38. Guidelines for rumble strip placement on a divided highway from Missouri DOT (1/3)



(Missouri DOT 2021a)

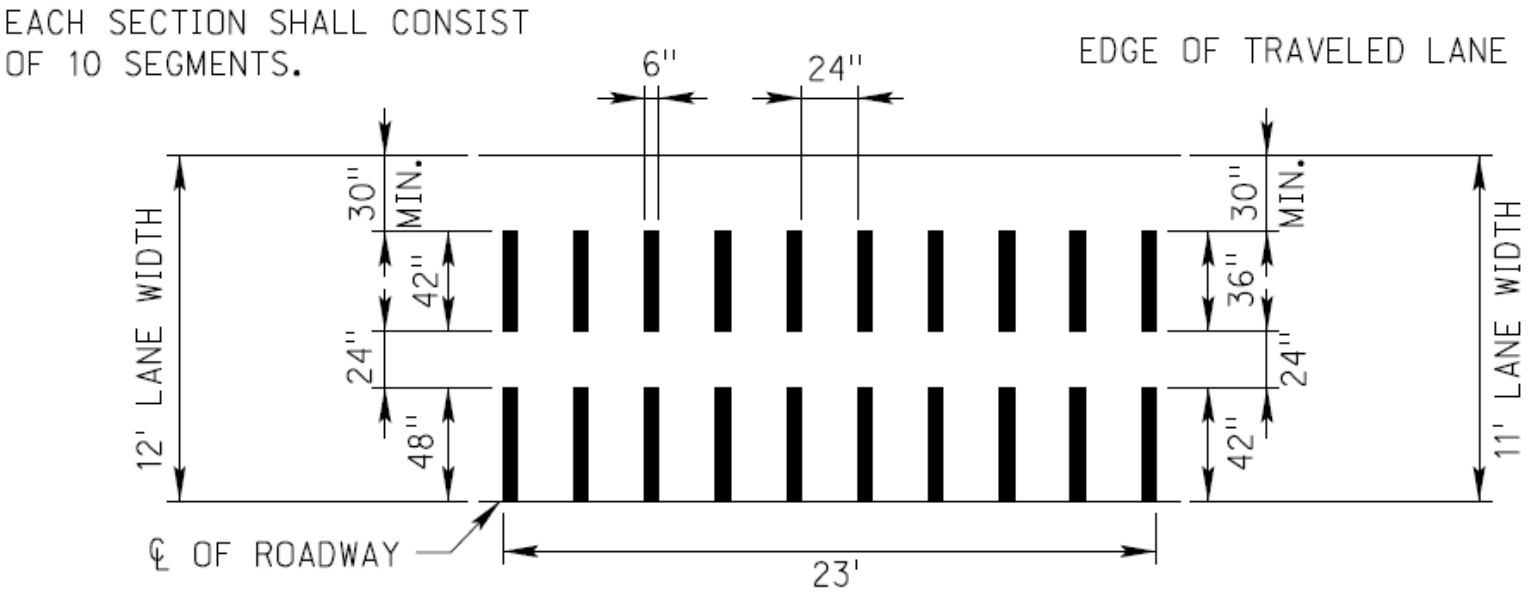
Figure C-39. Standard detail for placement of short-term temporary rumble strips on a divided highway from Missouri DOT (2/3)



(Missouri DOT 2021a)

Figure C-40. Standard detail for placement of long-term temporary rumble strips on a divided highway from Missouri DOT (3/3)

TEMPORARY RUMBLE STRIPS

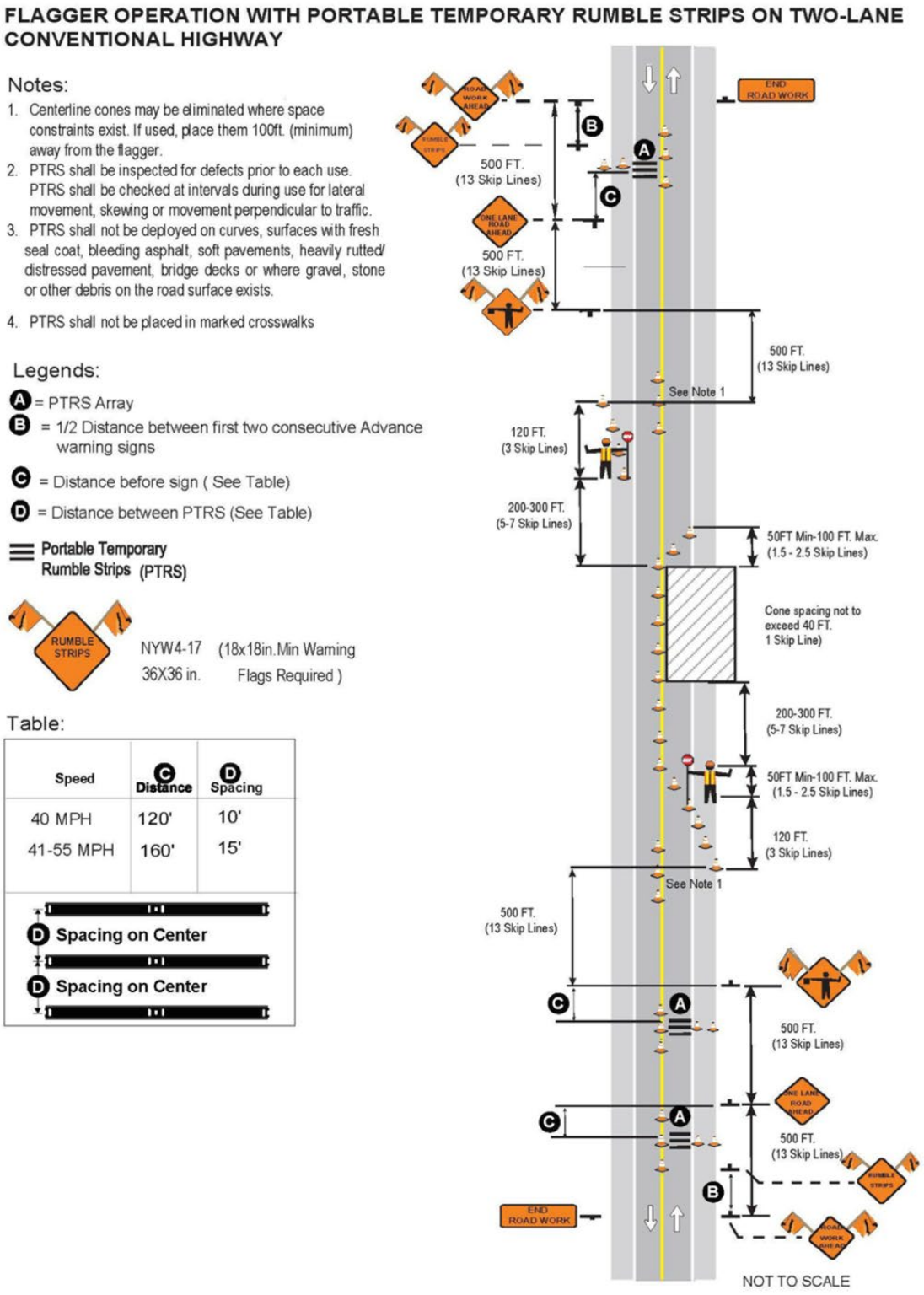


DESIGN

TEMPORARY RUMBLE STRIPS MAY BE MADE OF ASPHALT PAVING MATERIAL, EPOXY AND AGGREGATE OR OTHER SUITABLE MATERIAL WHICH WILL MAINTAIN A DESIRABLE RUMBLE EFFECT. THE TEMPORARY RUMBLE STRIP SHOULD HAVE AN INSTALLED HEIGHT OF $\frac{5}{8}$". PREFORMED RUMBLE STRIPS MAY BE USED PROVIDED THEY HAVE A MINIMUM $\frac{1}{2}$" HEIGHT.

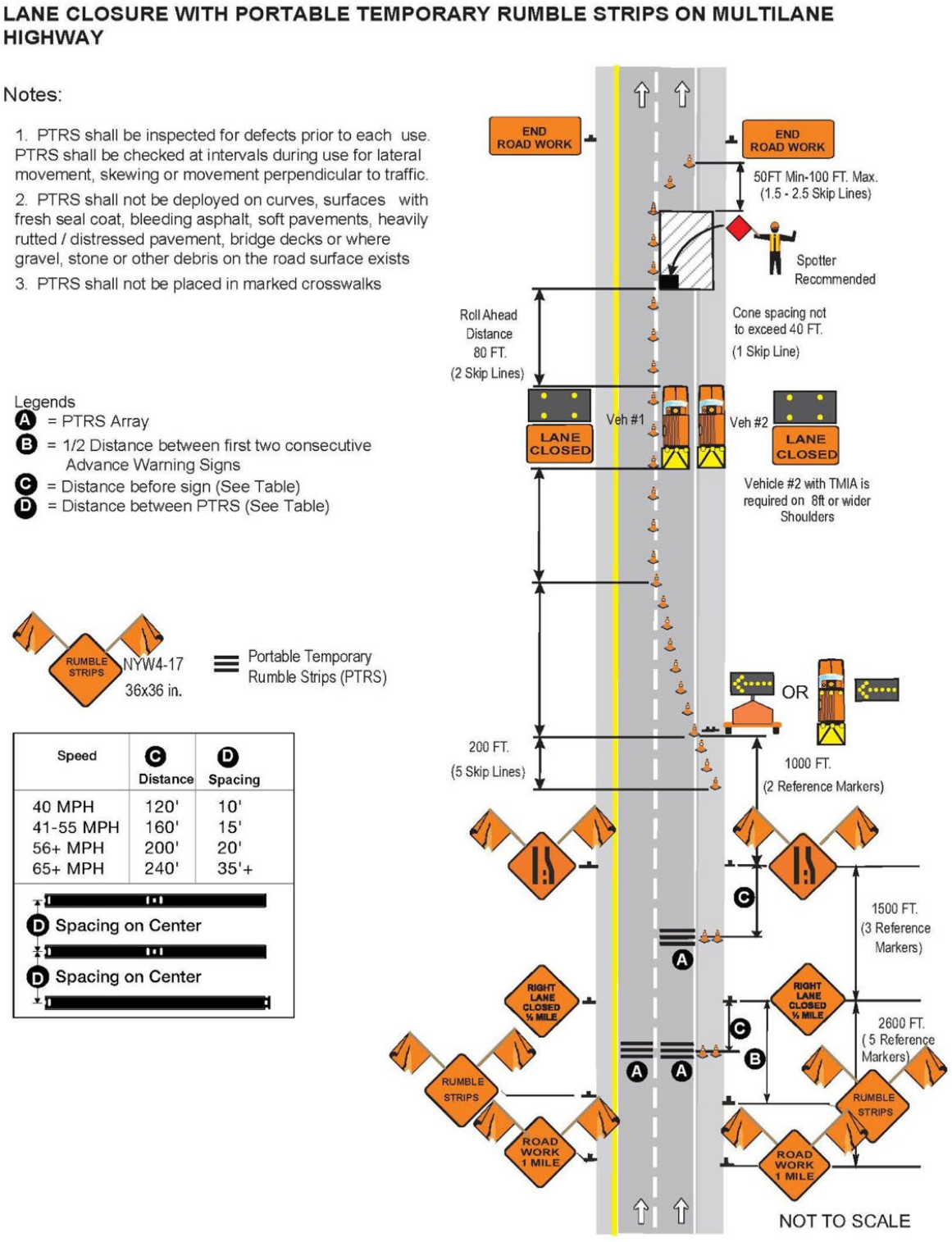
(Nebraska DOT 2021)

Figure C-41. Standard details for temporary rumble strips from Nebraska DOT



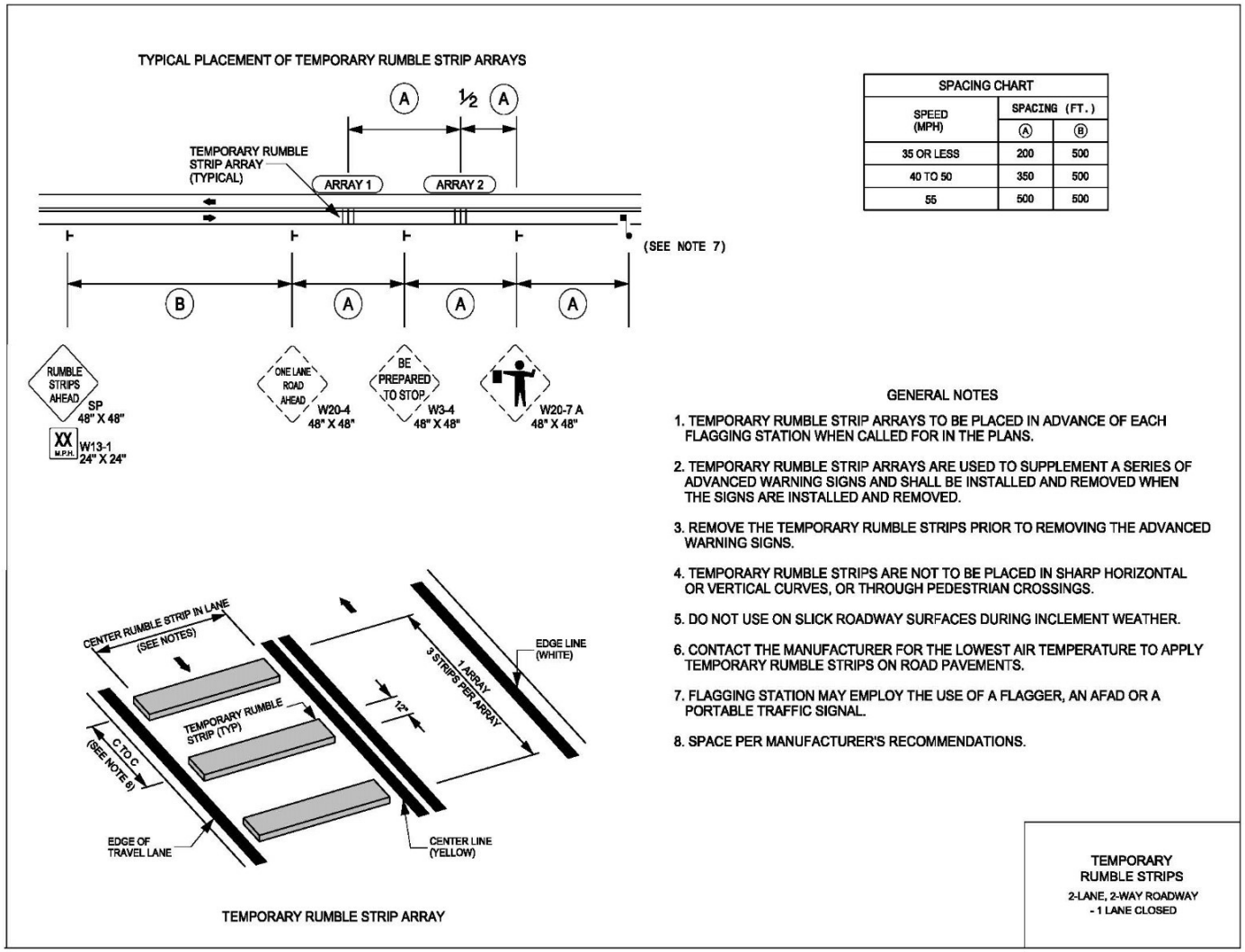
(New York State DOT 2020)

Figure C-42. Standard layout for flagger operation with TPRS on two-lane highway from New York State DOT



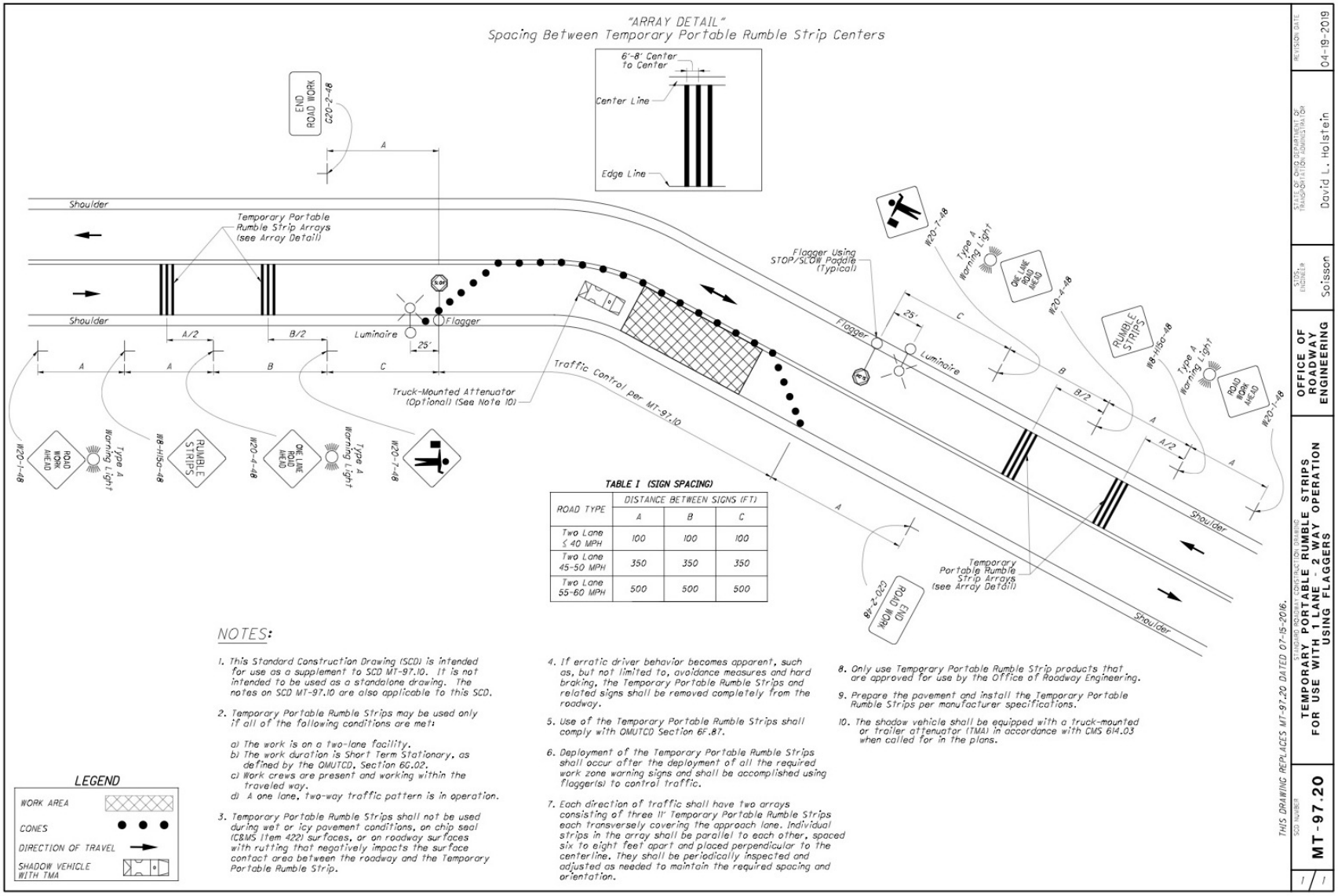
(New York State DOT 2020)

Figure C-43. Standard layout for lane closure with TPRS on multi-lane highway from New York State DOT



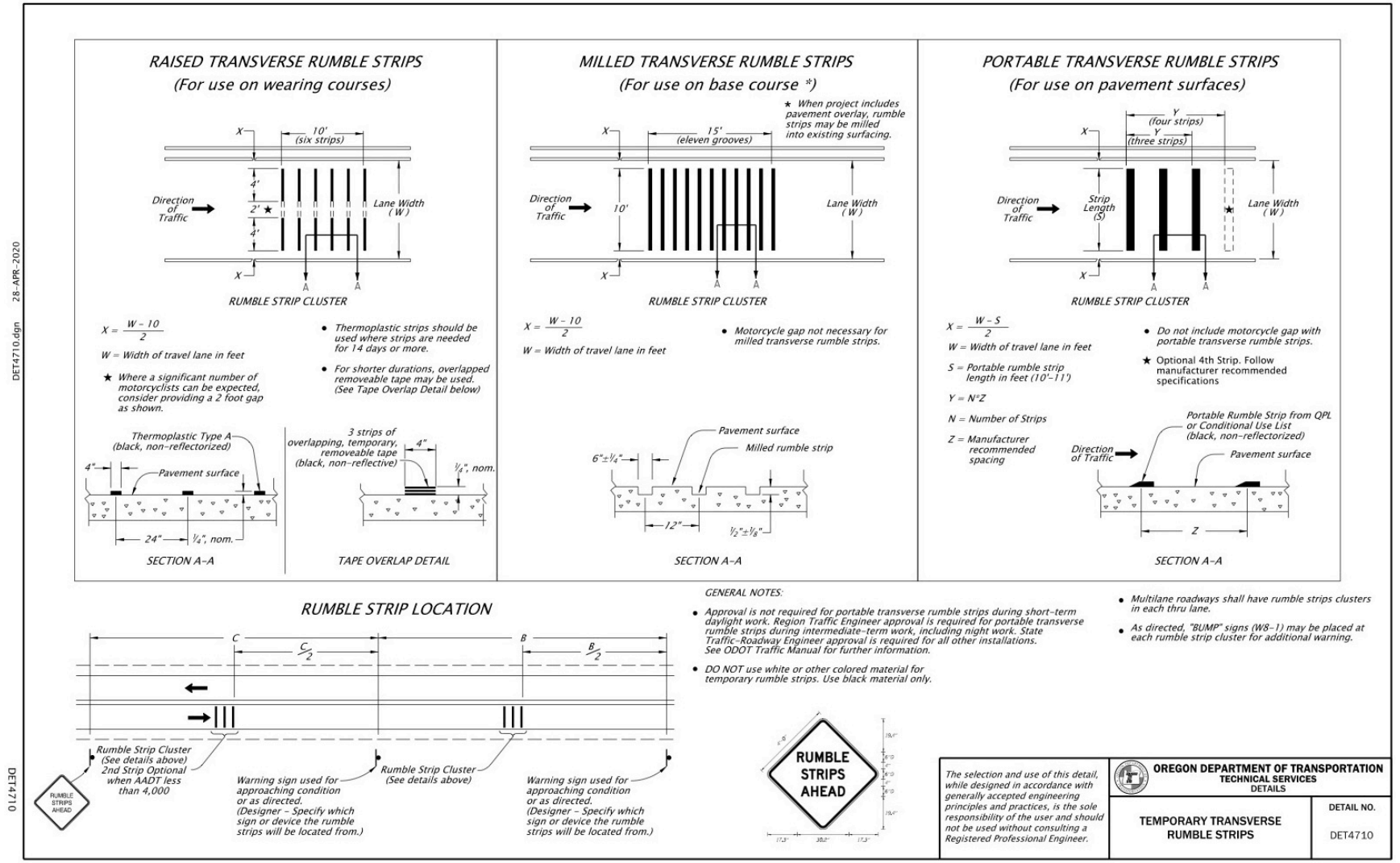
(North Carolina DOT 2015)

Figure C-44. Typical placement of temporary rumble strip sets for 2-lane, 2-way roadway with 1 lane closed from North Carolina DOT



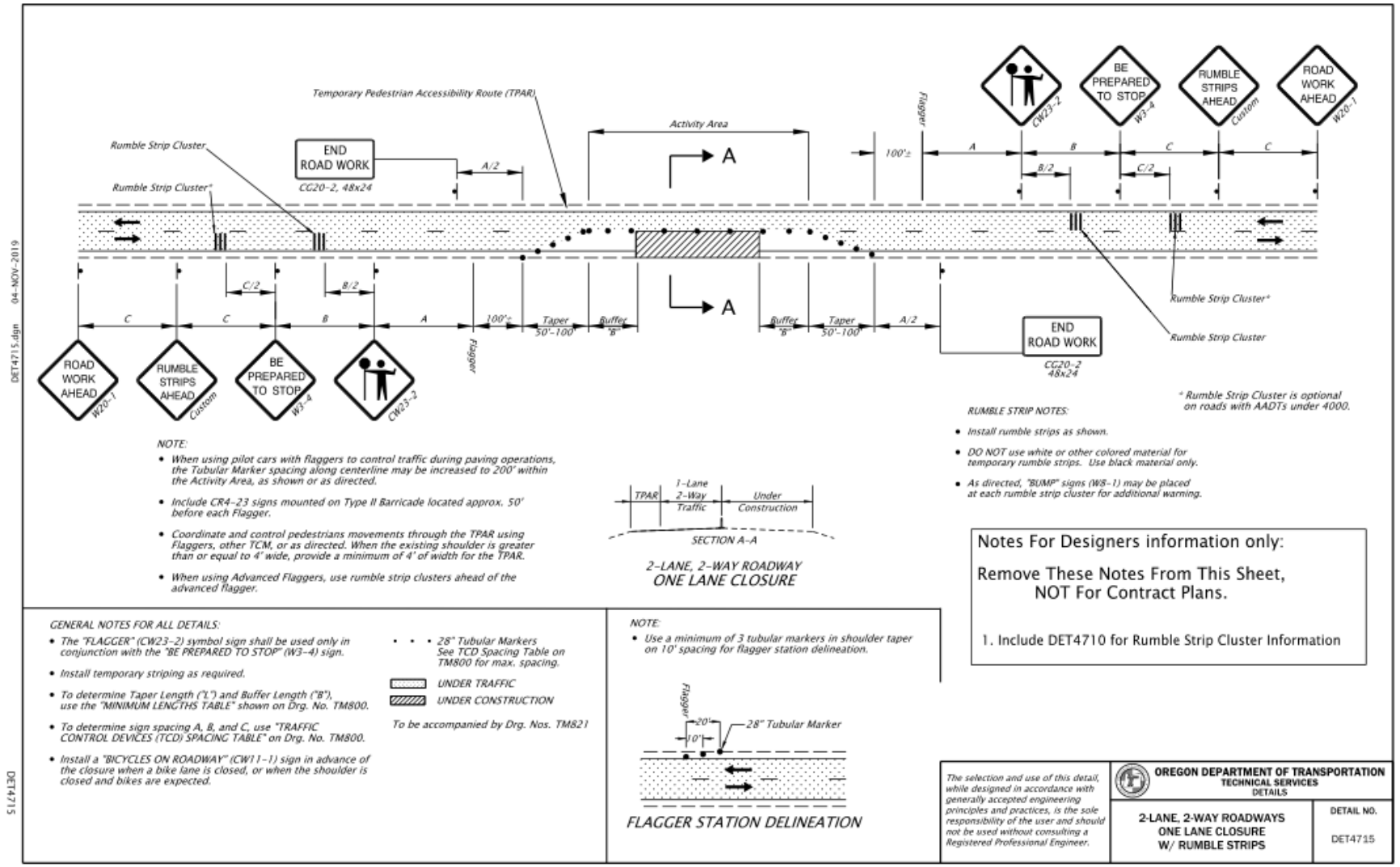
(Ohio DOT 2015)

Figure C-45. Layout of TPRS for use with 1 lane – 2 way operation using flaggers from Ohio DOT



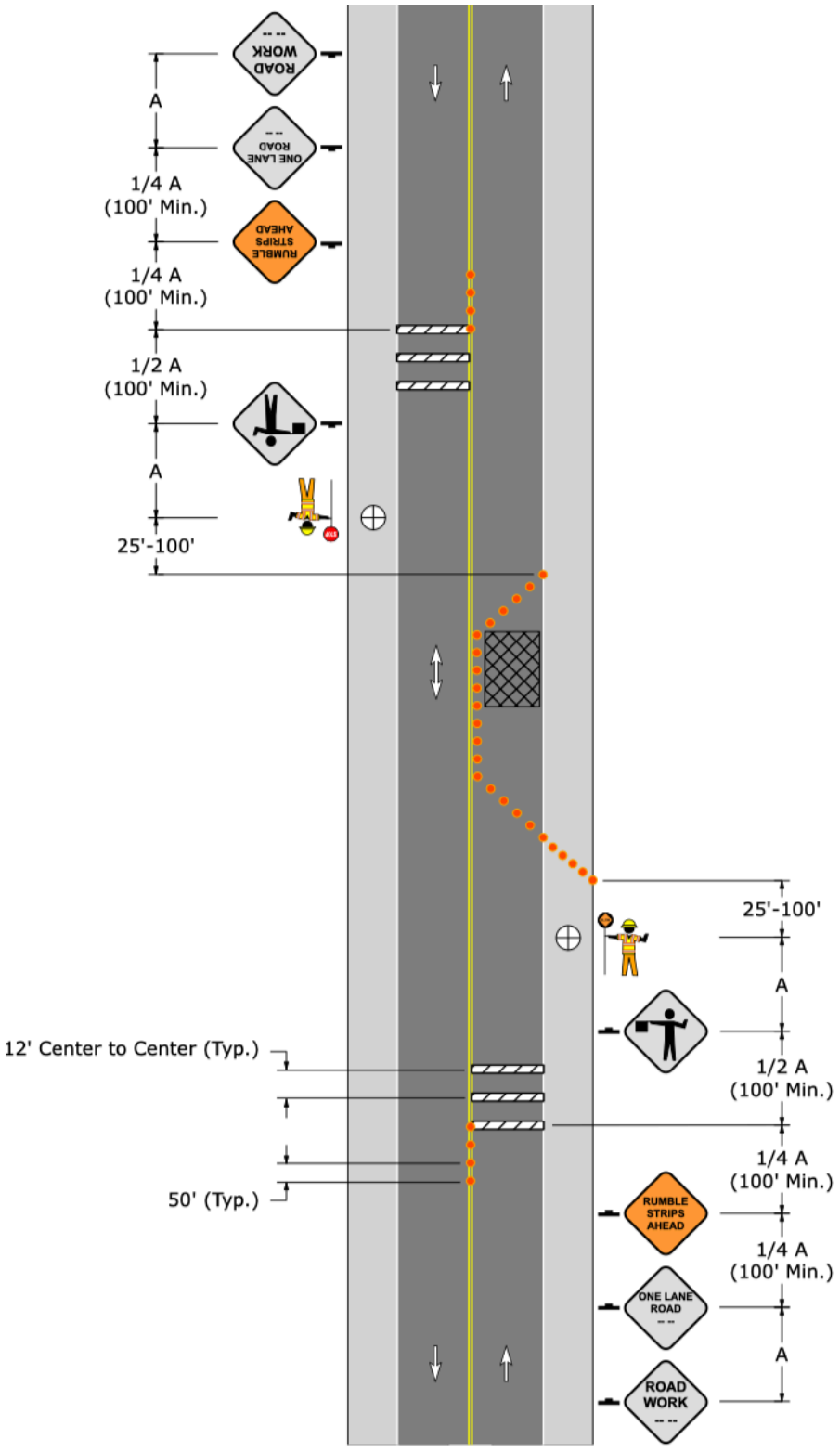
(Oregon DOT 2021b)

Figure C-46. Standard detail of temporary transverse rumble strips from Oregon DOT



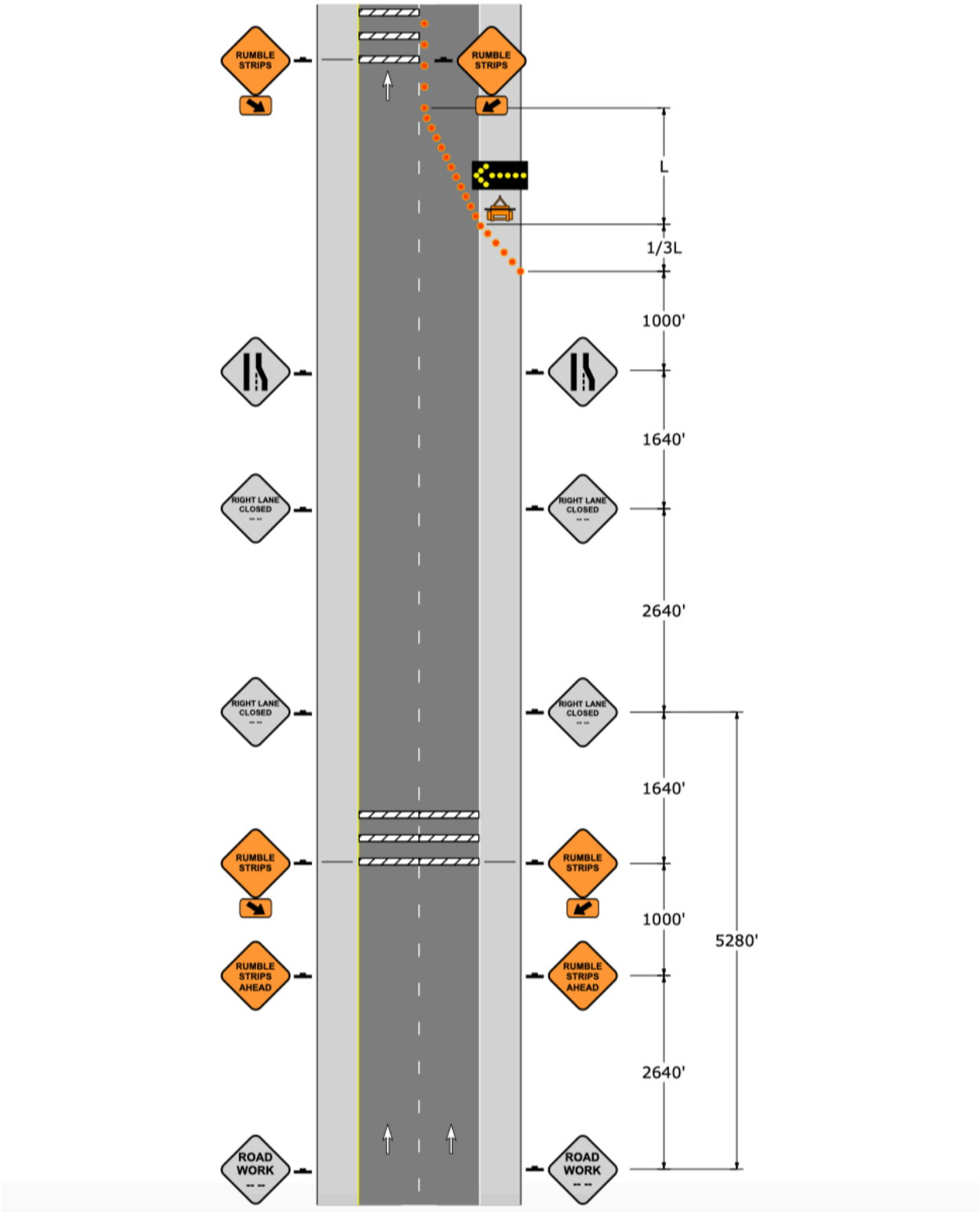
(Oregon DOT 2021b)

Figure C-47. Standard detail of rumble strip clusters for 2-lane, 2-way roadways with one lane closed from Oregon DOT



(Pennsylvania DOT 2021)

Figure C-48. Layout of TPRS on conventional highways from Pennsylvania DOT



(Pennsylvania DOT 2021)

Figure C-49. Layout of TPRS on freeways and expressways from Pennsylvania DOT

Raptor Deployment Plan for Temporary Portable Rumble Strips
Freeways and Expressways

NOTES

1. Temporary Portable Rumble Strips (TPRS) may be used for a lane closure while workers are present. Signs shown in grey are for a right lane closure and may vary depending on the Temporary Traffic Control (TTC) operation. TPRS placement for a left lane closure would be placed similarly.

2. Each TPRS array consists of three transversely placed rumble strips that are 12' wide and spaced evenly within the lane.

3. The Rumble Strips Ahead (W8-101) sign should be placed in conjunction with other warning signs.

4. TPRS may be installed after all other TTC devices have been placed. Upon completion of work. TPRS shall be removed before any other TTC device.

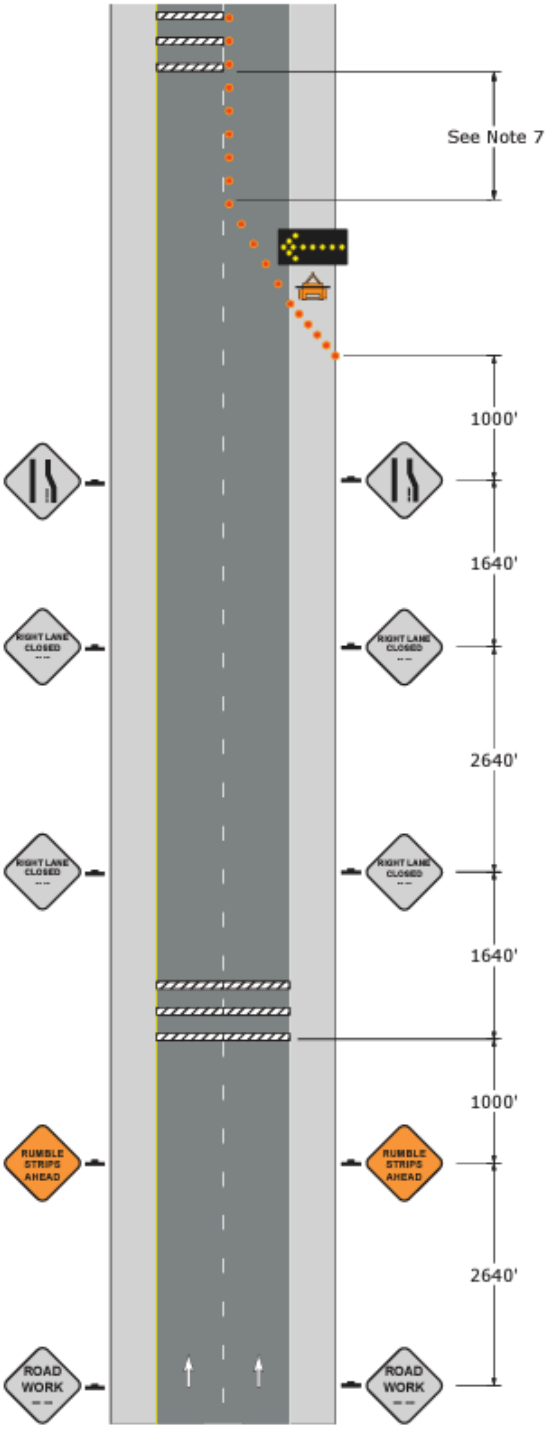
5. Reset TPRS as necessary to maintain proper alignment and spacing.

6. Do not use TPRS on horizontal curves unless approved by the District Traffic Engineer. Do not use TPRS on slippery surfaces or heavily rutted pavements.

7. Place TPRS array halfway between the last channelizer in the Merging Taper and the beginning of work space. This array may be omitted with approval from either the Bureau of Operations and Maintenance or the District Traffic Engineer.

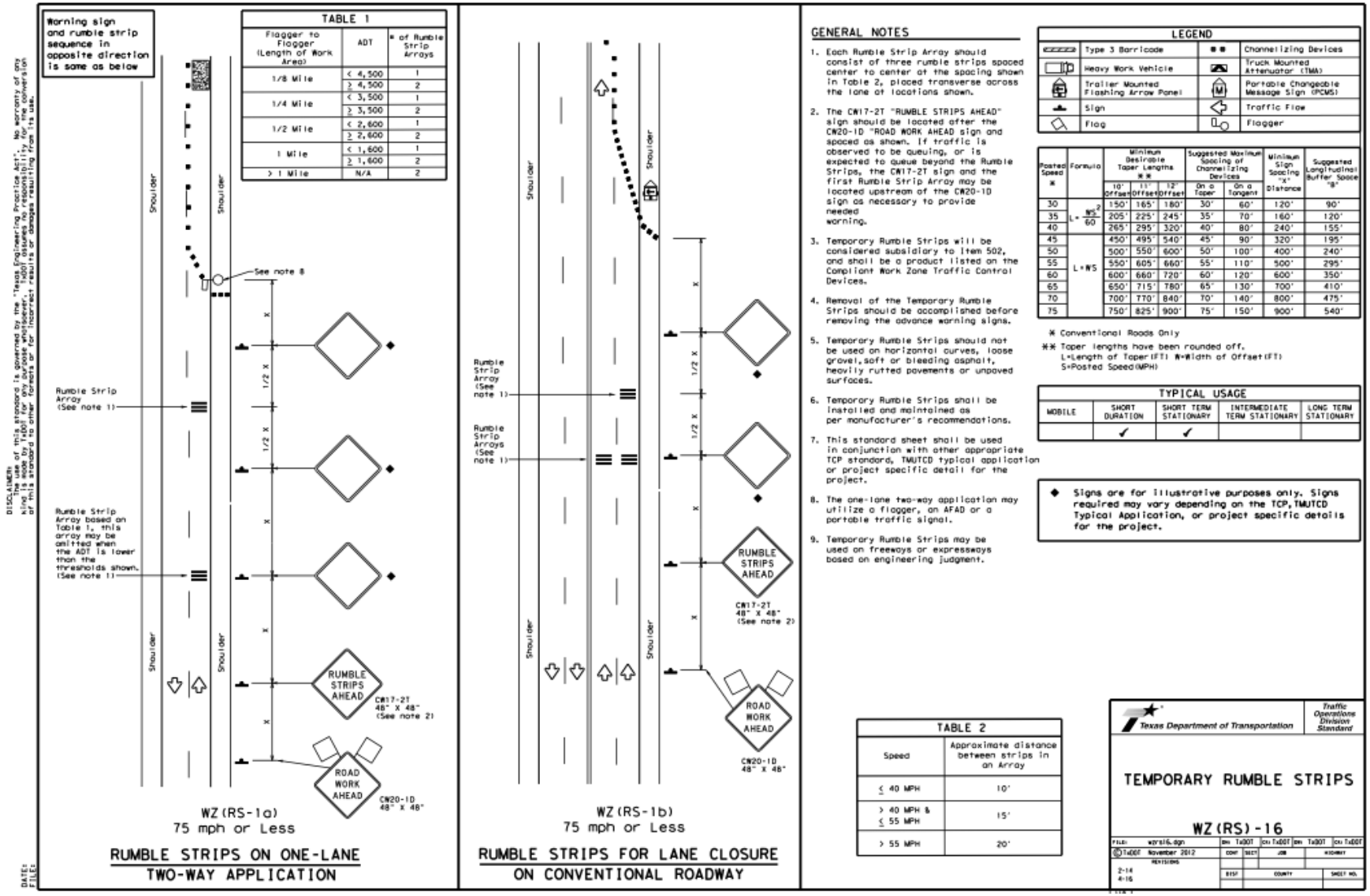
8. Do not use TPRS when the air temperature is less than 40 degrees Farenheit.

9. All TPRS must be the same color (black, white or orange).



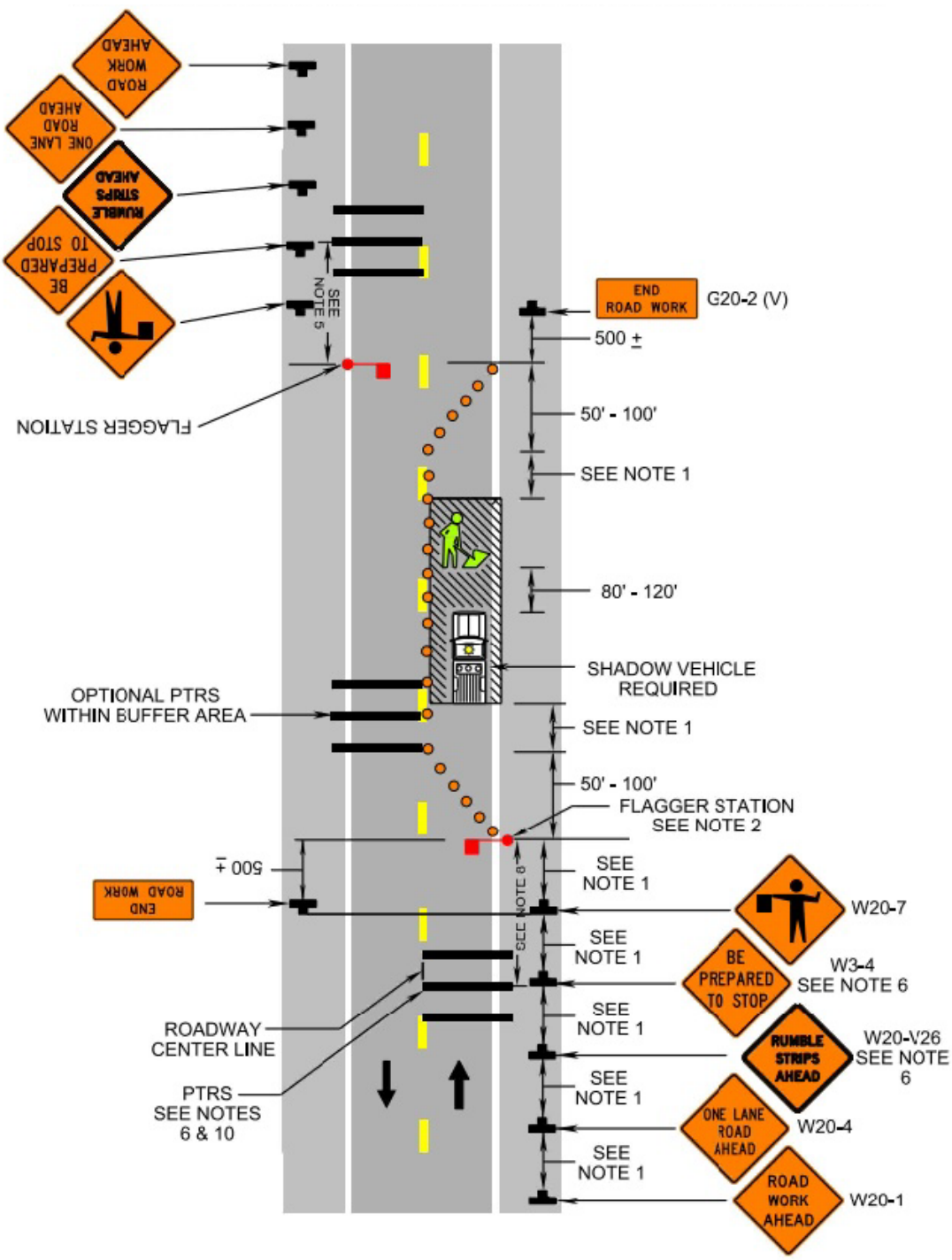
(Pennsylvania DOT n.d.a.)

Figure C-50. Layout of Raptor deployment plan for TPRS on freeways and expressways from Pennsylvania DOT



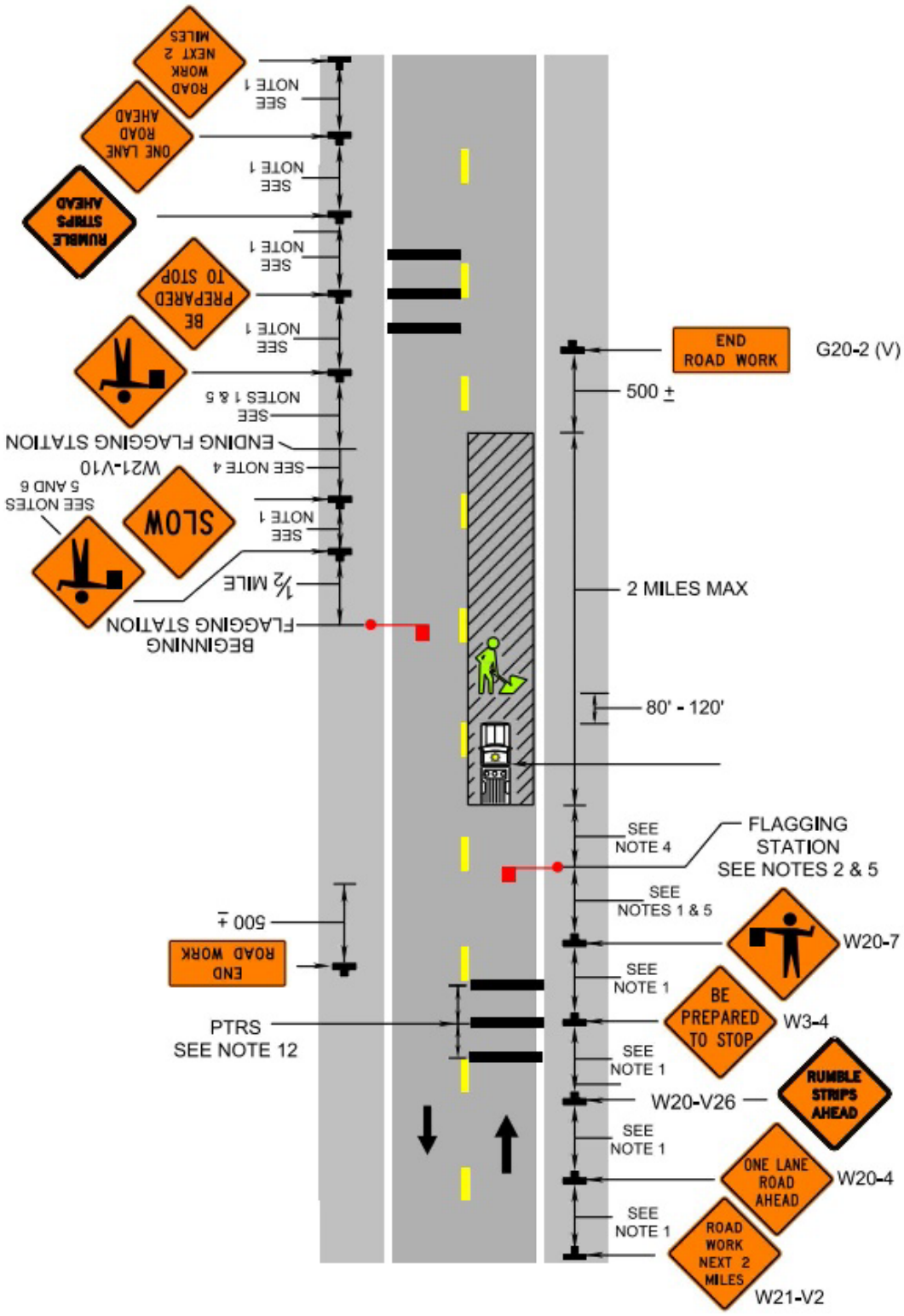
(Texas DOT 2021)

Figure C-51. Standard detail of temporary rumble strip set from Texas DOT



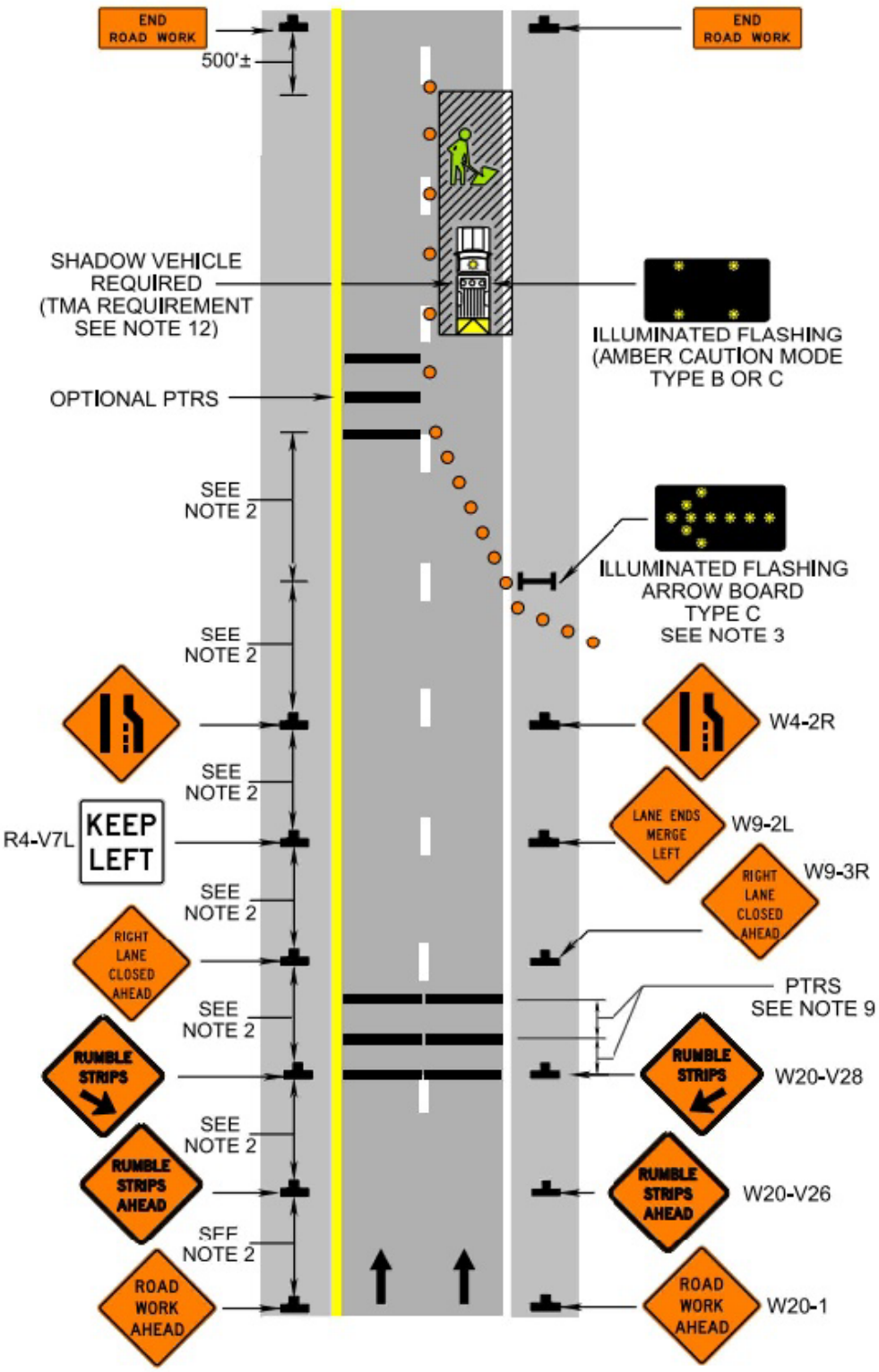
(Virginia DOT 2020b)

Figure C-52. Standard layout of typical TPRS installation on a two-lane road from Virginia DOT



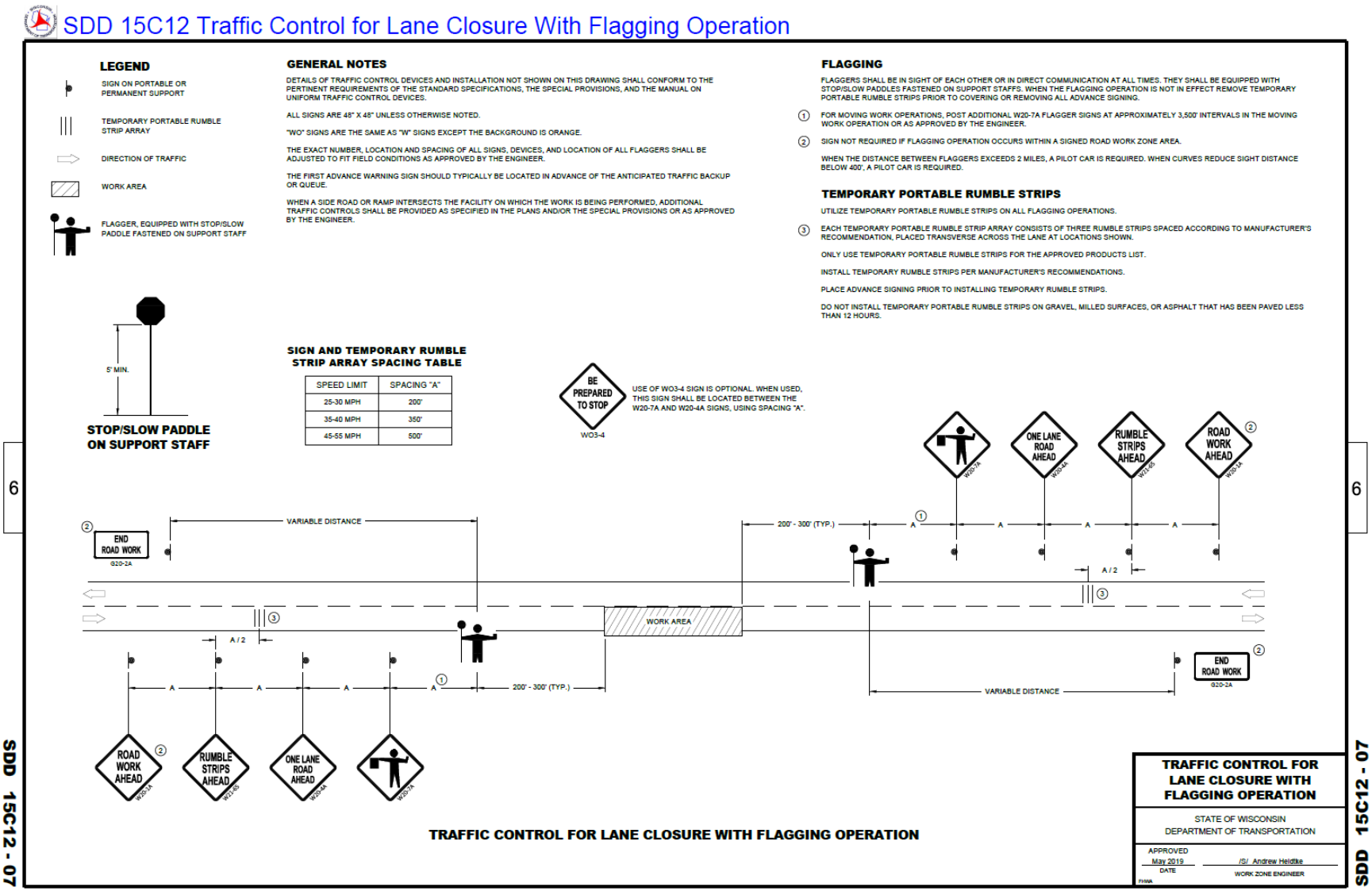
(Virginia DOT 2020b)

Figure C-53. Standard layout of typical TPRS installation on a non-stationary flagging operation from Virginia DOT



(Virginia DOT 2020b)

Figure C-54. Standard layout of typical TPRS installation on a multi-lane roadway from Virginia DOT



(Wisconsin DOT 2021a)

Figure C-55. Standard traffic control layout for lane closure with flagging operation from Wisconsin DOT

APPENDIX D. SUMMARY OF DOT PRACTICES BASED ON INTERVIEWS AND WRITTEN RESPONSES

Table D-1. Summary of DOT practices based on interviews and written responses

DOT	Type(s) of Temporary Rumbles Used	Summary of Practices and Experience
Arizona	• Short-term	• TPRS are used by maintenance groups, with each group having one set. • Uses trailer mounted carriage for deployment and removal. • Maintenance crews find them to be beneficial. • Developing modification to allow for mounting carriage in the front of the truck.
Delaware	• None	• Piloted use with maintenance forces but found that crews were not using them due to labor intensive setup and space they occupied in trucks.
Georgia	• Short-term	• Has performed a few pilot projects with TPRS for daytime flagger operations on two-lane highways with mostly positive results. • Concerns from contractor regarding weight and cost.
Idaho	• Short-term	• Has started to use TPRS in some work zones for daytime flagging operations on two-lane highways.
Illinois	• Long-term	• Use temporary rumble strips (special) (preformed plastic pavement marking) typically on contractor projects (Illinois DOT 2017). • Typically uses temporary rumble strips (special) on high-speed roadways (permanent posted speed limit = 70, 65, or 55 mph) in locations determined from impact analysis in advance of where the longest back of queue is expected, typically before the advanced warning area. • Utilized with smart work zones when the potential for queue buildup exists to help alert drivers to queue presence. • Temporary rumble strips (special) are deployed using work trucks and TMAs in accordance with highway standard 701428 (Illinois DOT 2020). • Find them to be beneficial in reducing incidents. • Sometimes utilizes temporary rumble strips made of high strength polycarbonate and held in place by adhesive on two-lane two-way highways when poor alignment or restricted sight distance create potential operational concerns (Illinois DOT 2020, Illinois DOT 2022). • Performed trials of TPRS but had concerns regarding cost and movement.

DOT	Type(s) of Temporary Rumbles Used	Summary of Practices and Experience
Indiana	• Short-term • Long-term (temporary buzz strips)	• TPRS were used on five contracts in contract letting years 2018-2020. • Temporary buzz strips (removable or durable marking materials) were implemented on 62 contracts in contract letting years 2018-2020.
Iowa	• Short-term	• Use TPRS for pilot car with flagger operations. • Working towards making use of TPRS optional for flagger operations. • Switched from two panels to single panel for final specifications. • Some concerns from contractors regarding weight. • Finds that signs help to reduce potential for erratic driver behavior. • Finds them to be beneficial and may expand use to include signalized setups.
Maine	• Short-term	• Initially began using TPRS in 2017 on Interstate projects and later expanded use to flagger operations. • On multi-lane highways, TPRS are installed and removed either by waiting for a gap in traffic and dragging the TPRS into place or using a rolling roadblock with attenuator truck and State Police. • Uses TPRS at night and finds that they show up well due to the color along with speed feedback signs and sequential flashing lights on barrel taper. Has observed some movement of TPRS at night, possibly due to higher truck speeds. • Currently re-evaluating their use due to concerns about driver behavior (for example, driving around rumble strips, abrupt braking). There are also some contractor concerns regarding weight. Plans to continue to put them in bid packages while working with contractors to address their concerns. • Exploring use of lighted signs; additional or larger “stay in lane,” “do not pass,” “rumble strips ahead” signs; and additional barrels or other traffic control devices to help notify drivers of the upcoming TPRS. • Does not use on maintenance projects. • Finds them to be effective in reducing vehicle speeds, getting drivers’ attention, and increasing worker awareness of vehicles in work zone.

DOT	Type(s) of Temporary Rumbles Used	Summary of Practices and Experience
Maryland	• Short-term	• Undertook demonstration deployment of TPRS on I-83 in January 2020. Results indicated that TPRS could effectively alert motorists to work zones and that periodic monitoring for displacement of TPRS is required. • Developed guidelines, typical drawings, and specifications for TPRS in 2021.
Massachusetts	• Short-term	• Requires use of TPRS for any short-term lane closures (12 hours or less).
Michigan	• Short-term • Long-term	• Per Special Provisions (20SP-812D-01), TPRS are required "on all Trunkline Regulating projects with existing speed limits 45mph or higher where traffic regulating will be in place longer than 4 hours" (Michigan DOT 2021a). • Use of TPRS is optional on local agency and other Trunkline projects. • Per Standard Specifications (Section 812.03.D.14), long-term temporary rumble strips [temporary rumble strips (orange)] are required when there is a lane closure or crossover shift on a freeway work zone at the same location for at least 14 consecutive days (Michigan DOT 2020). • Long-term temporary rumble strips are also used when a stop condition is modified or established. • For long-term temporary rumble strips, special provision for maintaining traffic should include off peak times for stationary and/or mobile lane closures, with mobile attenuators included (Michigan DOT 2021b). • Has used TPRS at night. Encounters infrequent concerns from residents regarding noise of temporary rumble strips (both TPRS and long-term) at night and addresses those concerns on a project-by-project basis. • Feedback from contractors has been positive.
Minnesota	• Short-term (portable) • Long-term (temporary)	• Use of TPRS is recommended for flagging operations on two-lane highways. • Does not deploy TPRS on multi-lane highways. • Generally does not use TPRS at night. • Long-term rumbles (temporary rumble strips) are not used very often. Typical use is for change in traffic control at an intersection. • Finds them to be beneficial in increasing driver awareness.
North Carolina	• Short-term • Long-term	• Allows TPRS for flagging operations, but they are not used often due to concerns about worker exposure and weight. • Limited use of temporary thermoplastic rumble strips in advance of work zones.

DOT	Type(s) of Temporary Rumbles Used	Summary of Practices and Experience
North Dakota	• Short-term	• TPRS installed when a specific sign set is used. • Reduced frequency of use a few years ago due to concerns about overuse.
Oregon	• Short-term • Long-term	• TPRS are not required for any operations but are generally used for flagging operations (only 1 set of TPRS is required when AADT < 4,000 vpd). • TPRS have been used on Interstates with varying success. Some concerns about movement due to higher speeds. • Believes they are beneficial in reducing vehicle speeds and alerting drivers. • Contractors also generally find them to be beneficial despite challenges of placement. • Long-term temporary rumble strips (removable tape, thermoplastic strips, or milled) are used less frequently than TPRS. • Allows traffic to be stopped for 20 minutes for the installation of temporary rumble strips on two-lane highways. • Typically uses a rolling slowdown to install temporary rumble strips on high-speed roadways with free flow traffic. • Deployment of temporary rumble strips at night requires approval from Region Traffic Engineer to avoid noise impacts to residential areas. Has encountered some issues with drivers stopping or swerving to avoid temporary rumble strips at night.
Pennsylvania	• Short-term	• TPRS may be used for short-term lane closures when workers are present. Typical deployment for conventional highways and freeways/expressways are shown in Publication 213 Temporary Traffic Control Guidelines (Pennsylvania DOT 2021). • Encourages use of TPRS as countermeasure for drowsy and distracted driving. • Purchased Raptor Rumble Strip Deployment Device for experimental placement/removal procedures. Raptor to be shared amongst PennDOT Maintenance Forces in 11 Engineering Districts. • TPRS are installed on multi-lane highways using a mobile operation with the Raptor Rumble Strip Deployment Device that is followed by a shadow vehicle. • Has not encountered any issues with use of TPRS at night.

DOT	Type(s) of Temporary Rumbles Used	Summary of Practices and Experience
Virginia	• Short-term • Long-term	• Requires use of TPRS when a set of specific conditions exists. • Some moderate use on multi-lane highways. • Mixed feedback from contractors regarding benefits (getting attention of distracted drivers) and concerns (weight, installation and removal process, and cost). • Allows but does not require use of TPRS at night. Has not encountered any issues with infrequent use of TPRS at night. • For occasional deployments of TPRS on multi-lane highways, maintenance crews use a mobile operation for the installation. • Limited use of long-term temporary rumble strips (two layers of white preformed pavement marking tape). Finds that they perform well but start to wear off after six months. Has used both static lane closure and mobile operation with TMAs for installation of long-term temporary rumble strips.
Wisconsin	• Short-term	• Requires use of TPRS for all flagging operations with speed limit 40 mph or higher. • Pilot-testing of long-term temporary rumble strips (pre-applied adhesive tape) is in progress. Long-term temporary rumble strips have been installed on three projects. Lane closure was used for the installation. • In first one to two years of implementation, DOT received concerns about deployment, weight, and cost. Since then, DOT has not received any complaints and believes they provide a benefit to work zones. • Reduced required number of TPRS sets from two to one. • Has not encountered any issues with occasional use of TPRS at night for flagging operations.

APPENDIX E. CHECKLISTS FOR OBSERVATION OF DRIVER BEHAVIOR

Table E-1. Checklist for observation of driver behavior with temporary rumble strips on US 24 in Moberly

Field	Response
Observer Name	Henry Brown, Ho Jun Baek, Qingzhong Zeng
Date	8/30/2021
Job ID	201218-B04
Route	US 24 Westbound
Location	Behind the rumble strips and work zone, across the street from Rothwell Park, Moberly
Start Time of Observation	9:05 pm
End Time of Observation	1:10 am (next day)
Type of Work Zone	Two-Lane Undivided Highway with Flagger
Type of Rumble Strips	Short-Term
Work Zone Speed Limit	60 mph
Speed Limit when Work Zone is not Present	60 mph
Direction of Travel for Adjacent Lane	Westbound
Weather Conditions	• Partly Cloudy • Night average temperature was 68°F
General Observations About Driver Behavior	• It seemed temporary rumble strips at site were hard to spot by some motorists due to low visibility at night. • After a certain period, the vehicles tend to travel faster without intention of braking or reducing speeds regardless of the presence of the strips and signs. • The strips seemed to help drivers to become aware of work zone ahead. • As vehicles ran over the rumble strips, the vehicles' body bumped up and generated a resonating warning sound. • Construction vehicles tended to speed and not to brake on rumble strips more frequently.

Table E-2. Checklist for observation of driver behavior with temporary rumble strips on MO 370 in St. Charles County

Field	Response
Observer Name	Henry Brown, Ho Jun Baek, Qingzhong Zeng
Date	09/10/2021
Job ID	210122-F02
Route	I-370 Eastbound
Location	Near Elm Street on-ramp of I-370 Eastbound
Start Time of Observation	9:15 am
End Time of Observation	1:15 pm
Type of Work Zone	Multi-lane (6 lanes, 3 lanes in each direction) with closure of two lanes
Type of Rumble Strips	Long-Term
Work Zone Speed Limit	45 mph
Speed Limit when Work Zone is not Present	60 mph
Direction of Travel for Adjacent Lane	Eastbound
Weather Conditions	Hot and sunny
General Observations About Driver Behavior	• Motorists tended not to brake and directly ran over the rumble strips. • There was a short period of congestion and traffic slowdown due to the lane closure and work zone.

Table E-3. Checklist for observation of driver behavior with temporary rumble strips on I-55 in Ste. Genevieve County

Field	Response
Observer Name	Henry Brown, Ho Jun Baek, Qingzhong Zeng
Date	9/13/2021
Job ID	MoDOT Maintenance
Route	I-55 Northbound
Location	Bridge #A2460 RT Z over I-55 in Ste. Genevieve County
Start Time of Observation	10:40 a.m.
End Time of Observation	2:40 p.m.
Type of Work Zone	Four-lane interstate highway (Two lanes in each direction) with lane closure
Type of Rumble Strips	Long-Term
Work Zone Speed Limit	70 mph
Speed Limit when Work Zone is not Present	70 mph (minimum 40 mph)
Direction of Travel for Adjacent Lane	Northbound
Weather Conditions	Clear and hot
General Observations About Driver Behavior	• Tractor trailers tend to brake more (Upstream). • Lane closure is visible distance that may have caused increase in braking percentage (Downstream). • Since this is second set of strips, the traffic flow seemed to be more slowed down and moved to the opened lane (first lane) (Downstream). • It seemed that flagging and sign display were utilized well compared to the other two observed work zones. • Higher traffic counts seemed to cause the strips on the first lane to wear more than the other one.

APPENDIX F. CHECKLIST USED FOR OBSERVATION OF INSTALLATION OF TEMPORARY RUMBLE STRIPS

1. Is the rumble strip long-term or short-term?
    a. If long-term, is additional adhesive used?

2. What manufacturer name or product installed?

3. Color of rumble used?

4. How many strips per set? How many sets per direction? Spacing between strips and spacing between sets?

5. Operation type, for example, chip seal, patching, resurfacing, etc.?

6. Roadway type, two-lane/two-way, 2-lane divided roadway, multi-lane (number)?

7. Speed limit?

8. Surface type, asphalt or concrete?

9. Weather conditions?

10. Duration to install and/or remove the rumble strips?

11. What type of protection is used when installing and/or removal?

12. Dialogue Comments from Installing/Removal Crew?
    a. Ease of installation and/or removal? 1 – 10 1 – difficult, 10 – easy
    b. Any suggestions or techniques to simplify or to make it easier to install/remove the rumble strips?
    c. For short-term, did the rumbles move any or move consistently with others?
    d. Perception of the effectiveness of rumbles to alert, reduce speed, etc.?

13. Comments from observer?

APPENDIX G. INSTALLATION OBSERVATIONS

Table G-1. Checklist for observation of installation of temporary rumble strips on US 24 in Moberly

Question	Response
1. Is the rumble strip long-term or short-term? a. If long-term, is additional adhesive used?	Short-term
2. What manufacturer name or product installed?	Roadquake2 TPRS by Plastic Safety Systems, Inc. ("PSS")
3. Color of rumble used?	Orange
4. How many strips per set? How many sets per direction? Spacing between strips and spacing between sets?	• Three strips per set • Two sets of strips per direction • Westbound 15 feet 8 inches (center to center) • Eastbound 19 feet 3 inches", 16 feet 4 inches (center to center)
5. Operation type, for example, chip seal, patching, resurfacing, etc.?	Patching
6. Roadway type, two-lane/two-way, 2-lane divided roadway, multi-lane (number)?	Two-lane/Two-way
7. Speed limit?	• 60 mph with work zone • 60 mph without work zone
8. Surface type, asphalt, or concrete?	Concrete
9. Weather conditions?	• Partly cloudy • Night average temperature was 68 degrees
10. Duration to install and/or remove the rumble strips?	No more than 10 minutes to install the temporary rumble strips
11. What type of protection is used when installing and/or removal?	Traffic control
12. Dialogue Comments from Installing/Removal Crew? a. Ease of installation and/or removal? 1 – 10 1 – difficult, 10 – easy b. Any suggestions or techniques to simplify or to make it easier to install/remove the rumble strips? c. For short-term, did the rumbles move any or move consistently with others? d. Perception of the effectiveness of rumbles to alert, reduce speed, etc.?	The temporary rumble strips are difficult to work with due to their weight.

Question	Response
13. Comments from observer?	• Installation went fast. • Does not need professional skills to install. • Seemed to need precautions during the installation. • Installation seemed to need more specific instructions such as spacing, position, and flaggers operation for the effect of the strips, and for workers safety. • Road work ahead signage was placed around 2000 feet from work zone. • Flaggers on both side of highway conducted traffic control management. • Traffic control was placed first before installation of temporary rumble strips. • Work zone was two miles.

Table G-2. Checklist for observation of installation of temporary rumble strips on MO 370 in St. Charles County

Question	Response
1. Is the rumble strip long-term or short-term? a. If long-term, is additional adhesive used?	• Long-term • Additional adhesive was used.
2. What manufacturer name or product installed?	ATM Rumble Strips
3. Color of rumble used?	Orange
4. How many strips per set? How many sets per direction? Spacing between strips and spacing between sets?	• Five strips per set for each lane • Two sets per lane per direction • 12-feet spacing between strips (Observed 11 feet 10 inches on site)
5. Operation type, for example, chip seal, patching, resurfacing, etc.?	Pavement repair
6. Roadway type, two-lane/two-way, 2-lane divided roadway, multi-lane (number)?	Multi-lane (6 lanes total for two directions)
7. Speed limit?	• 45 mph with work zone • 60 mph without work zone
8. Surface type, asphalt, or concrete?	Concrete
9. Weather conditions?	• Sunny • Hot, 75°F in the morning
10. Duration to install and/or remove the rumble strips?	15 minutes to install
11. What type of protection is used when installing and/or removal?	Moving operation with TMA, Traffic Control escorting includes contractor vehicle light flashing, CMS signage “One lane closed ahead” and local law enforcement vehicle improving visibility.
12. Dialogue Comments from Installing/Removal Crew? a. Ease of installation and/or removal? 1 – 10 1 – difficult, 10 – easy b. Any suggestions or techniques to simplify or to make it easier to install/remove the rumble strips? c. For short-term, did the rumbles move any or move consistently with others? d. Perception of the effectiveness of rumbles to alert, reduce speed, etc.?	a. 8-install, 2-removal b. It’s hard to remove them, especially on asphalt. Field workers suggested not to use them. d. Some people do slow down depending on the area.
13. Comments from observer?	• Brushed glue first and then installed rumbles. • Two work zone workers needed to complete the process.

Table G-3. Checklist for observation of installation of temporary rumble strips on I-55 in Ste. Genevieve County

Question	Response
1. Is the rumble strip long-term or short-term? a. If long-term, is additional adhesive used?	Long-term
2. What manufacturer name or product installed?	ATM Rumble Strips
3. Color of rumble used?	Orange
4. How many strips per set? How many sets per direction? Spacing between strips and spacing between sets?	• Three strips per set • Two sets of strips per lane • Approximate spacing: Upstream-First Lane: 2 feet, 1 foot 11 inches Upstream-Second Lane: 2 feet, 2 feet 4 inches' Downstream-First Lane: 2 feet 1inch, 2 feet 3 inches' Downstream-Second Lane: 2 feet 2 inches, 2 feet 3 inches
5. Operation type, for example, chip seal, patching, resurfacing, etc.?	Bridge repair (MoDOT Maintenance)
6. Roadway type, two-lane/two-way, 2-lane divided roadway, multi-lane (number)?	4-lane interstate highway (2 lanes in each direction)
7. Speed limit?	• 70 mph with work zone • 70 mph without work zone (minimum 40 mph)
8. Surface type, asphalt, or concrete?	Asphalt
9. Weather conditions?	Clear, hot
10. Duration to install and/or remove the rumble strips?	13 minutes 57 seconds 1st set, 12 minutes 40 seconds 2nd set.
11. What type of protection is used when installing and/or removal?	Moving work zone with TMA, lane closure signs in trailed truck deployed before the installation.
12. Dialogue Comments from Installing/Removal Crew? a. Ease of installation and/or removal? 1 – 10 1 – difficult, 10 – easy b. Any suggestions or techniques to simplify or to make it easier to install/remove the rumble strips? c. For short-term, did the rumbles move any or move consistently with others? d. Perception of the effectiveness of rumbles to alert, reduce speed, etc.?	a. 3 or 4 (install), 7 or 8 removal b. Install straightforward but concerned about time to install with moving operation. Maybe use permanent lane closure to place. Roller and pan would be easier than brush for applying primer. Plastic difficult to get off the back. Removal was easy using a shovel. d. Could help to alert distracted drivers. Might be more effective with higher spacing between strips and five strips instead of three.

Question	Response
13. Comments from observer?	• Tamped with wood block • Adhesive a little hard to peel off back and would sometimes tear

Table G-4. Checklist for observation of installation of temporary rumble strips on US 63 near Ashland

Question	Response
1. Is the rumble strip long-term or short-term? a. If long-term, is additional adhesive used?	Short-term
2. What manufacturer name or product installed?	RoadQuake 2
3. Color of rumble used?	Orange
4. How many strips per set? How many sets per direction? Spacing between strips and spacing between sets?	• Three strips per set for each lane • Two sets in each lane • Approximate spacing on 1st set: 21 feet 5 inches, 26 feet 5 inches, 20 feet 0 inches, 13 feet 5 inches • 2nd set placed just before the signs • Approximate spacing on 2nd set: 18 feet 4 inches, 13 feet 5 inches, 18 feet 0 inches, 13 feet 5 inches
5. Operation type, for example, chip seal, patching, resurfacing, etc.?	Install J-turn
6. Roadway type, two-lane/two-way, 2-lane divided roadway, multi-lane (number)?	Multi-lane highway (Two lanes per direction)
7. Speed limit?	60 mph with work zone 70 mph without work zone
8. Surface type, asphalt, or concrete?	Asphalt
9. Weather conditions?	Cloudy
10. Duration to install and/or remove the rumble strips?	Five minutes
11. What type of protection is used when installing and/or removal?	Pick-up truck
12. Dialogue Comments from Installing/Removal Crew? a. Ease of installation and/or removal? 1 – 10 1 – difficult, 10 – easy b. Any suggestions or techniques to simplify or to make it easier to install/remove the rumble strips? c. For short-term, did the rumbles move any or move consistently with others? d. Perception of the effectiveness of rumbles to alert, reduce speed, etc.?	a. 1 for installation and removal. Challenges with placing and removing in live traffic. b. Would prefer to use long-term temporary rumble strips on this project. Believes they would be easier to place. c. Some movement of the rumbles occurs. d. They help slow down vehicles. Potential for sudden braking. In a few instances, the metal hinge broke apart after the strips were pulled down the road by trucks. Some damage to cars was reported. Strips sometimes arch up.

Question	Response
13. Comments from observer?	• Waited for gap in traffic and then ran across lanes to drop strips quickly. • MoDOT indicated strips sometimes get dislodged. • Per MoDOT, the cost of the temporary rumble strips on this project is $50k.

Table G-5. Checklist for observation of installation of temporary rumble strips on US 63 near Columbia

Question	Response
1. Is the rumble strip long-term or short-term? a. If long-term, is additional adhesive used?	• Long-term • Yes, used primer
2. What manufacturer name or product installed?	ATM rumble strip
3. Color of rumble used?	Orange
4. How many strips per set? How many sets per direction? Spacing between strips and spacing between sets?	• Four strips per set • One set (southbound) (both driving and passing lane). Rumbles installed north of Brown School Road interchange • Approximate spacing on driving lane: 10 feet 7 inches, 10 feet 10 inches, 9 feet 10 inches • Approximate spacing on passing lane: 10 feet 3 inches, 9 feet 11 inches, 10 feet 0 inches
5. Operation type, for example, chip seal, patching, resurfacing, etc.?	Concrete replacement (MoDOT Maintenance)
6. Roadway type, two-lane/two-way, 2-lane divided roadway, multi-lane (number)?	Multi-lane highway (Two lanes per direction)
7. Speed limit?	• 70 mph with work zone • 70 mph without work zone
8. Surface type, asphalt, or concrete?	Concrete
9. Weather conditions?	• Cloudy • 50°F • It rained the day before.
10. Duration to install and/or remove the rumble strips?	• Driving lane: 12 minutes • Passing lane: 10 minutes
11. What type of protection is used when installing and/or removal?	Moving work zone with TMA

Question	Response
12. Dialogue Comments from Installing/Removal Crew? a. Ease of installation and/or removal? 1 – 10 1 – difficult, 10 – easy b. Any suggestions or techniques to simplify or to make it easier to install/remove the rumble strips? c. For short-term, did the rumbles move any or move consistently with others? d. Perception of the effectiveness of rumbles to alert, reduce speed, etc.?	a. Both installation and removal of the strips were straightforward. Removal took approximately five minutes per side using a loader bucket. One strip shifted initially, possible because it was set too soon. b. No thought it was easy and straightforward. d. Believes that they were a great tool that helped to reduce vehicle speeds and expressed interest in using them again in the future.
13. Comments from observer?	• Put primer down, then strips, walked on to help set. • Placed on driving lane, then looped back around to do passing lane. • When back to do passing lane, it looked like some of the rumbles in driving lane may have shifted a bit. • One strip on passing looked a little shorter than the others. • Work is expected to last two days. • Installation instructions from manufacturer indicate minimum required air temperature of 50°F, so this was at the low end of the temperature range for installation.

APPENDIX H. MEMORANDUM SENT TO MODOT DISTRICTS TO REQUEST SPEED AND COUNT DATA

MEMORANDUM

Aug. 19, 2021 (Revised Sept. 1, 2021)

To: MoDOT District Traffic Personnel

From: Mr. Henry Brown, PE, Research Engineer, University of Missouri

Re: Armadillo Data Collection for MoDOT Research Project on Temporary Rumble Strips

Overview

The research team from the University of Missouri (MU) is requesting that MoDOT Districts collect speed data for several work zones with and without temporary rumble strips (both long-term and short-term temporary rumble strips) as part of a MoDOT research project to look at the effectiveness of temporary rumble strips. This document provides general guidance for the data collection, including placement guidance, data output files, other resources, and technical support contact information for Houston Radar.

The MU research team will coordinate with each District regarding the work zone locations for the study. In general, the estimated number of work zones to be studied in each District is six (two work zones with long-term temporary rumble strips, three work zones with short-term temporary rumble strips, and one work zone without temporary rumble strips).

Data Requested

The research team is requesting the collection of the following speed data for each work zone location.

Work Zones with Short-Term Temporary Rumble Strips

- 24 hours of data with short-term temporary rumble strips
- 24 hours of data without short-term temporary rumble strips

Work Zones with Long-Term Temporary Rumble Strips

- 24 hours of data with long-term temporary rumble strips

- 24 hours of data without long-term temporary rumble strips (only if long-term temporary rumble strips have not yet been installed)

Work Zones without Temporary Rumble Strips

- 24 hours of data without temporary rumble strips

Guidance for Placement

Figure 1 provides an overview of Armadillo mounting options. For this project, the bidirectional configuration will be used for two-lane highways, and the unidirectional configuration will be used for multi-lane highways.

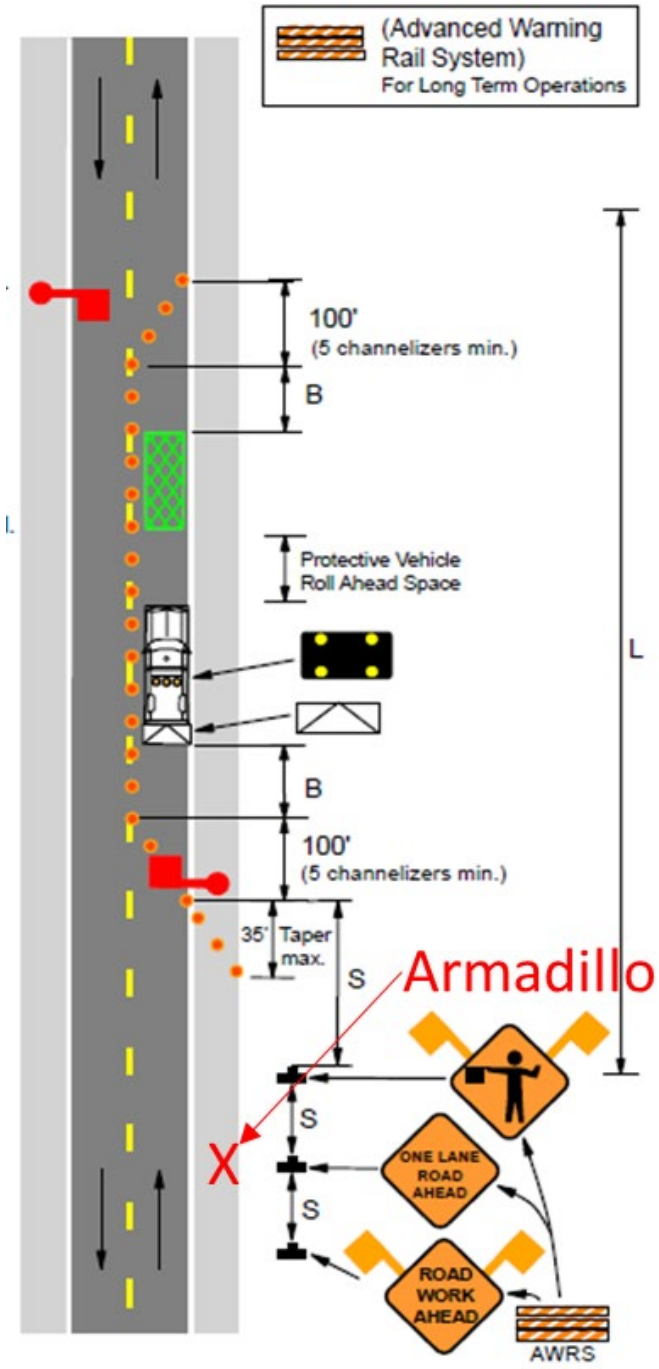
(Houston Radar)

Figure 1. Tracker mounting options for Armadillo (Houston Radar)

Some general tips for mounting the Armadillo sensor are provided below:

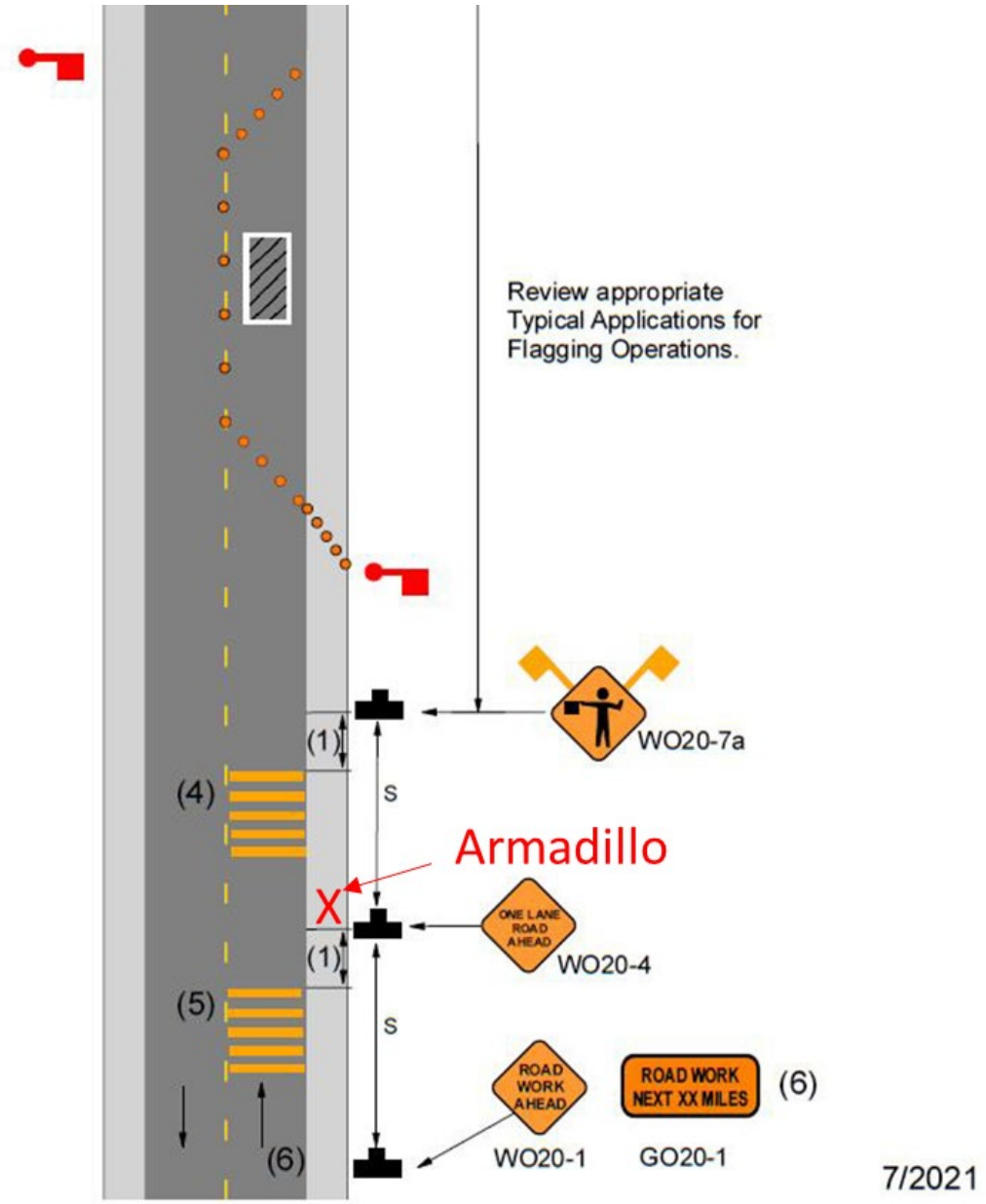
- Mounting height: 6 ft to 10 ft.
- Mount within 6 ft of nearest travel lane.
- The sensor should generally be placed at an angle of 15-30 degrees from straight on incoming traffic. This angle of placement depends on the road and the distance to the farthest lane of detection.
- Try to keep the area within 100 ft on each side of sensor free of obstacles.
- Use system beeps during first five minutes to verify vehicle detection.
- "Live Data" feature of the Android app can also be used for data verification.

Recommended locations for placement of the Armadillo units are shown in Figure 2 through Figure 7. For flagger operations, the recommended location is near the “ONE LANE CLOSED AHEAD” sign. For divided highways, the recommended location is near the “RIGHT (OR LEFT) LANE CLOSED AHEAD” Sign. These locations may need to be adjusted based on field conditions.



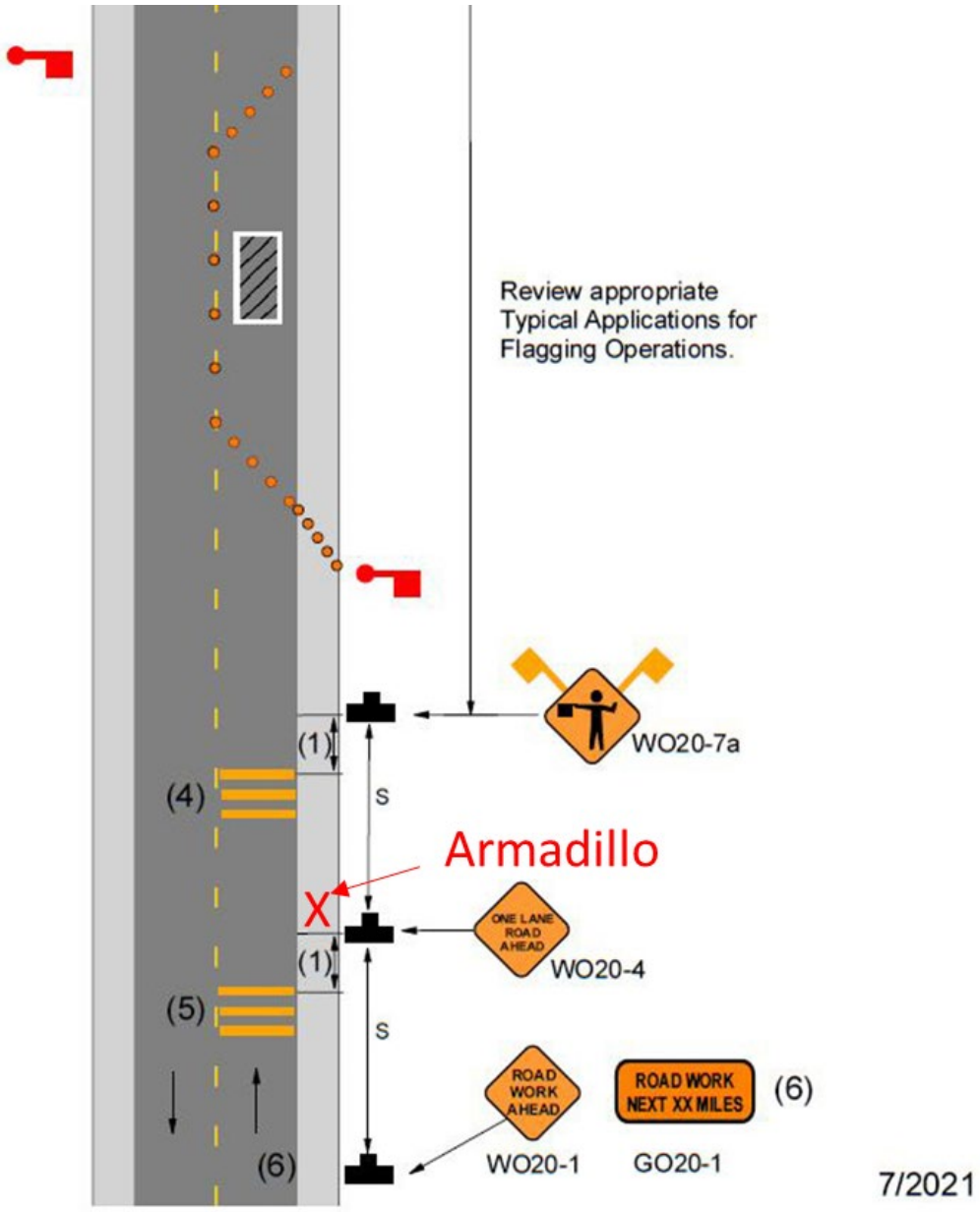
(Adapted from MoDOT EPG 616.8: Typical Applications, TA-10: Lane Closure on Two-Lane Highways with Edgelines Using Flaggers - MT)

Figure 2. Armadillo placement for no temporary rumble strips for flagging operations



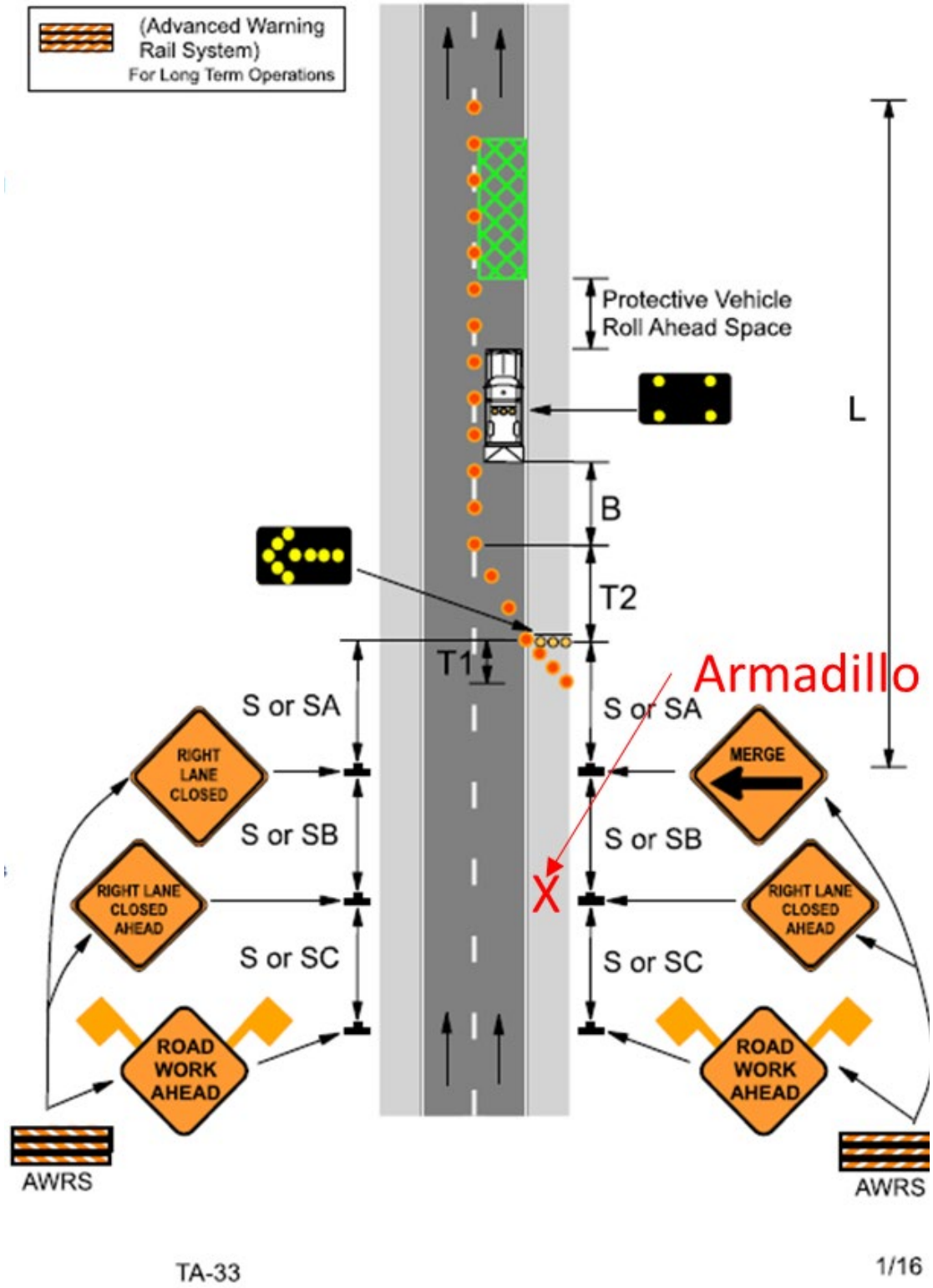
(Adapted from MoDOT EPG 616.6.87: Temporary Rumble Strips, Figure 616.6.87.1: Temporary Rumble Strip Placement in Flagging Operations)

Figure 3. Armadillo placement for long-term temporary rumble strips for flagging operations



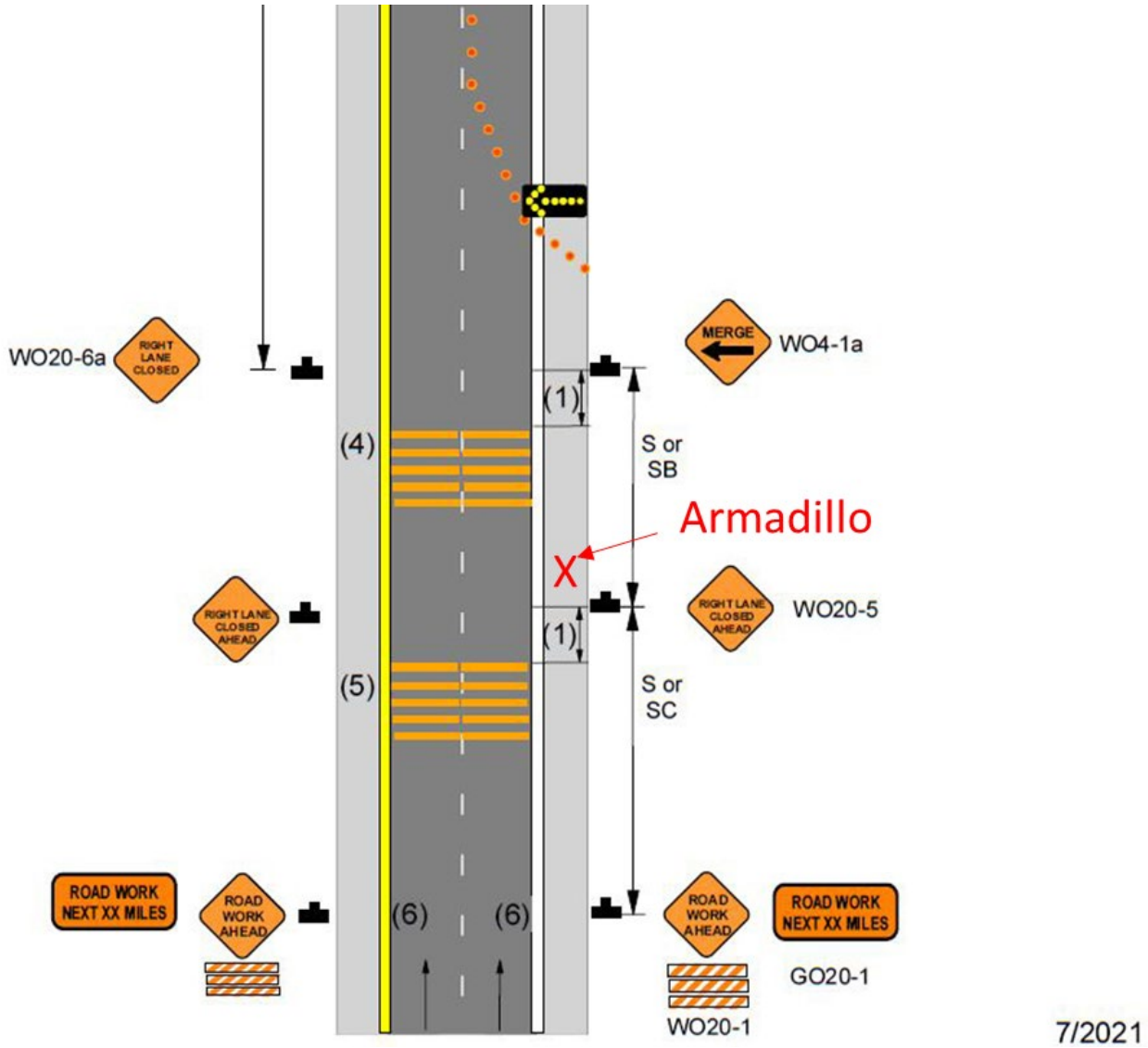
(Adapted from MoDOT EPG 616.6.87: Temporary Rumble Strips, Figure 616.6.87.1: Temporary Rumble Strip Placement in Flagging Operations)

Figure 4. Armadillo placement for short-term temporary rumble strips for flagging operations



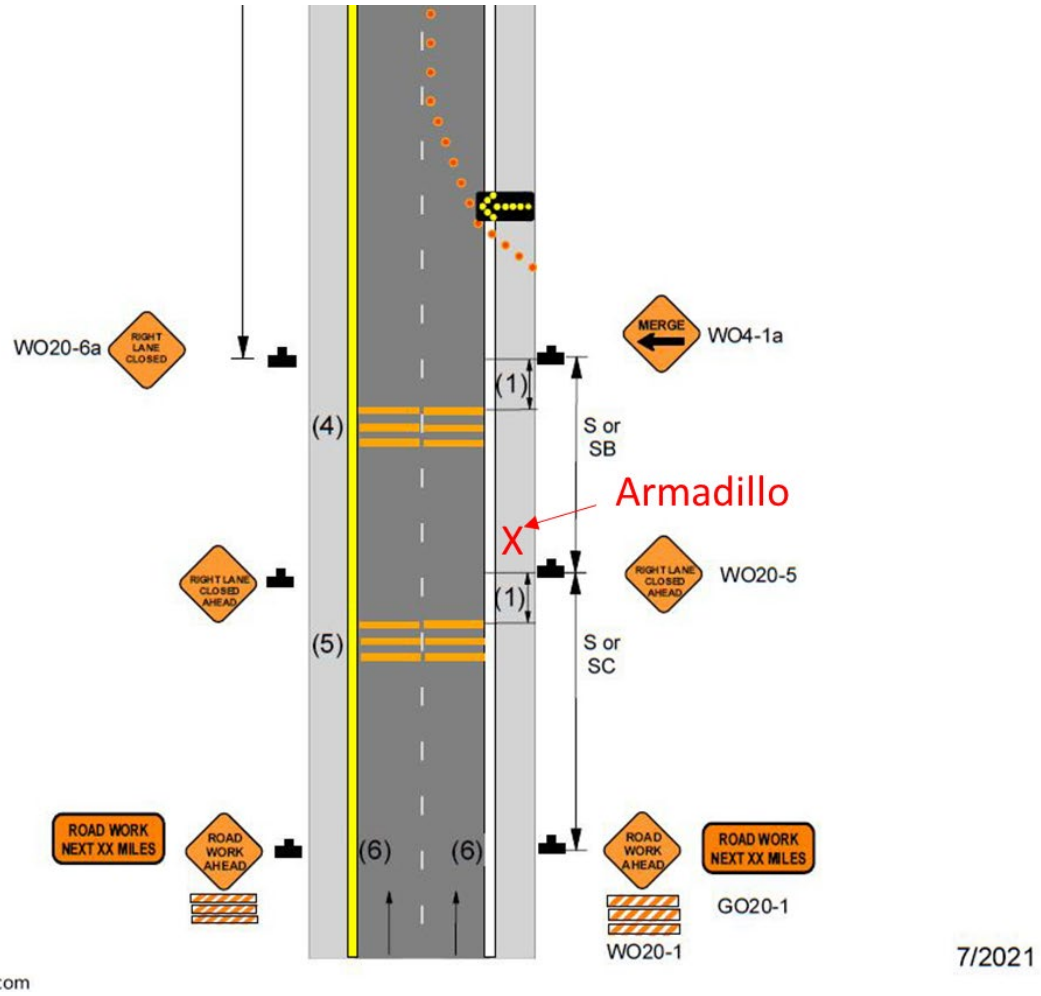
(Adapted from MoDOT EPG 616.8: Typical Applications, TA-33: Lane Closure on Left or Right Lane on Divided Highway-MT)

Figure 5. Armadillo placement for no temporary rumble strips on divided highway



(Adapted from MoDOT EPG 616.6.87: Temporary Rumble Strips, Figure 616.6.87.2: Rumble Strip Placement on a Divided Highway)

Figure 6. Armadillo placement for long-term temporary rumble strips on divided highway



(Adapted from MoDOT EPG 616.6.87: Temporary Rumble Strips, Figure 616.6.87.2: Rumble Strip Placement on a Divided Highway)

Figure 7. Armadillo placement for short-term temporary rumble strips on divided highway

Output Data

The MU research team requests the following output data file for each location:

- Stats Analyzer data file (.dat). Filename should include job number and date.

An example data file may be found at this OneDrive link.

In addition, please provide the following information for each data collection:

- Job Number
- Route
- Approximate milepost for Armadillo placement

- Approximate latitude and longitude for Armadillo placement
- Type of work zone (Two-Lane Highway / Divided Highway)
- Type of temporary rumble strips (Long-Term / Short-Term / None)
- Start date and time for data collection
- End date and time for data collection
- Date and time for installation of temporary rumble strips
- Date and time for removal of temporary rumble strips
- Work zone speed limit
- Speed limit when work zone is not present
- Direction of travel for lane immediately adjacent to Armadillo (Northbound / Southbound / Eastbound / Westbound)
- Picture of the rumble and the armadillo in same frame

Data files and other information should be sent to Henry Brown at brownhen@missouri.edu.

Other Resources

The following other resources from Houston Radar are available at this OneDrive link:

- Houston Radar Armadillo Tracker Quick Start Guide
- Armadillo Tracker Technical Specification
- Stats Analyzer Fact Sheet
- Stats Analyzer User Manual
- Example installation photographs

Technical Support Contact Information

Casey Inoue
Business Development Manager
Houston Radar
casey@houston-radar.com
+1.404.731.2927

APPENDIX I. SUMMARY OF REQUESTED LOCATIONS FOR SPEED AND COUNT DATA

Table I-1. Summary of locations for which speed and count data were received

District	Job ID	Job Description	County	Temp. Rumble Type	Data with and without Temp. Rumbles	Data for Multiple Locations
CD	210219-D05	J5P3195 - ROUTE 63 - BOONE COUNTY 11/01/21 COMPLETION DATE	BOONE	Short-term		
CD	210416-D07	J5I3366 - ROUTE I-70 - BOONE COUNTY 12/01/21 COMPLETION DATE (Westbound)	BOONE	Long-term		
KC	201218-C03	11/01/21 COMPLETION DATE J4I3216 - ROUTE 29 - PLATTE COUNTY	PLATTE	Short-term	X (Southbound)	
KC	201218-C04	07/01/22 COMPLETION DATE J4P3015, J4P3015B - ROUTE 24 - JACKSON COUNTY	JACKSON	Long-term		
KC	210122-C03	J4I3291, J4I3297 - ROUTE 29 - PLATTE COUNTY 05/15/23 COMPLETION DATE	PLATTE	Long-term		
NE	201218-B04	11/01/21 COMPLETION DATE J2P3254, J2S3206, J2S3207, J2S3255, J2S3350 - VARIOUS ROUTES - MACON, RANDOLPH COUNTIES	MACON, RANDOLPH	Short-term	X	
NW	191115-A04	J1I3109/J1I3241 I-29 BRIDGE REPLACEMENT, HEAD TO HEAD TRAFFIC	ANDREW	None		
NW	201120-A02	J1S3221 - ROUTE 46 - NODAWAY COUNTY 11/01/21 COMPLETION DATE	NODAWAY	Short-term		
NW	210219-A01	J1I3110 - ROUTE I-29 - ATCHISON COUNTY 12/01/22 COMPLETION DATE	ATCHISON	Long-term		
NW	MoDOT Maintenance	US 169 FLAGGER	ANDREW	None		
SE	210122-H01	J9P3169 - ROUTE 160 - OZARK COUNTY 11/01/21 COMPLETION DATE	OZARK	Short-term		
SE	210319-H04	J9S3213 - ROUTE C - MADISON COUNTY 09/01/22 COMPLETION DATE	MADISON	Long-term		

District	Job ID	Job Description	County	Temp. Rumble Type	Data with and without Temp. Rumbles	Data for Multiple Locations
SE	MoDOT Maintenance	I-55 NB MM 140 (MAINTENANCE WORK)	STE. GENEVIEVE	Long-term		
SE	MoDOT Maintenance	ROUTE 60 (MAINTENANCE WORK - CONCRETE REPLACEMENT)	NEW MADRID	None		
SL	201120-F01	J6I3356 - ROUTE I-70 - ST. CHARLES COUNTY 11/01/21 COMPLETION	ST. CHARLES	Long-term		X
SL	210122-F02	J6P3325 - ROUTE 370 - ST. LOUIS, ST. CHARLES COUNTIES 07/29/22 COMPLETION DATE	ST. CHARLES, ST. LOUIS	Long-term		X
SW	201016-G02	J7P3107C I-44 WB	JASPER	Short-term	X	
SW	201120-G01	J7I3361B I-49 SB	NEWTON	Long-term	X	

Table I-2. Summary of locations for which speed and count data were requested but not received

District	Job ID	Job Description	County	Temp. Rumble Type
CD	200918-D12	11/01/21 COMPLETION DATE J5S3385 - ROUTE U - WASHINGTON COUNTY	WASHINGTON	Short-term
CD	201120-D03	MO 740 (STADIUM BLVD.) BOONE COUNTY	BOONE	None
CD	210319-D01	J5I3324 - ROUTE I-44 - LACLEDE COUNTY 12/01/21 COMPLETION DATE	LACLEDE	Long-term
CD	210416-D07	J5I3366 - ROUTE I-70 - BOONE COUNTY 12/01/21 COMPLETION DATE (EASTBOUND)	BOONE	Short-term
CD	MoDOT Maintenance	US 63 (CONCRETE REPLACEMENT NEAR BROWN SCHOOL ROAD - SOUTHBOUND)	BOONE	Long-term
KC	200918-C02	12/01/2021 COMPLETION DATE - J3S3137 - ROUTE Y	PETTIS	None
KC	201218-C06	10/30/21 COMPLETION DATE J4S3251, J4S3258 - ROUTE 78 - JACKSON COUNTY	JACKSON	Short-term
KC	201218-C08	J4S3280 - ROUTE 69	CLAY	None
NE	201016-B01	J2P3334 - ROUTE 36 - MARION, SHELBY COUNTIES 10/01/21 COMPLETION DATE	MARION, SHELBY	Short-term
NE	201218-B01	12/01/21 COMPLETION DATE J2P3137, J2P3138 - ROUTE 61 - RALLS COUNTY	RALLS	Long-term
NE	201218-B05	12/01/21 COMPLETION DATE J2S3186, J2S3187, J2S3200 - VARIOUS ROUTES - MONTGOMERY COUNTY	MONTGOMERY	Short-term
NE	210122-B03	J2P3283 - ROUTE 63 - ADAIR, MACON COUNTIES 11/01/21 COMPLETION DATE	ADAIR, MACON	None
NE	210416-B01	J2P3247, J2S3071- ROUTE J,54 - AUDRAIN COUNTY 12/01/21 COMPLETION DATE	AUDRAIN	Long-term
NW	201218-A01	BUCHANAN, DEKALB J1P0862, J1P3237 - ROUTE 36 - BUCHANAN, DEKALB COUNTIES	BUCHANAN, DEKALB	Short-term

District	Job ID	Job Description	County	Temp. Rumble Type
NW	210122-A01	J1I3020B, J1I3099B, J1P3023B, J1S3181 - VARIOUS ROUTES - VARIOUS COUNTIES 12/01/22 COMPLETION DATE	ANDREW, CLINTON, DAVIESS, HOLT, SULLIVAN	Long-term
NW	210416-A03	J1P3334 ROUTE 36 MICROSURFACING	LINN	None
SE	201016-H01	J9I3545 - ROUTE 55 - SCOTT COUNTY 11/01/21 COMPLETION DATE	SCOTT	Short-term
SE	201016-H02	J9P3233 - ROUTE 61 - VARIOUS COUNTIES 10/01/22 COMPLETION DATE	CAPE GIRARDEAU, PERRY, STE. GENEVIEVE	Short-term
SL	210219-F01	ROUTE A (NIGHT WORK)	JEFFERSON	Short-term
SW	200918-G02	11/08/21 COMPLETION DATE J7P3281 - ROUTE US54 - VERNON COUNTY	VERNON	Short-term
SW	201120-G11	J8S3152 - ROUTE D - GREENE COUNTY 12/01/21 COMPLETION DATE	GREENE	Long-term
SW	210122-G02	J7I3362 - ROUTE 49 - BARTON COUNTY 12/01/21 COMPLETION DATE	BARTON	Long-term
SW	210219-G07	J8P2391 - ROUTE 13 - STONE COUNTY 12/01/21 COMPLETION DATE	STONE	Short-term
SW	210319-G03	J7P3484 - ROUTE 7 - BENTON, HENRY COUNTY 11/01/21 COMPLETION DATE	BENTON, HENRY	Short-term

APPENDIX J. ATTRIBUTE DATA FOR SITES AND TIME PERIODS

Table J-1. Attribute data for sites and time periods

Site ID	Time Period	District	Route	Direction	County	Type of Temp. Rumble Strip*	Start Date (2021)	Start Time	End Date (2021)	End Time	Work Zone Speed Limit	Permanent Posted Speed Limit	Notes
1	1	CD	US 63	SB	Boone	ST	9/21	7:00 AM	9/21	3:00 PM	60	70	Rumbles were in place 7 am to 3 pm each day
1	2	CD	US 63	SB	Boone	ST	9/22	7:00 AM	9/22	3:00 PM	60	70	Rumbles were in place 7 am to 3 pm each day
1	3	CD	US 63	SB	Boone	ST	9/23	7:00 AM	9/23	3:00 PM	60	70	Rumbles were in place 7 am to 3 pm each day
2	1	CD	I-70	WB	Boone	LT	9/21	12:01 AM	9/22	12:32 AM	60	70	-
3a	1	KC	I-29	NB	Platte	ST	10/5	6:48 PM	10/6	3:59 AM	60	70	Dearborn
3b	1	KC	I-29	SB	Platte	N	10/6	6:04 PM	10/7	3:59 AM	60	70	Dearborn
3c	1	KC	I-29	SB	Platte	ST	10/7	6:28 PM	10/8	5:59 AM	60	70	Dearborn (2.6 miles from site 3b)
4a	1	KC	US 24	EB	Jackson	LT	10/7	1:37 PM	10/12	10:55 AM	55	65	
4b	1	KC	US 24	WB	Jackson	LT	10/7	1:55 PM	10/12	10:48 AM	55	65	
5	1	KC	I-29	SB	Platte	LT	10/12	2:11 PM	10/13	2:10 PM	50	55	56th St
6	1	NE	US 24	EB	Randolph	ST	9/8	8:00 PM	9/9	6:00 AM	60	60	EB is rumbles
6	2	NE	US 24	EB	Randolph	N	9/9	8:00 PM	9/10	6:00 AM	60	60	EB is approaching work zone

Site ID	Time Period	District	Route	Direction	County	Type of Temp. Rumble Strip*	Start Date (2021)	Start Time	End Date (2021)	End Time	Work Zone Speed Limit	Permanent Posted Speed Limit	Notes
7	1	NW	I-29	SB	Andrew	N	9/8	11:55 AM	9/9	11:58 AM	55	70	Bridge replacement
8	1	NW	MO 46	EB	Nodaway	ST	9/8	10:55 AM	9/8	4:54 PM	55	55	Flagging one-lane work zone at top of hill
9	1	NW	I-29	NB	Atchison	LT	10/6	9:04 AM	10/7	8:55 AM	55	70	Bridge replacement
10	1	NW	US 169	NB	Andrew	N	10/19	9:22 AM	10/19	3:22 PM	55	60	Flagger job with no rumbles
11a	1	SE	US 160	WB	Ozark	ST	9/20	10:19 AM	9/20	3:00 PM	35	55	Use only 9 am to 3 pm as conservative estimate from District when rumbles were in
11a	2	SE	US 160	WB	Ozark	ST	9/21	9:00 AM	9/21	3:00 PM	35	55	Use only 9 am to 3 pm as conservative estimate from District when rumbles were in
11b	1	SE	US 160	EB	Ozark	ST	9/20	10:00 AM	9/20	3:00 PM	35	55	Use only 9 am to 3 pm as conservative estimate from District when rumbles were in.
11b	2	SE	US 160	EB	Ozark	ST	9/21	9:00 AM	9/21	3:00 PM	35	55	Use only 9 am to 3 pm as conservative estimate from District when rumbles were in
12	1	SE	RTE C	NB	Callaway	LT	9/15	12:29 AM	9/15	8:26 PM	55	55	No work zone speed limit was posted
13	1	SE	I-55	NB	Ste. Genevieve	LT	9/13	10:21 AM	9/15	11:31 PM	70	70	
14	1	SE	US 60	EB	New Madrid	N	9/20	11:05 AM	9/24	8:31 AM	55	55	Concrete replacement
15a	1	SL	I-70	EB	St. Charles	LT	9/7	8:45 AM	9/8	9:13 AM	65	70	Before strips (EB)

Site ID	Time Period	District	Route	Direction	County	Type of Temp. Rumble Strip*	Start Date (2021)	Start Time	End Date (2021)	End Time	Work Zone Speed Limit	Permanent Posted Speed Limit	Notes
15b	1	SL	I-70	EB	St. Charles	LT	9/7	8:57 AM	9/8	9:18 AM	65	70	Between the two rumble strips (EB)
15c	1	SL	I-70	WB	St. Charles	LT	9/7	8:06 AM	9/8	9:32 AM	60	70	Before strips (WB)
15d	1	SL	I-70	WB	St. Charles	LT	9/7	8:16 AM	9/8	9:36 AM	60	70	Between the two rumble strips (WB)
16a	1	SL	MO 370	EB	St. Charles	N	9/14	7:57 AM	9/15	8:15 AM	45	60	Before rumble strips
16b	1	SL	MO 370	EB	St. Charles	LT	9/14	8:07 AM	9/15	8:20 AM	45	60	In between strips
16c	1	SL	MO 370	EB	St. Charles	N	9/14	11:39 AM	9/15	11:45 AM	45	60	At lane drop no rumble strips
17	1	SW	I-44	WB	Jasper	N	9/13	7:00 PM	9/14	5:35 AM	60	70	
17	2	SW	I-44	WB	Jasper	NWZ	9/14	7:00 PM	9/15	5:35 AM	60	70	No work zone due to rain
17	3	SW	I-44	WB	Jasper	ST	9/15	7:00 PM	9/16	5:35 AM	60	70	
17	4	SW	I-44	WB	Jasper	ST	9/16	7:00 PM	9/17	5:35 AM	60	70	
18	1	SW	I-49	SB	Newton	NWZ	9/17	9:29 AM	9/20	8:00 AM	60	70	No work zone
18	2	SW	I-49	SB	Newton	N	9/20	8:00 AM	9/21	10:00 AM	60	70	Work zone set up, no lane drop
18	3	SW	I-49	SB	Newton	LT	9/21	10:00 AM	9/21	10:15 PM	60	70	Rumble strips installed
18	4	SW	I-49	SB	Newton	LT	9/21	10:15 PM	9/23	9:40 AM	60	70	Lane drop added

* LT = Long-term, N = None, NWZ = No work zone, ST = Short-term