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Traffic Control Device Analysis, Testing, and Evaluation Program: FY2018 Activities

Technical Report 0-6969-R1

Cooperative Research Program

TEXAS A&M TRANSPORTATION INSTITUTE
COLLEGE STATION, TEXAS

in cooperation with the
Federal Highway Administration and the
Texas Department of Transportation
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16. Abstract

This project provides the Texas Department of Transportation with a mechanism to conduct high-priority, limited-scope evaluations of traffic control devices. Work conducted during the 2018 fiscal year included:

- Evaluation of the safety of wet-weather pavement markings.
- Identification of effective work zone pavement marking removal techniques.
- Review of raised retroreflective pavement marker practices in other states.
- Identification of current uses and effectiveness of safety corridors.
- Hosting of a wrong-way driving forum.
- Assessment of pedestrian crashes on freeways and high-speed arterials.
- Review of the design and application of lane control signs on frontage roads.
- Review of the application of embedded light-emitting diodes in signs.

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TRAFFIC CONTROL DEVICE ANALYSIS, TESTING, AND EVALUATION PROGRAM: FY2018 ACTIVITIES

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DISCLAIMER

This research was performed in cooperation with the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA). The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of FHWA or TxDOT.

This report does not constitute a standard, specification, or regulation. This report is not intended for construction, bidding, or permit purposes. The engineer in charge of the project was Melisa D. Finley, P.E. (TX-90937).

The United States Government and the State of Texas do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

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CHAPTER 1: INTRODUCTION

This project provides the Texas Department of Transportation (TxDOT) with a mechanism to conduct high-priority, limited-scope evaluations of traffic control devices. Research activities conducted during the 2018 fiscal year (September 2017–August 2018) included:

- Evaluation of the safety of wet-weather pavement markings.
- Identification of effective work zone pavement marking removal techniques.
- Review of raised retroreflective pavement marker (RRPM) practices in other states.
- Identification of current uses and effectiveness of safety corridors.
- Hosting of a wrong-way driving (WWD) forum.
- Assessment of pedestrian crashes on freeways and high-speed arterials.
- Review of the design and application of lane control signs on frontage roads.
- Review of the application of embedded light-emitting diodes (LEDs) in signs.

The first five of these activities have been completed and are documented herein. The remaining three activities are ongoing.

With respect to pedestrian crashes, researchers have reviewed literature, identified countermeasures and their effectiveness, highlighted select tools and resources for choosing appropriate treatments, developed a methodology to identify clusters of pedestrian crashes on high-speed roads, and made observations on what may be contributing to pedestrian crashes on high-speed roads. All these tasks are documented herein. Additional tasks related to this activity will be documented in future reports.

For the last two activities, researchers surveyed the 25 TxDOT districts in summer 2018 to identify:

- Types of signs and applications for which flashing lights embedded in the sign face are used.
- Challenges with designing and installing advance intersection lane control signs on frontage roads.
- Various uses of turnaround signs on Texas roadways.

Researchers will reduce and analyze the survey results in fall 2018. The survey findings and any further related activities conducted will be documented in future reports.

CHAPTER 2: SAFETY EVALUATION OF WET-WEATHER PAVEMENT MARKINGS

Wet-night conditions pose a significant safety hazard to motorists for many reasons. One safety issue is that typical pavement markings lose their visibility and are generally unable to adequately delineate the roadway in wet-night conditions. TxDOT often supplements typical markings with raised retroreflective pavement markers (RRPMs) to aid in wet-night visibility, but these markers can fail and thus do not provide supplemental guidance to drivers. To aid in wet-weather conditions, some pavement markings are designed to provide increased levels of retroreflectivity in wet-night conditions. These markings are typically more expensive than standard markings, and their durability has not been adequately studied.

This study sought to build on previous work to explore the safety effect on wet-night crashes of using non-standard pavement markings that have increased wet-weather performance. The researchers developed a database of roadway segments with non-standard markings and acquired the roadway characteristics and crash information for those segments. To increase the robustness and statistical validity of the results, researchers employed two different evaluation approaches to assess the safety benefits of the wet-weather pavement markings: Empirical Bayes (EB) before-after analysis and Full Bayes (FB) before-after analysis with comparison groups.

DATA COLLECTION METHODOLOGY

While evaluating the safety effectiveness of wet-weather pavement markings in 2017, researchers collected various types of data on 135 segments totaling 737.7 mi, including crash counts, roadway characteristics, traffic, retroreflectivity, and weather information. To further improve the analysis results and reduce uncertainty of the crash reduction estimates, researchers expanded the data sets in 2018. The data collection process was generally the same as that in 2017, but necessary improvements were carried out to accomplish the objective of the analyses. All of the data were collected for sites in the TxDOT Atlanta District. This section introduces the detailed process for collecting the data.

The following information was gathered to conduct the safety analysis of the wet-weather pavement markings:

- Pavement marking location and retroreflectivity data.
- Roadway inventory data.

- Crash data.
- Weather data.

Pavement Marking Location and Retroreflectivity Database

The location of the pavement markings was based on contractor-supplied mobile retroreflectivity reports. The retroreflectivity readings were recorded for every marking line (i.e., center lines, lane lines, and edge lines) on the roadway. The initial retroreflectivity data were measured by the contractor and provided to TxDOT. Table 1 describes the information provided in the mobile retroreflectivity report.

Table 1. Information Provided in Mobile Retroreflectivity Reports.

Variable	Description
County	The county in which the markings were applied
Roadway	The roadway on which the markings were applied
Date	The date on which the retroreflectivity readings were taken
Color	The color of the marking
Material	Marking material type
From and To	Start and end point of the project
Left and Right Retro	Retroreflectivity readings of the markings

TxDOT provided researchers two sets of data. The first set was an Excel table with summarized information from numerous sets of contractor-supplied mobile retroreflectivity information. TxDOT also included the Routine Maintenance Contact (RMC)/Control Section Job (CSJ) project number for each of the jobs listed. The second set of data was a hard copy of the mobile retroreflectivity data collected by the contractors that had not yet been manually entered into the database. The data in the hard copies did not have the RMC/CSJ numbers. Researchers entered the rest of the data in the format TxDOT had started to generate a single database of information based on the contractor-supplied mobile retroreflectivity readings. Each individual project was given a unique ID (U_ID) so that the information gathered in future steps could be linked together.

Three databases were combined for the crash study—the marking location, marking type, and marking retroreflectivity data; the road-highway inventory network (RHiNo) database; and the Crash Records Information System (CRIS) database. The databases were integrated through the means of the Unique Id (U_ID), and the Distance from Origin (DFO) of the start and end point of each of the projects was maintained as the same in all three databases. The DFO information identified the roadway segment that was being considered.

The RMC/CSJ numbers were used to obtain the plans and specifications files for each of the projects. Some of the projects had the Reference Marker (RM) and distance from RM for both the start and end point for each of the stretches over which the marking retroreflectivity was evaluated. However, researchers observed that several project plans and specifications did not specify the RM data. The RM data needed to be converted to the DFO data to be useful for the data analysis. The DFO data could also be obtained if the global positioning system (GPS) coordinates of the end points are available. The coordinates of the start and end point were obtained through the following means:

- The hard copies of the mobile retroreflectivity data have the GPS coordinates of the point where the retroreflectivity readings were evaluated. The coordinates of the start and end point of the roadway segment were obtained from these data.
- In the cases where the hard copies of data were not provided and the RM information could not be found, researchers obtained the GPS data from Google® Earth. The name of the project stretch along with the name of the start and end point of the stretch could be used to obtain the coordinates of the point. However, some of the data points were not reliable since the names of the start and end points did not always clearly define points in Google Maps.

Most of the project stretches had either the RM data or the coordinates of the start and end point (obtained from the field retroreflectivity data or Google® Maps). However, a few sites did not have either of these data and thus were not useful for further analysis. These segments were discarded. For some segments, the DFO information could not be obtained, and these sites were discarded. The methodology to evaluate DFO using the RM or GPS coordinates is described in the next section.

Steps to Calculate DFO from RM or GPS Coordinates

The DFO information of start and end points of each treatment segment were identified using the statewide point data set of Texas RM locations maintained by the Transportation Planning and Programming Division of TxDOT (*1*). The detailed steps are shown below.

Step 1: Obtain the RM or GPS Coordinate Information of Start and End Points

A. RM

In the case where the location information of a treatment segment is available from the TxDOT Daily Work Report, the RMs of the start and end points can be identified.

B. GPS Coordinates

In the case where the location information is not available in the TxDOT Daily Work Report, the GPS coordinates of start and end points are identified in Google Maps.

Step 2: Automatically Match the RM or Coordinates with the Texas RM Database

A. RM

If the RM of the start or end point of a treatment segment is available, the RM can be matched in the Texas RM database.

B. GPS Coordinates

The distance between the start or end points and the RM listed in the Texas RM database are calculated using the GPS coordinates. The equations used to calculate distance between two GPS coordinates are shown below:

$$d = R * c \tag{1}$$

$$c = 2 * \arccos(\sin(x_1) \times \sin(x_2) + \cos(y_1) \times \cos(y_2) \times \cos(\Delta)) \tag{2}$$

where

d = distance between two points.

R = the radius of the Earth (i.e., 6,378,137 m).

x_1, x_2, y_1, y_2 = coordinates of two points.

Δ = the absolute difference.

Researchers developed an algorithm and an automatic programming software package to match the RM or coordinates with the Texas RM database. Then the DFOs of begin and end points of each segment were identified.

Step 3: Manually Match the RM or Coordinates with the Texas RM Database

For some sites, the algorithm failed to identify the locations from the Texas RM database. To collect the data on these sites, researchers manually identified the DFOs of the sites. The identification was conducted through Google Earth and TxDOT's Statewide Planning Map (https://www.txdot.gov/apps/statewide_mapping/StatewidePlanningMap.html). Researchers first located the begin and end points on Google Earth based on the description in the data sets provided by TxDOT. The location information was typically presented in the form of intersections or boundaries (e.g., US 59 at FM 2148, or county line). The Google Earth map provided the latitude and longitude coordinates of the points. This process is similar to Step 1(b), as described above. Researchers located the points in the Statewide Planning Map through the coordinates and then searched the closest RM on the same route. DFOs were then calculated based on the RM information and the distance between the point and the closest RM.

Step 4: Duplicated Sites and Re-segmentation

Duplicated Sites: After the identification of the exact locations of each site, researchers examined all the sites. A few sites were duplicated, and the duplications were removed from the data set.

Re-segmentation: Further examination showed that some sites were treated multiple times during the study period (2011 to 2018). For example, FM 2253 from 0.0 to 4.6 in Bowie County was stripped on February 16, 2011, and this segment was re-stripped two years later on February 14, 2013. Since the assumption is that the wet-weather pavement marking reduces the occurrence of crashes, the re-strip issue makes it difficult to estimate the true safety effect of the treatments. In the above example, the safety level in 2011 should be the same as that of 2013 due to the re-strip, which created discrepancy for the before-after analysis. To prevent biased results, this site was removed from the final data set.

In addition, a few sites were found to have overlaps with others. For example, SH 8 from 0.0 to 6.7 was treated on February 9, 2015. However, a segment from 0.8 to 1.0 on SH 8 was restriped on March 7, 2016. There was an overlap segment between the two wet-weather pavement marking implementation projects. The whole segment was split into three parts: 0.0 to 0.8, 0.8 to 1.0, and 1.0 to 6.7. Since the part from 0.8 to 1.0 was treated twice, in February 2015 and March 2016, respectively, it was excluded from the analysis. The remaining two parts were both treated once during the study period and were kept in the data set. As a result, the total number of segments increased, but the length decreased.

TTI researchers checked all the sites and included those sites with only one-time treatment during the study period. Finally, 196 sites were selected. The original treatment site information provided by the TxDOT Atlanta District does not include any sites that were treated in 2012; thus, there were no 2012 sites in the 196-site data set (i.e., no site has an implementation year of 2012).

Summarizing the Location and Retroreflectivity Database

The retroreflectivity database has several rows for every project because most of the roads usually have multiple pavement markings. The retroreflectivity readings are collected for each line on each road. The material types for each of these line types may be different even on the same stretch of roadway. The retroreflectivity readings are taken in both directions for yellow center line markings. Researchers summarized the data for each of the sites into a single row. There was a maximum of two material types on any given project stretch. In the case of center lines, the retroreflectivity values for the two lines were averaged and a single value was reported.

Roadway Inventory Database

The roadway inventory data are collected and updated regularly by TxDOT (usually once every year). The roadway inventory data were an essential component of this study since the annual average daily traffic (AADT), road geometrics, and traffic characteristics were expected to affect the number of crashes. The TxDOT roadway inventory has data for years 2011 to 2016 (note that 2016 RHiNo data were the latest available to the researchers). This study considered data from the seven years between 2011–2017. Thus, some assumptions had to be made for the 2017 data. These assumptions will be described later. The roadway inventory database has numerous parameters. In this study, only selected parameters of interest were considered. The first column of the RHiNo data is the unique ID, which enabled the researchers to identify the project stretch and thus the start and end DFO.

The RHiNo data were extracted through the aid of ArcGIS and R. The start and end point of the RHiNo data did not exactly match with the start and end DFO from the retroreflectivity report data. This anomaly was because the start and end DFO in RHiNo were the start DFO of the first segment in the stretch and the end DFO of the last segment in that stretch. The first and last segment considered in a stretch were based on the actual DFOs of the project stretch. The segments closest to the actual DFOs (start and end of stretch) were considered for extracting the inventory data. These segments may not be the same over the years; thus, the total project length was not expected to be same in every year.

The parameters considered in this study and the methodology adopted are described in the following list:

- AADT—A single project stretch may have several segments of different lengths and different AADTs. The presence of intersections on the stretch can sometimes create a large variation of AADT between the segments. In this study, the AADT of a project stretch was evaluated by taking the weighted average of the AADTs of all the segments, with segment length being the weight. The AADTs were evaluated the same way in every year. The AADT for the year of 2017 does not exist in the database. The researchers forecast the AADTs in 2017 using two methodologies:
    - Researchers evaluated the percentage change in AADT in the consecutive years and averaged these values. This average percentage was used to forecast the AADT for 2017.
    - Researchers developed a linear model using six years of AADT data for every project stretch and used that model to project the AADTs in 2017.
- Length of the Section—This parameter gives the total length of the project stretch. The length of the section was determined by adding the sum of the length of segments that are part of that project stretch. For each stretch, its length was calculated by subtracting the begin DFO from the end DFO.
- Functional System—This parameter gives the functional class of the project roadway. The functional class of individual segments that form a project stretch may be different, but this feature only happens for long stretches. Researchers used the mode of the functional class of all the segments and assigned it as the functional class of the project stretch. This value was evaluated for each year. The functional system of each site in 2017 was assumed to be the same as that in 2016.
- Rural/Urban Classification—This parameter gives the type of area near the project stretch. For this parameter, researchers used the mode of the values of each of the

segments that constituted the stretch and assigned it to the stretch. Researchers evaluated the value for every year from 2011 to 2016 and used the value of year 2016 for 2017 at each site. The codes for the rural/urban classification, as defined in the RHiNo database, are:

  - 1 = Rural (Population < 5,000).
  - 2 = Small Urban (Population 5,000–49,999).
  - 3 = Urbanized (Population 50,000–199,999).
  - 4 = Large Urbanized (Population 200,000+).

- Speed Limit—This parameter gives the speed limit of the project stretch. There may be changes in the speed limit among the segments that form the project stretch. The mode of the speed limits was taken and assigned to the entire project stretch. The speed limits for each site was evaluated for every year up to 2016, and the value of 2016 was used for 2017. The speed limit is given in mph in the RHiNo database.
- Number of Lanes—The mode of the number of lanes of the segments in a project stretch was assigned to the entire stretch. The values in 2016 were again used for 2017 at each site. The number of lanes does not include the turning, climbing, or auxiliary lanes but includes Super 2 and exclusive high-occupancy vehicle/high-occupancy toll lanes.
- Surface Type and Median Type—The similar methodology described earlier was used, where the mode of the segment values was assigned to the entire stretch. The values for 2016 were assigned to 2017 for each site. The codes for the surface type in the RHiNo database are:
  - 01 = Road Is Unpaved (unpaved).
  - 02 = Low Type Bituminous Surface-Treated (paved, flex).
  - 03 = Intermediate Type Mixed (paved, flex).
  - 04 = High Type Flexible (paved, flex).
  - 05 = High Type Rigid (paved, concrete).
  - 06 = High Type Composite (paved, flex).
  - 99 = Unknown (new in 2014).

The codes for the median type in the RHiNo database are:

- 0 = No Median.
- 1 = Curbed.
- 2 = Positive Barrier.
- 3 = Unprotected.
- 4 = One-Way Pair.
- 5 = Positive Barrier Flexible.
- 6 = Positive Barrier Semi-Rigid.
- 7 = Positive Barrier Rigid.

Note: Include Median Type 1 and 3 for medians that include grass, gravel, dirt, and the like.

- Median Width—The median width of the project is the mode of the median width of the segments that constitute the stretch. The value is evaluated every year. For the year 2017, the value from 2016 was used. The median width is given in feet.
- Lane Width—The lane width is not directly specified in the RHiNo database. The surface width as well as the number of lanes are given. The lane width is calculated as the surface width divided by the number of lanes. The lane width is given in feet. The individual segments in a project stretch may have different lane widths. The lane width of the project stretch is calculated as the weighted average of all the segments in that stretch. The weights are the individual segment lengths. Year 2017 used the same data as 2016.
- Shoulder Width—The shoulder width is given for both the inside and outside shoulder. However, only one value of shoulder width, which is the average of the inside and outside shoulder widths, is reported. The individual segments within a project stretch may have different shoulder widths. The shoulder width of the project stretch is calculated as the weighted average of the shoulder widths of the segments. The weights are the segment lengths. The shoulder width is specified in feet in RHiNo. The shoulder width is evaluated every year. The values in year 2016 were used for 2017.

Researchers gathered the above information and included it with the location and retroreflectivity data that were previously put into the database. Each of the unique IDs has the values for all these parameters for the seven-year study period. Thus, each U_ID has seven rows of data in the database, one row per year of analysis.

Crash Database

Crash data are usually recorded by the police and later processed, which includes adding additional variables usually related to geometric and traffic conditions. TxDOT has a database for crash data that is known as the CRIS database. The CRIS database has the data for several years, but TxDOT started validating the crash data only in 2011. The data from 2011 to 2017 were considered in this study since they are reliable.

The crash data in this study are summarized for each section and do not account for the direction of roadway in which the crash occurred. The crashes in this study are summarized by the month for every year between January 2011 and December 2017. The period was used to identify the before-and-after period for each of the project stretches. The months before the markings are applied are marked as −1, the month during which the marking is applied is marked as 0, and the months after which the markings are applied are marked as 1. The crash counts are obtained using ArcGIS and R by considering the crashes between the start and end DFO of every stretch.

The crashes in this study should be the ones that are related or potentially affected by the presence or absence of markings or affected by the retroreflectivity of the markings. The total count crashes in the study are the crashes that are obtained after excluding the following types of crashes (since these crashes cannot be attributed only to the pavement markings):

- Pedestrian crashes and animal crashes.
- Crashes resulting from driving under influence (DUI).
- Bicyclist crashes.
- Work zone crashes.
- Intersection crashes.

The total crashes on a project stretch are calculated after excluding the above types of crashes. In this study, researchers were interested in specific types of crashes (potentially affected by the markings). The crash types included are the following:

- Night/day crashes (light condition).
- Wet/dry crashes (weather conditions).

- Run-off-road crashes.
- Head-on collisions.
- Same direction sideswipe collisions.
- Night fatal and injury crashes.
- Night head-on crashes.
- Night same direction sideswipe collisions.
- Night property damage only crashes.
- Nighttime run-off-road crashes.
- Nighttime run-off-road crashes of fatal and injury crashes.

Weather Database

Weather data were collected to identify the number of rainy days in a year to get an estimation of the exposure of the roadway segments to wet-weather. If the number of rainy days does not vary significantly from year to year, analyzing the wet crashes without exposure may be acceptable, but if the number of rainy days varies greatly year to year, there is a need to establish some control by including exposure in the model.

Researchers sought weather information for all months from January 2011 to December 2017, the period over which the crash data were collected. Researchers used data from https://www.wunderground.com/ (*2*). However, researchers cannot consider these data highly reliable since they are not certified weather data. Researchers found certified weather data at https://www.ncdc.noaa.gov/ (*3*), which is the website of the National Climatic Data Center of the National Oceanic and Atmospheric Administration (NOAA). There are shortcomings to these data as well since the data are only available between January 2011 and December 2013. Researchers decided to use the wunderground data and validate it with the available NOAA data.

Methodology to Summarize Weather Data

Researchers adopted the following methodology to summarize the weather data.

Choosing the Weather Station to Record the Data

The wunderground information has weather records from thousands of stations located across the United States. The project segments are located in many cities in the Atlanta District, and it would be difficult to identify the weather station of every project segment to summarize the data. Researchers decided to choose the central city within each county to summarize the data for each segment in that county. The wunderground website gave the most reliable weather station closest to the city entered, and in all the cases it was the data of the nearest airport. Researchers decided to use this approach and summarize the weather data based on the nearest airports. In some cases, a group of counties use data from the same airport.

The county and the respective airport are as listed below:

- Bowie County—Texarkana Regional Airport.
- Cass County—Harrison County Airport.
- Harrison County—Harrison County Airport.
- Marion County—Harrison County Airport.
- Panola County—Harrison County Airport.
- Camp County—Mount Pleasant Airport.
- Morris County—Mount Pleasant Airport.
- Titus County—Mount Pleasant Airport.
- Upshur County—Gilmer Municipal Airport.

Whenever the data were missing or seemed incorrect at one of the airports during some of the months, the data from the next nearest airport were used.

Rainfall Thresholds

Researchers decided to consider a period (day or night) wet when the total rainfall exceeded 0.1 in. during the day or night period. Any rainy period with total precipitation less than 0.1 in. was considered dry.

Rain during Day or Night

The study summarized the number of rainy days and rainy nights in every month for the entire study period. Daytime in this study was defined as the time between the sunrise and sunset. The other time was defined as night. If rain occurred during the daytime, it was counted as a rainy day, and if rain occurred during the night, it was counted as a rainy night. When rain occurred during both day and night, it was counted as both a rainy day and rainy night.

Weather Database Limitations

The amount of rainfall was not considered directly. A threshold of 0.1 in. was used, but the effects of a very high rainfall would be different from that of a smaller rainfall. The rainfall may have occurred only during part of the day or part of the night; however, the exposure for the entire day/night could be determined by a single hour of precipitation.

CRASH ANALYSIS

Researchers assessed the safety benefits of wet-weather pavement markings on the following six crash types, which were considered the most relevant target crashes: wet-night, dry-night, wet-night fatal and injury, dry-night fatal and injury, wet-night run-off-road, and dry-night run-off-road crashes. To increase the robustness and statistical validity of the results, researchers employed two different evaluation approaches that are known to be rigorous and statistically defensible: EB before-after analysis and FB before-after analysis with comparison groups. Each method is described in detail in this report.

A total of 135 segments were included in the previous safety study conducted in 2017. Researchers compiled roadway and crash information for 61 additional segments, which led to a total of 196 segments included in the current safety study. In addition, the 2017 crash data that could not be included in the previous study were added to the current database and incorporated into the updated safety analysis. It was assumed that the existing marking prior to implementation of the wet-weather markings were typical TxDOT-specified pavement markings (spray thermoplastic markings with AASHTO Type II drop-on beads). Wet-weather markings in Texas are described in Special Specification 8994 and require initial retroreflectivity levels of 150 and 125 mcd/m^2/lx for white and yellow, respectively (the threshold retroreflectivity levels are to be measured 3 to 10 days after the markings are installed). The yearly crash data aggregated at each segment for years 2011–2017 were analyzed. The implementation year when wet-weather pavement markings were installed at each segment varied between 2011–2017. Table 2 gives the number of segments and the corresponding mileage for each implementation year.

Table 2. Number of Segments and Miles Included for Each Year.

Implementation Year	Number of Segments	Miles
2011	51	386.7
2013	32	117.2
2014	14	88.3
2015	67	307.1
2016	32	153.3
Total	196	1052.6

In addition to the information on the treatment (implementation of wet-weather pavement markings), researchers gathered data on important roadway characteristic variables, including number of lanes, median width, lane width, shoulder width, AADT, and segment length, as well as on the number of rainy nights and the number of rainy days (per year) that play a role in exposure variables for wet crashes. Table 3 provides the descriptive statistics for the roadway variables and weather variables used in the analysis.

Table 3. Descriptive Statistics for Atlanta District Roadway Segments.

Segment Variable	Number of Segments (mi): 196 Segments (1052.6 mi)		
	Minimum	**Maximum**	**Average**
Number of Lanes	2	6	2.43
Median Width (ft)	0	52.2	1.85
Lane Width (ft)	10	14.3	11.5
Shoulder Width (ft)	0	13.9	4.1
AADT	79	30468	3402.1
Segment Length (mi)	0.12	75.63	5.37
Number of Rainy Nights	22	57	34.1
Number of Rainy Days	14	58	36.3

Empirical Bayes Before-After Analysis

The EB methods have been regarded as statistically defensible methods that can cope with several threats to validity of observational before-after studies, including the regression-to-the-mean bias, changes in traffic volumes, and the effects of other unmeasured factors that might change from the before to the after period. In the EB method, safety performance functions (SPFs) developed based on the data from the reference sites are used to estimate the expected crash frequencies at the treated sites had treatments not been applied. Negative binomial regression models are often used to derive the SPFs. While the success of an EB evaluation largely depends on reliable estimation of SPFs, it is often hard to identify a sufficiently large reference group that is similar enough to the treatment group in the roadway characteristics, weather, and traffic volumes. In this evaluation, daytime crashes obtained from mostly the same sites as nighttime crashes were used as a reference group. The wet-weather pavement markings provide higher levels of retroreflectivity, which is a nighttime visibility property of the markings. The night crashes, especially in wet conditions, are the target crashes; thus daytime crashes can serve as the reference group because the different striping material should have no impact on daytime crashes. The 51 segments with the implementation year 2011 in Table 2 were excluded from the treatment group in the EB analysis because there was no before data (for 51 segments). However, the daytime crashes from those segments could still be included in the reference group data for developing SPFs. Appendix A provides the steps of the EB procedure used in the current data analysis. Note that in this evaluation, SPFs are calibrated for each year of the before-and-after periods rather than just for each period.

The negative binomial regression models, with indicator variables for years 2011–2017 to control for general trends, along with the variables in Table 3, as independent variables, were employed to develop SPFs based on the reference group (daytime crashes). Table 4 presents the estimated coefficients for SPFs for wet-day, dry-day, wet-day fatal injury, dry-day fatal injury, wet-day run-off-road, and dry-day run-off-road crashes. The predicted number of nighttime crashes had wet-weather pavement markings not been installed can then be obtained by applying a multiplier α_f (computed as the number of nighttime crashes divided by the number of daytime crashes) to the SPF for daytime crashes. Note that α_f needs to be estimated based on the segments where wet-weather pavement markings were not installed. The crashes for 2011 to 2015 of 32 segments with the implementation year 2016 were used for computing α_f. The estimated multipliers (α_f) for the crash types considered in this study are also included in Table 4.

Table 4. Estimates of Coefficients for SPFs Developed Based on a Reference Group Consisting of Daytime Crashes at 196 Segments (1052.6 mi).

Variable		Wet-Day	Dry-Day	Wet-Day Fatal Injury	Dry-Day Fatal Injury	Wet-Day Run-Off-Road	Dry-Day Run-Off-Road
Year	2011	−3.7349	−0.9875	−5.5138	−7.9835	−2.2711	−4.2033
	2012	−4.0466	−5.9323	−5.5779	−7.8881	−2.6801	−4.1018
	2013	−4.0496	−6.2111	−5.5123	−8.1880	−2.6486	−4.3539
	2014	−3.9089	−6.0945	−5.3566	−8.0340	−2.5498	−4.3539
	2015	−3.2744	−5.9877	−5.1334	−8.3526	−2.0235	−4.4457
	2016	−3.6033	−6.1251	−4.9061	−7.9868	−2.3035	−4.3828
	2017	−3.5671	−5.9773	−5.1427	−7.8171	−2.3537	−4.2082
Number of Lanes		0.0165	−0.0692	0.1038	0.0046	−0.0026	−0.1219
Median Width		−0.0077	0.0054	−0.0322	0.0090	−0.0040	0.0116
Lane Width		−0.3986	−0.1586	−0.4956	−0.0878	−0.4171	−0.1877
Shoulder Width		0.0063	−0.0781	0.0394	−0.0659	0.0385	−0.0377
Log(Segment Length)		1.0971	0.8446	1.1716	0.8384	1.1661	0.9507
Log(AADT)		0.8866	0.8864	0.7114	0.6912	0.7406	0.5440
Log(Rainy Nights)		−0.1114	−0.3635	−0.1425	0.2069	−0.4144	−0.3087
Log(Rainy Days)		−0.2907	0.4698	0.4151	0.3622	−0.1359	0.5378
Dispersion		0.5881	0.0377	0.5112	0.0410	0.7828	0.0364
Pearson Chi-square/DF		0.9826	1.1804	0.9342	1.0547	1.0164	1.2096
α_f for the Corresponding Nighttime Crashes		0.84	0.50	1.10	0.55	0.78	0.66

Table 5 presents the results of an EB before-after evaluation for nighttime crashes. For each type of nighttime crash in Table 5, the SPFs estimated from the corresponding daytime crashes after multiplying α_f were used to predict the expected number of crashes had wet-weather pavement markings not been installed. The results in Table 5 support positive safety effects of wet-weather pavement markings for nighttime crashes. The effects are statistically significant for wet-night crashes, wet-night fatal injury crashes, and dry-night fatal injury crashes at the 95 percent confidence level and for wet-night run off crashes at the 90 percent confidence level. The estimated crash reductions in wet crashes (wet-night crashes, wet-night fatal injury crashes, and wet-night run-off-road crashes) are larger than those reductions for the corresponding dry crashes, which is consistent with the expectation that the safety benefit of wet-weather pavement markings are indeed larger for wet crashes.

Table 5. Results of EB Before-After Evaluations Based on the Nighttime Crashes Obtained from 145 Segments (665.9 mi).

Crash Type	Crashes in the After Period		$\hat{\theta}$ (SE)	95% CI for θ	90% CI for θ	Percent Crash Reduction
	Observed (L)	EB Estimate ($\hat{\pi}$)				
Wet-Night	63	93.6	0.668 (0.100)	(0.473, 0.864)	(0.505, 0.832)	**33.2**
Dry-Night	188	208.2	0.902 (0.070)	(0.766, 1.039)	(0.788, 1.016)	9.8
Wet-Night Fatal Injury	20	46.8	0.424 (0.101)	(0.226, 0.622)	(0.258, 0.590)	**57.6**
Dry-Night Fatal Injury	77	97.1	0.792 (0.092)	(0.611, 0.973)	(0.641, 0.944)	**20.8**
Wet-Night Run-Off-Road	43	57.0	0.748 (0.132)	(0.490, 1.007)	(0.532, 0.964)	*25.2*
Dry-Night Run-Off-Road	128	134.4	0.952 (0.086)	(0.782, 1.121)	(0.810, 1.093)	4.8

Note: EB estimate ($\hat{\pi}$) is the predicted number of crashes in the after period had wet-weather pavement markings not been installed; $\hat{\theta}$: estimated index of effectiveness; Percent Crash Reduction $= 100(1-\hat{\theta})$; SE: Standard Error; CI: Confidence Interval; Statistically significant results with 95% (90%) confidence level are shown in **bold** (*italic*).

Full Bayes Before-After Analysis with Comparison Groups

Researchers also analyzed nighttime crashes by employing a FB before-after evaluation method. Although the EB method has been widely used as a safety evaluation tool in observational before-after studies for more than two decades, there are some known limitations of EB: (a) it requires a development and calibration of reliable SPFs based on a fairly large reference group of which characteristics are assumed to be as similar as possible to the treatment group other than the treatment itself; and (b) uncertainty in the estimated SPFs is not reflected in the final safety effectiveness estimate of EB. See Park et al. (*4*) for more in-depth discussions of these issues. In the application of EB described in the previous section, the SPFs were estimated based on daytime crashes, and then the estimated SPFs were again multiplied by the estimated ratio of nighttime crashes and daytime crashes at the segments where wet-weather pavement markings were not installed until 2016. Because both the SPF coefficients and the estimated ratios (α_f) are sample quantities, there are inherent uncertainties associated with them, but the mechanism of EB does not allow those uncertainties to be incorporated into the estimated index of effectiveness or percent crash reduction.

FB methods have been introduced as an alternative to EB methods in order to cope with the aforementioned issues of EB (*5*). They have been successfully applied in many observational before-after studies over the last decade (*4, 6,* 7). However, was some confusion on the concept of FB at the beginning of its use, and some of the early applications of FB were actually a hybrid of EB and FB rather than genuine FB. Park et al. (*4*) developed a fully Bayesian multivariate approach to before-after evaluation with a comparison group/comparison groups within the formal Bayesian modeling framework (rather than as a hybrid of EB and FB) and provided step-by-step guidelines for implementation of the before-after FB evaluations. The FB evaluation of wet-weather pavement markings in this study builds on the basic modeling framework of Park et al. (*4*) and is further modified so that it can model the nature of the current crash data better.

Modeling Framework for FB Analysis of Before-After Designs with Comparison Groups

A before-after evaluation design with comparison groups was adapted as a study design for FB analysis to assess safety effectiveness of wet-weather pavement markings. FB methods generally refer to estimation methods and can be applied to any study design, including both cross-sectional designs and before-after designs. On the other hand, EB in safety analysis refers to the combination of a specific study design (a before-after design with a reference group) and the estimation method. Although some researchers have been referring to a hybrid of EB and FB (that is confined within the same framework of EB with some modifications in estimating the predicted crash count without treatment) as FB (see, *8, 9*), FB methods are more general and should not be restricted to any single framework.

Park et al. (*4*) generalized multivariate Poisson Lognormal models, developed in Park and Lord (*10*), for jointly modeling the crash frequencies of different severities or crash types obtained from multiple sites (cross-sectional data) to analyze before-after data with a comparison group/comparison groups. In this study, researchers employed a univariate framework with Poisson-gamma mixture models (instead of Poisson Lognormal models) because Poisson-gamma mixture models can lead to explicit marginal distributions (negative binomial distributions) for observed crash frequencies, whereas Poisson Lognormal models do not have explicit marginal distributions.

The modeling framework of Poisson-gamma mixture models for a fully Bayesian before-after evaluation with comparison groups is presented below. Let y_{it} denote an observation at site i (i = 1, …, I) during time (year) t (t =1, …, T). That is, y_{it} is the number of crashes observed in year t at site i. Let K be the number of covariates and $X_{it} = (1, X_{1it}, \ldots, X_{Kit})$ be a ($K+1$)-dimensional vector of covariates. Let $\boldsymbol{\beta} = (\beta_0, \beta_1, \ldots \beta_K)'$ denote the ($K+1$)-dimensional column vector of the regression coefficients for the crash count. Let υ_{it} denote a vector of yearly random effects corresponding to site i and year t, explaining extra-Poisson variability. Suppose that, conditional on υ_{it} and $\boldsymbol{\beta} \in \mathrm{R}^{K+1}$, the crash count at site i in year t, y_{it}, follows a Poisson distribution with mean μ_{it}, i.e.,

$$y_{it} \mid \upsilon_{it}, \boldsymbol{\beta} \sim Poisson\left(\mu_{it}\right) \tag{3}$$

where

$$\mu_{it} = \upsilon_{it} \exp\left(X_{it}\boldsymbol{\beta}\right). \tag{4}$$

The y_{it} 's are independent given the μ_{it} 's:

$$\upsilon_{it} \sim Gamma\left(\eta, \quad 1/\eta\right) \tag{5}$$

Under the model (3)-(5), the marginal distribution of y_i is given as a negative binomial (NB) distribution with mean λ_i and variance $\lambda_i\left[1+\lambda_i/\eta\right]$, where $\lambda_i = \exp\left(X_i\boldsymbol{\beta}\right)$.

Let the elements of the covariate vector $X_{it} = (1, X_{1it}, \ldots, X_{Kit})$ be:

$$X_{1it} = Trt_i,$$

$$X_{2it} = time,$$

$$X_{3it} = Trt_i \times time,$$

$$X_{4it} = \mathbf{I}\left[t > t_{0i}\right],$$

$$X_{5it} = Trt_i \times \mathbf{I}\left[t > t_{0i}\right],$$

$X_{6it}, \ldots, X_{Kit}$: roadway characteristic variables such as lane width, shoulder width, number of lanes, log(AADT), and so forth for the ith site,

where

Trt_i = 1 if the ith site is a treatment site and is zero otherwise.

$time$ = tth year in the study period (t = 1, 2, … T).

t_{0i} = year in which the countermeasure was installed at site i (for a site in the comparison group, it is defined to be the same year as that for the corresponding treatment group), and $\mathbf{I}[t>t_{0i}]$ is the intervention variable, which takes a value of 1 if t belongs to the after period and zero otherwise.

Then, Equation 4 can be rewritten as follows:

$$\begin{aligned}\mu_{it} = \upsilon_{it}\exp\Big(&\beta_0 + \beta_1 Trt_i + \beta_2 time + \beta_3 Trt_i \times time + \beta_4 \mathbf{I}\left[t > t_{0i}\right] \\ &+ \beta_5 Trt_i \times \mathbf{I}\left[t > t_{0i}\right] + \beta_6 X_{6it} + \cdots + \beta_K X_{Kit}\Big)\end{aligned} \tag{6}$$

This model can be viewed as a change-point model that assumes that, at the time of implementation, there is a possible change in the level with respect to time at treatment sites that might be attributable to the implementation of the countermeasure. Specifically, the coefficient for $X_{5it} = Trt_i \times \mathbf{I}\left[t > t_{0i}\right]$ represents a possible jump or drop effect of the countermeasure on crashes at the treatment site. Note that the comparison group also has the imaginary before-and-after periods defined the same as for the matching treatment group although no treatment is applied to sites in the comparison group (see *4*). Note also that, unlike the model in Park et al., the term corresponding to the change in the slope before and after the countermeasure implementation was not included in (*4*) due to the limited number of crash years (e.g., there was only one year of after crashes at 32 sites with the implementation year 2016). For each group (Comp: Comparison, Trt: Treatment) and period (B: Before, A: After), Equation (6) can be rewritten in terms of *mean crash count* versus *time*, as follows:

$$\left(\mu_{it}\right)_{Comp,B} = \upsilon_{it}\exp\left(\beta_0 + \beta_2 time + \beta_6 X_{6it} + \cdots + \beta_K X_{Kit}\right),$$

$$\left(\mu_{it}\right)_{Comp,A} = \upsilon_{it}\exp\left(\beta_0 + \beta_4 + \beta_2 time + \beta_6 X_{6it} + \cdots + \beta_K X_{Kit}\right),$$

$$\left(\mu_{it}\right)_{Trt,B} = \upsilon_{it}\exp\left\{\beta_0 + \beta_1 + \left(\beta_2 + \beta_3\right) time + \beta_6 X_{6it} + \cdots + \beta_K X_{Kit}\right\},$$

$$\left(\mu_{it}\right)_{Trt,A} = \upsilon_{it}\exp\left\{\beta_0 + \beta_1 + \beta_4 + \beta_5 + \left(\beta_2 + \beta_3\right) time + \beta_6 X_{6it} + \cdots + \beta_K X_{Kit}\right\}$$

A fully Bayesian analysis of the model given in equations 3-6 requires the (second-level) prior distributions for the parameters, β_0, β_1, β_2,…, β_K, as well as η, to be chosen. Implementation of such a model calls for simulation-based methods such as a Markov Chain Monte Carlo (MCMC) method (*11, 12*). Once the posterior samples for model parameters and the true averages crash counts (μ_{it}) are obtained, the steps given below (extracted from Park et al. [*4*]) can be followed to estimate the cumulative effects (θ) of wet-weather pavement markings over time.

Steps for Implementing Fully Bayesian Before-After Evaluations with Multiple (G) Comparison Groups

Step 1. Specify the hyperparameter values, $\left(c_0, C_0, r_0, R_0\right)$ for prior distribution of model parameters.

Step 2. Obtain the draws of model parameters and the expected annual crash frequency for each site (*i*) and year (*t*) by MCMC.

Step 3. Obtain posterior distributions of crash frequencies during the before period for the treatment group (μ_{TA}), during the after period for the treatment group (μ_{TA}), during the before period for the comparison group (μ_{CB}), and during the after period for the comparison group (μ_{CA}) by taking an average of the expected crash frequencies over the appropriate years and the sites.

Step 4. Obtain a posterior distribution of the ratios of the expected crash frequencies' before-and-after periods for the comparison group (comparison ratio) for the g^{th} comparison group by:

$$R_{C(g)} = \frac{\mu_{CA(g)}}{\mu_{CB(g)}}, \qquad g = 1,\ldots, G.$$

Step 5. Obtain a posterior distribution of the predicted frequencies that would have occurred without treatment in the after period for the g^{th} treatment group as:

$$\pi_{(g)} = \mu_{TB(g)} R_{C(g)}.$$

Step 6. Obtain a posterior distribution of the index of effectiveness (of the countermeasure) for the crashes as:

$$\theta = \frac{\sum_{g=1}^{G} \mu_{TA(g)}}{\sum_{g=1}^{G} \pi_{(g)}} = \frac{\sum_{g=1}^{G} \mu_{TA(g)}}{\sum_{g=1}^{G} \left\{ \mu_{TB(g)} R_{C(g)} \right\}}.$$

Step 7. Obtain the point estimates for β_k and θ as the sample means of corresponding posterior distributions.

Step 8. Obtain the uncertainty estimates for β_k and θ as the sample standard deviations of corresponding posterior distributions.

Step 9. Construct the 95 percent (or 90 percent) credible intervals of β_k and θ using the 2.5th (or 5th) percentiles and the 97.5th (or 95th) percentiles of the corresponding posterior distributions. If the credible interval contains the value 1, then no significant effect has been observed. The credible interval placed below 1 (i.e., the upper limit of the interval is less than 1) implies that the countermeasure has a significant positive effect (i.e., a reduction in crashes) on safety. The credible interval placed above 1 (i.e., the lower limit of the interval is greater than 1) implies that the countermeasure has a significant negative effect (i.e., an increase in crashes) on safety.

FB Analysis of the Effects of Wet-Weather Pavement Markings

The daytime crashes used as reference groups in EB analysis can be utilized as comparison groups in this FB analysis. Unlike the EB analysis, which cannot account for the uncertainty in the SPF estimates in the safety effectiveness estimate, the FB analysis can incorporate uncertainty in model parameters into the final safety effectiveness estimate. The treatment group consisted of nighttime crashes from segments where wet-weather pavement markings were installed during 2011 through 2016. As in the case of EB analysis, the 51 segments with the implementation year 2011 in Table 2 were excluded from the treatment group because there were no before data. Thus, the FB analysis is also based on crashes from 145 segments (665.9 mi) where wet-weather pavement markings were installed in 2013, 2014, 2015, or 2016.

Wet-night, dry-night, wet-night fatal injury, dry-night fatal injury, wet-night run-off-road, and dry-night run-off-road crashes were fitted by the Poisson-gamma mixture model with a change point in Equation (4) with predictors, an indicator function specifying whether a segment is a treatment site or a comparison site, time trend (year), treatment by time, an indicator function specifying whether it belongs to the before or the after period, treatment by implementation date, number of lanes, median width, lane width, shoulder width, log of segment length, log of AADT, log of number of rainy nights, and log of number of rainy days. The steps for implementing FB before-after evaluations with four comparison groups (corresponding to implementation years 2013, 2014, 2015, and 2016 with $G = 4$) presented in the previous section were followed. For the prior distributions of the model parameters, proper but diffuse priors were used to reflect the lack of precise knowledge on the parameters a priori. The inferences on the parameters of interest were made based on the samples from the posterior distribution obtained by the MCMC algorithm coded in MATLAB.

Table 6 summarizes the results from the FB analysis based on 4,000 posterior samples collected for 50,000 iterations by subsampling every 5th sample after the first 10,000 draws are discarded. Note that the regression coefficient for the intervention at the treatment sites, β_5, is negative for all six crash types, suggesting that crashes decreased after the installation of wet-weather pavement markings for the treatment group compared to those occurrences for the comparison group. The estimated index of effectiveness ($\hat{\theta}$) was obtained by accounting for the changes in unmeasured factors between the before and the after period using the comparison ratio outlined in Steps 4–6 above. The uncertainty estimates for the estimated index of effectiveness—the posterior standard deviation and 95 percent (or 90 percent) credible interval—play the same role as the standard error and the 95 percent (or 90 percent) confidence interval in non-Bayesian or EB approaches. It can be observed from Table 6 that crash reductions are considerably larger for wet-night crashes than for dry-night crashes. Reductions of wet-night crashes, wet-night fatal injury crashes, and wet-night run-off-road crashes are statistically significant with 95 percent probability.

Table 6. Results of FB Safety Evaluation for Wet-Weather Pavement Markings for Wet-Night and Dry-Night Crashes.

Regression Coefficients	Predictors	Crash Type					
		Wet-Night	Dry-Night	Wet-Night Fatal Injury	Dry-Night Fatal Injury	Wet-Night Run-Off-Road	Dry-Night Run-Off-Road
β_0	Intercept	**−6.5587**	**−5.0478**	**−8.2975**	**−5.6412**	**−5.1370**	**−2.8653**
β_1	Trt	**−0.2133**	**−0.7514**	0.2260	**−0.6333**	**−0.5176**	**−0.5228**
β_2	time	**0.0777**	−0.0092	0.0543	−0.0049	0.0165	0.0099
β_3	Trt×time	0.0084	0.0158	−0.1142	−0.0198	**0.0569**	0.0162
β_4	I[t>t₀]	**0.3094**	0.0465	0.0243	0.0019	0.0800	**−0.1601**
β_5	Trt×I[t>t₀]	**−0.7149**	−0.0748	**−0.5156**	−0.0226	**−0.5974**	0.0042
β_6	Number of Lanes	0.0712	**−0.0354**	0.0387	0.0504	−0.0317	**−0.0577**
β_7	Median Width	−0.0037	**0.0114**	**−0.0248**	**0.0095**	−0.0046	**0.0176**
β_8	Lane Width	**−0.3791**	**−0.1810**	**−0.3264**	**−0.1283**	**−0.4281**	**−0.1882**
β_9	Shoulder Width	−0.0051	**−0.0717**	0.0086	**−0.0700**	0.0435	**−0.0518**
β_{10}	Log(Length)	**1.1459**	**0.8844**	**1.2544**	**0.9081**	**1.2638**	**0.9949**
β_{11}	Log(AADT)	**0.7325**	**0.7820**	**0.6925**	**0.6402**	**0.6950**	**0.4925**
β_{12}	Log(Rainy Night)	**0.7778**	**−0.3319**	**−0.5712**	**−0.5458**	0.2828	**−0.5665**
β_{13}	Log(Rainy Day)	−0.2737	**0.4114**	**1.1534**	**0.6174**	0.0114	**0.4535**
Index of effectiveness		**Wet-Night**	**Dry-Night**	**Wet-Night Fatal Injury**	**Dry-Night Fatal Injury**	**Wet-Night Run-Off-Road**	**Dry-Night Run-Off-Road**
$\hat{\theta}$		**0.5258**	0.9644	**0.4019**	0.9298	0.6529	1.0567
Std Dev		0.0963	0.0999	0.0908	0.1429	0.1068	0.1158
95% Credible Interval		(0.3992, 0.7420)	(0.7907, 1.1508)	(0.2579, 0.5831)	(0.7156, 1.2531)	(0.4627, 0.8657)	(0.8524, 1.2844)
90% Credible Interval		(0.4099, 0.7092)	(0.8170, 1.1257)	(0.2709, 0.5558)	(0.7376, 1.2191)	(0.4816, 0.8279)	(0.8760, 1.2537)
$100(1-\hat{\theta})$: Percent reduction		**47.4%**	3.6%	**59.8%**	7.0%	**34.7%**	−5.7%

Note: $\hat{\theta}$ is the estimated index of effectiveness; Std Dev represents the posterior standard deviation for θ; $100(1-\hat{\theta})$ denotes the estimated percent crash reduction; Statistically significant results with 95% (*90%*) probability are shown in **bold** (*in italic*).

SUMMARY

Table 7 summarizes the results from the EB analysis and the FB analysis. The results from both analyses appear to be consistent in general. As expected, the reductions are much larger for wet crashes compared to dry crashes. The effects are statistically significant for wet-night crashes, wet-night fatal injury crashes (with 95 percent confidence for EB or with 95 percent probability for FB), dry-night fatal injury crashes (with 95 percent confidence for EB), and wet-night run-off-road crashes (with 90 percent confidence for EB or with 95 percent probability for FB). Although the uncertainty estimates from the FB approach appear to be slightly larger than those estimates from the EB approach for some crash types, it is a natural consequence of incorporating parameter uncertainty that is ignored in EB into the safety effectiveness estimates of FB. In conclusion, both evaluation results lend support to positive safety effects of wet-weather pavement markings for wet-night crashes.

Table 7. Comparison of Safety Effectiveness Estimates for Wet-Weather Pavement Markings Obtained by Different Before-After Evaluation Approaches.

	Percent Crash Reduction (Uncertainty Estimate)					
Approach	**Wet- Night**	**Dry- Night**	**Wet-Night Fatal Injury**	**Dry-Night Fatal Injury**	**Wet-Night Run-Off-Road**	**Dry-Night Run-Off-Road**
EB	**33%** (10%)	10% (7%)	**58%** (10%)	**21**% (9%)	*25*% (13%)	5% (9%)
FB	**47%** (10%)	4% (10%)	**60%** (9%)	7% (14%)	**35**% (11%)	−6% (12%)

Note: Uncertainty estimate is standard error for EB and posterior standard deviation for FB; Statistically significant results with 95% (*90%*) confidence/probability are shown in **bold** (*in italic*).

NEXT STEPS

To build upon the current data collection and analysis, the researchers hope to conduct additional work with the data set. This additional work will include the following:

- Expand the data set to incorporate 2018 crashes.
- Expand the data set to include the crash data before 2011 so that the sites with the implementation year 2011 can also be utilized in the before-after analysis.
- If enough data are available, conduct analysis for particular marking types.
- If enough data are available, conduct analysis for particular roadway types.
- Incorporate the initial retroreflectivity values into the analysis.

- Collect in-service retroreflectivity values to model degradation.
- Explore benefit-cost analysis.

CHAPTER 3: WORK ZONE PAVEMENT MARKING REMOVAL

The removal of pavement markings for work zone applications can often lead to confusing conditions for drivers and advanced driver assistance systems due to improper removal. Incomplete removal, ghost markings, and pavement scarring may all be perceived as delineation that competes with the intended work zone or final alignment delineation. This chapter summarizes current TxDOT documentation on the subject and provides information on past research that may provide benefit if incorporated into TxDOT practices. Several research studies have been conducted and provide guidance to help improve pavement marking removal for work zones. This chapter also provides TxDOT with recommendations to improve current specifications governing marking removal.

CURRENT TXDOT DOCUMENTATION CONCERNING PAVEMENT MARKING REMOVAL

TxDOT has two documents that include information on pavement marking removal. The first is Standard Specification Item 677, the second is the *Pavement Marking Handbook* (*13*). The relevant contents of these two documents and some discussion are provided below.

Standard Specification Item 677

Standard Specification Item 677 is titled "Eliminating Existing Pavement Markings and Markers." The description provided in the specification indicates that the document provides governance to "eliminate existing pavement markings and raised pavement markers (RPMs)." Several materials are listed in the specification to furnish a surface treatment to patch and repair damaged surfaces as a result of marking removal:

- Item 300, "Asphalts, Oils, and Emulsions."
- Item 302, "Aggregates for Surface Treatments."
- Item 316, "Seal Coat."

The equipment specified must use moisture and oil traps in air compression equipment to remove all contaminants from the blasting air and prevent the depositions of moisture, oil, or other contaminants on the roadway surface. Four construction methods are listed, and additional details as to the construction requirements are provided.

Item 677 states that removal activities should "eliminate existing pavement markings and markers on both concrete and asphaltic surfaces in such a manner that color and texture contrast of the pavement surface will be held to a minimum. Remove all markings and markers with minimal damage to the roadway to the satisfaction of the Engineer. Repair damage to asphaltic surfaces, such as spalling, shelling, etc., greater than 1/4 in. deep resulting from the removal of pavement markings and markers. Dispose of markers in accordance with federal, state, and local regulations."

The four methods provided for eliminating existing pavement markings are the surface treatment method, burn method, blasting method, and mechanical method. Other methods are allowable if indicated on the plans. A brief description of each method is provided in the specification. The descriptions are as follows:

- **Surface Treatment Method—**Apply surface treatment material at rates shown on the plans, or as directed. Place a surface treatment a minimum of 2 ft wide to cover the existing marking. Place a surface treatment, thin overlay, or microsurfacing a minimum of one lane in width in areas where directional changes of traffic are involved, or other areas as directed.
- **Burn Method—**Use an approved burning method. For thermoplastic pavement markings or prefabricated pavement markings, heat may be applied to remove the bulk of the marking material before blast cleaning. When using heat, avoid spalling pavement surfaces. Sweeping or light blast cleaning may be used to remove minor residue.
- **Blasting Method—**Use a blasting method such as water blasting, abrasive blasting, water abrasive blasting, shot blasting, slurry blasting, water-injected abrasive blasting, or brush blasting as approved. Remove pavement markings on concrete surfaces by a blasting method.
- **Mechanical Method—**Use any mechanical method except grinding. Flail milling is acceptable in the removal of markings on asphalt and concrete surfaces.

Several areas in Item 677 should be improved to generate higher quality pavement marking removal. These areas include modifying the construction requirement details to provide less pavement scarring, providing additional information on the removal techniques, and providing additional information to improve areas where removal has occurred to reduce confusion to drivers. Further discussion of these areas will occur later in this document.

Pavement Marking Handbook

Section 3 of the *Pavement Marking Handbook* (*13*) covers pavement surface preparation prior to marking application. Part of surface preparation may consist of removing existing pavement markings. The *Pavement Marking Handbook* indicates existing markings should be removed if they are too thick, losing adhesion to the pavement surface, of an incompatible material with what is to be applied, or if the marking layout must be reconfigured. The *Pavement Marking Handbook* indicates that removal should be performed in accordance with TxDOT Specification Item 677.

The *Pavement Marking Handbook* indicates approved methods are flailing, waterblasting, and sandblasting. The list of removal techniques does not apply to buttons or tape. The *Pavement Marking Handbook* indicates that, painting out markings by covering over old pavement markings with black paint is not an acceptable removal technique. A picture of a properly removed marking using the flailing technique (prior to final brooming) is provided in the handbook (see Figure 1).

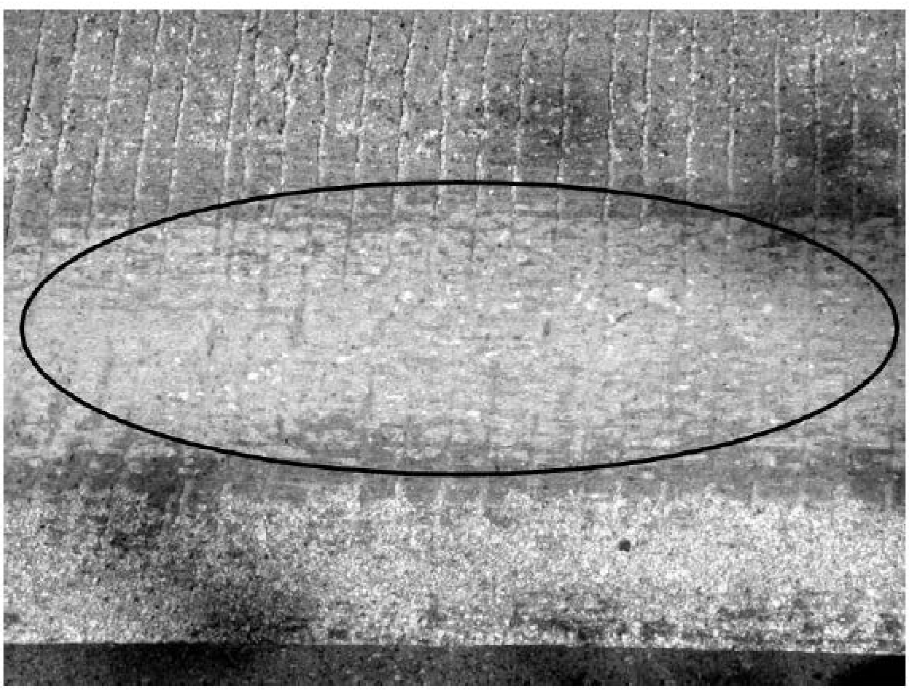


Figure 1. Properly Removed Marking Using Flailing Technique (*13*).

The *Pavement Marking Handbook* has a section describing preformed tapes. This section describes the two classifications of tape, permanent and temporary. Permanent applications cannot be removed by hand and have a service life of at least one year. Temporary tapes are typically used for short duration applications, such as work zones. There are two forms of temporary marking tapes based on their adhesive strengths. The first type of temporary tape is intended for use in projects where marking removal will not be required because it is not easily removable. The second type is easier to remove by hand, leaving no trace of a marking. The latter type of removable marking is often used in work zones when markings must be removed.

The *Pavement Marking Handbook* also addresses the removal of both permanent and temporary preformed tapes. Pavement marking tapes should always be removed prior to installation of new markings. Removal of permanent tapes is difficult due to the strong bond to the pavement surface. Removal can only be achieved by certain removal methods and often results in scarring of the pavement surface. The *Pavement Marking Handbook* indicates that burning and scraping of the marking materials with an oxygen torch is one method of removal, but this method is not in the list of approved methods. The *Pavement Marking Handbook* indicates that permanent tapes are often ground off, which scars the pavement. The *Pavement Marking Handbook* indicates that most temporary tapes are easily removed by hand or by a mechanical roller with no special equipment required.

The *Pavement Marking Handbook* provides some supplementary information to Specification Item 677 that can be used to facilitate good pavement marking removal results. The information is lacking in several areas and could be improved to provide more information to make informed decisions about removal techniques and methods to limit issues associated with marking removal. Additional information on removal techniques and areas where the *Pavement Marking Handbook* can be improved are provided later in this document.

SUMMARY OF PAVEMENT MARKING REMOVAL RESEARCH

Several research studies have been conducted to better understand pavement marking removal techniques and the advantages and disadvantages of each. A general consensus is that not one removal technique is best for all applications and that tradeoffs often need to be made when selecting which removal method to use. The most comprehensive study of pavement marking removal techniques is documented in National Cooperative Highway Research Program

(NCHRP) Report 759, *Effective Removal of Pavement Markings* (*14*). The results of the NCHRP study, as well as additional information on other research projects that are fully described in the NCHRP report, are provided below.

NCHRP Report 759

The objective of the NCHRP pavement marking removal research was to determine best practices for the safe, cost-effective, and environmentally acceptable removal of work zone and permanent pavement markings with minimal damage to the underlying pavement or visible character of the surface course. The project consisted of a literature review, survey of agencies regarding removal practices, summary of each state's pavement marking removal specifications, marking removal at pavement marking test deck locations, and field evaluations of typical removal operations. The research provided a set of recommendations and best practices to improve pavement marking removal.

Selection of the most appropriate removal system requires an examination of many factors that may change from project to project. Thorough consideration of each factor is the best way to consistently achieve acceptable pavement marking removal results. The research recommended consideration of the following factors (*14*):

- What marking material is being removed.
- What road surface the material is on.
- How much material needs to be removed (what is the purpose of the removal).
- Whether speed of removal is important.
- What removal techniques are available and at what cost.
- Whether special environmental conditions need to be considered.
- How long the removed area will be viewed by drivers (whether a new surface will be installed or markings will be restriped in the future).
- Whether the removed area will be in a location where confusion could lead to an accident.
- Whether there are other measures that can be taken to minimize confusion to the driver.

The research provided tables of the advantages and disadvantages of the most common forms of pavement marking removal (see Table 8). This table should be considered to help determine which type of pavement marking removal may be best. In addition to the advantages and disadvantages of the removal methods, the research provided a table summarizing the effectiveness of various removal techniques with respect to different types of pavement marking materials (see Table 9).

Table 8. Advantages and Disadvantages of Removal Techniques (*14*).

Removal Method	Advantages	Disadvantages
High-Pressure Water	• Byproduct does not create dust and is contained within the equipment. • Little to no scarring on PCC. • With the exception of drying time, the pavement surface is prepped for pavement marking reinstallation. • Relatively fast for a blasting method. • Large vehicle mobile systems available with additional utility carts for smaller nearby areas.	• Limited to above-freezing conditions. • May polish surface aggregate and/or clean the surrounding pavement, creating a color contrast. • May remove some surface asphalt and fines that could lead to water penetration. • Potential for damage to pavement joints. • Currently not widely available, higher costs. • Proper equipment operation critical to achieve good results.
Grinding	• Fast and economical. • Depending on the system configuration (effective vacuum system installed to remove dust), dust created by removal can be contained. • High availability.	• Damage to pavement surface. • Scarring with full marking removal, minimizing damage to roadway may leave marking material behind. Orbital flailing may result in less noticeable scarring than drum flailing due to tapered edges. • Non-vacuum systems can create dust clouds and be hazardous.
Sand Blasting	• Minimal pavement degradation. • Little to no scarring. • Hand-operated precision.	• Creates considerable byproduct. • Creates considerable dust. • No current large vehicle mobile system, therefore slower than mobile methods. • Health hazards depending on blast media.
Shot Blasting	• Minimal byproduct. • Byproduct does not create dust and is contained within the equipment. • Minimal pavement degradation. • Little to no scarring.	• Shot recovery can be problematic especially on uneven surfaces. • Cannot be used in wet conditions. • Can be slow especially for thicker markings. • Can cause pavement damage on non-smooth surfaces. • Limited availability of equipment.
Soda Blasting	• Minimal pavement degradation. • Little to no scarring. • Hand-operated precision.	• Creates a moderate amount of byproduct. • Creates considerable dust. • No current large vehicle mobile system. • Can be slow especially for thick markings. • Only useful on some markings.
Dry Ice Blasting	• Minimal environmental concerns with respect to debris generated. • Minimal pavement degradation. • Marking can be completely removed. • Hand-operated precision.	• Dry ice is a difficult medium to handle and store. • Very noisy. • Slow. • No current large vehicle mobile system. • Only useful on some markings.
Hydroblasting	• Similar advantages to high-pressure water and sand blasting. • Minimal pavement degradation. • Limited scarring.	• Similar disadvantages to high-pressure water and sand blasting. • Creates considerable byproduct. • No current large vehicle mobile system. • Limited to above-freezing conditions.
Excess-Oxygen Burning	• Minimal pavement degradation.	• Requires at least one additional pass to remove residue. • Slow. • No current large vehicle mobile system. • Only useful on some markings.
Laser	• Non-contact and should have little to no wear, which reduces maintenance costs. • Minimal pavement degradation. • Minimal environmental concerns.	• Slow. • Requires at least one additional pass to remove residue. • No current large vehicle mobile system. • Only useful on some markings.

Table 8. Advantages and Disadvantages of Removal Techniques (Continued) (*14*).

Removal Method	Advantages	Disadvantages
Chemical	• Byproduct does not create dust. Can get complete removal without scarring.	• Potential to damage pavement surface if incorrect removing agents are used. • Requires at least one additional pass to remove residue. • Slow, need to wait for chemical to react then proceed with removal. • No current large vehicle mobile system. • Only useful on some markings.
Hand Removal	• Detailed removal.	• Slow. • Typically only for removable tapes.
Masking	• No damage to road surface. • Existing markings can be temporarily covered with tape that matches the road surface color and texture, and later reused when the tape is removed. • Removed areas can be masked to help blend in scarring or surface color changes. • Can be used in lane-shift areas to reduce driver confusion due to ghost markings or scarring.	• Can be expensive. • Material may wear away exposing the markings being covered. • Difficult to match color and texture with tape. • Tape is for temporary purposes only. • Cannot use marking materials other than tape to cover a marking.

Table 9. Effectiveness of Pavement Marking Material (*14*).

Removal Method	Paint	Thermoplastic	Epoxy	Tape	Foil Tape
High-Pressure Water	Good (Berg and Johnson 2009; Ellis et al. 1999)	Good (Ellis et al. 1999)	Good (Berg and Johnson 2009)	Good	Ineffective
Sand Blasting	Good	Slow	Good	Ineffective	Very Slow
Hydroblasting	Good	Slow	Good	Ineffective	Ineffective
Soda Blasting	Slow (Berg and Johnson 2009, Cho et al. 2011, Oregon DOT 2001)		Slow (Berg and Johnson 2009, Cho et al. 2011)		
Dry Ice Blasting	Slow (Berg and Johnson 2009, Cho et al. 2011)		Slow (Berg and Johnson 2009)		Slow (Cho et al. 2011)
Shot Blasting	Good (13)				
Grinding	Good (Berg and Johnson 2009, Cho et al. 2011, Ellis et al. 1999, Oregon DOT 2001)[c]	Good (Ellis et al. 1999, Oregon DOT 2001)[c]	Good (Berg and Johnson 2009, Ellis et al. 1999)[c]	Ineffective	Ineffective
Hot Compressed-Air Burning	Slow (Niessner 1979)				
Excess-Oxygen Burning[b]	Thin Only	Ineffective	Ineffective	Ineffective	Good
Laser[b]	Slow (Pew and Thorne 2000)				
Chemicals[b]	Slow (Cho et al. 2011)	Ineffective	Ineffective	Ineffective	Ineffective
Hand Removal		Very Slow		Very Slow	Ineffective

[a] Table modified from original table presented in the *Roadway Delineation Practices Handbook* (Migletz et al. 1994) based on more recent research.
[b] Method requires a second pass to remove debris/residue, which could be another method such as high-pressure water.
[c] Removal can be successful but typically results in pavement scarring.

The NCHRP report recommended a series of best practices to improve pavement marking removal quality. The recommendations from the NCHRP report (*14*) are summarized below and should be considered for inclusion into specifications, standards, and guidelines.

The purpose of the removal (realignment or remove and replace) should play a role in the removal method selected as well as other measures used to provide a roadway with delineation that is not confusing to drivers. Changing pavement marking patterns (realignment) is the most critical pavement marking removal scenario because the old markings are no longer conveying the desired travel path to the drivers. Errors in removal can lead to confusion between the new and old markings or the removed areas. A high percentage of the material needs to be removed when changing alignments to mitigate confusion, but damage to the road surface also needs to be considered. Removal should be 90–95 percent, with 100 percent removal in some cases. Damage to the road surface should be 1/8 in. in depth or less while changing the road surface texture as little as possible. Open-graded or tined surfaces may require the material below the pavement surface to be removed with a blasting technique to minimize scarring. When changing marking patterns, especially in lane shift areas, additional measures may need to be taken to reduce driver confusion with areas of removed markings. These additional measures can include fog or slurry seals over the removed area or the entire lane width on asphalt surfaces. On Portland cement concrete (PCC) surfaces, additional light removal around the removed area or across the entire lane width can be conducted with a blasting technique such as water blasting to help blend in the removed area. For remove and replace with compatible markings, the whole marking does not always need to be removed, so removal can be limited to at or above the road surface to help limit scarring. Removal by grinding may be the best option, but if full removal or removal of material below the surface is needed, then water blasting or another blasting technique may be a better option to minimize impact to the roadway.

The construction work phasing and the final road surface need to be considered when selecting marking materials and removal methods. If markings are to be removed for a short duration prior to a new surface, then damage to the road surface is not as critical compared to a removed area that will be visible for a longer duration. Removal on the final surface needs to be accomplished with minimal damage. It is recommended that temporary pavement markings on the final road surface be used until the final marking configuration so that removal will do as little damage to the road surface as possible.

Symbols and text should be removed in a square or rectangular pattern so that the previous shape is not identifiable as a scar or discoloration. This practice requires removal of the marking and the necessary removal/cleaning around the marking to help blend in the area with the surrounding pavement, resulting in a slightly larger removal area that is no longer recognized as a symbol or text.

Older road surfaces that are experiencing cracking or surfaces with joints may need special consideration when removal occurs around these areas. The use of high-pressure water blasting on these surfaces can lead to road damage if the water is allowed to penetrate into the cracks or joints. Grinding may also pose a threat to cracks and joints. Removal around these areas should be conducted carefully such that the joints are not disturbed and the cracks are not made worse by the removal.

All pavement marking removal projects should begin with testing the removal equipment and operator in a non-critical area to evaluate the removal quality. The initial testing will show how well the operators can use the equipment to remove the marking while minimizing damage to the road surface. The test area can be used to adjust the equipment to find the ideal setup for the work required. If the operator and equipment cannot provide satisfactory results, another removal system or plans for corrective actions should be considered.

Marking removal inspection needs to occur during the day, at night, and during wet conditions. Surface color changes and scarring will have a greater impact during the day than at night, whereas retroreflectivity from remaining marking material or retroreflectivity differences because of surface texture changes will be more noticeable at night. The direction of travel and the position of the sun also need to be considered. Wet conditions may fill pavement scarring, resulting in an area that looks like a wet marking and thus creating confusing delineation. Any areas with color, texture, or retroreflectivity issues should be corrected to reduce or eliminate driver confusion.

Pavement marking specifications for areas where removal has occurred should consider post-removal conditions. Wider markings and continuous markings in transition areas will provide better guidance to drivers and may reduce confusion of the removed marking areas by enhancing the new markings. Markings with high retroreflectivity levels should also be maintained in areas where previous removal may be confusing to drivers at night. The high retroreflectivity of the new markings will be more noticeable to drivers than removed areas of markings with lower retroreflectivity levels.

These recommendations were part of the NCHRP 759 Report and are applicable to any pavement marking removal activities (*14*). There are multiple areas in the report that provide valuable information that can be used to improve the TxDOT standards, specifications, and guidelines.

Other Research

A study conducted in Utah focused on evaluating five specific removal technologies (*15*). Three blasting methods (high-pressure water, soda, and dry ice) and two grinding methods (carbide and diamond bit) were evaluated. Waterborne paint on an asphalt chip seal pavement and waterborne paint over an existing epoxy line on a PCC pavement were the removed marking materials. The grinding removal methods were faster than the high-pressure water blasting, but the high-pressure water blasting resulted in the least amount of pavement damage. The high-pressure water blasting also had the least amount of complications during and post application for dust and noise concerns. The research recommendations/implementations indicated that the two grinding technologies are still the most effective in removing lines quickly and leaving the surface ready to be restriped. The water blasting technology was the most effective at marking removal with the least amount of damage to the pavement and should be investigated for future use.

The Florida Department of Transportation (DOT) sponsored two separate research efforts to investigate how to eradicate pavement markings, with one focused on the removal of the pavement markings (*16*) and one focused on methods to mask or cover the pavement markings (*17*). The first study investigated the removal of paint, thermoplastic, and temporary tape on asphalt concrete (AC) using high-pressure water blasting, grinding, and a combination of those two methods. The researchers focused on AC because it is the most common pavement surface in Florida and had the most pavement marking removal problems. A specific removal method was not recommended. Results showed that pavement scarring is possible with both grinding and water blasting, but grinding appears to present the largest possibility for pavement scarring. High-pressure water blasting appeared to be the most effective at removing pavement markings with the least amount of surface scarring.

In the second Florida study (*17*), Ellis investigated pavement marking eradication alternatives that masked or covered pavement markings with an inexpensive surface treatment or temporary black tape in lieu of marking removal. The measures of effectiveness were focused on the blending of the masking material with the existing pavement, the durability of the surface, the surface friction of the seal coat material, and the associated costs with each method. The researchers recommended both methods be adopted as optional methods to mask markings.

The Oregon DOT evaluated several different pavement marking removal methods to determine which were most effective (*18*). Oregon DOT had contractors remove 4-in. wide, 15-mil and 30-mil thick paint pavement markings from AC. The removal methods evaluated were soda blasting and three mechanical methods—a scarifier, a grinder, and a planar. The mechanical methods were all faster than the soda blasting, but the soda blasting outperformed the mechanical methods with respect to minimal pavement surface scarring. The authors noted that pavement scarring is possible with any mechanical removal method and that operator skill and experience can affect results.

The Nebraska Department of Roads sponsored a research project on the effectiveness of temporary pavement marking removal methods on concrete and asphalt surfaces (*19*). Researchers conducted a five-question survey on which removal methods are used, which are most common, which are most satisfactory, what common problems exist, and what marking materials are used most. The survey was completed by 50 respondents, including at least one representative each from 25 states. Grinding was indicated as being used in all responding states, with 80 percent of states stating they use water blasting, and 60 percent stating they use sand blasting. The most commonly used removal methods by the respondents were grinding (92 percent); water blasting (56 percent); and sand blasting (24 percent). The removal method with the most satisfactory results was grinding (48 percent), water blasting (52 percent), and sand blasting (20 percent). Researchers generated a list of common problems identified for each of the removal methods. Based on the comments, each technique can damage the road surface or leave a scar while removing markings.

In addition to the survey, researchers conducted a controlled field evaluation of several removal techniques: water blasting, dry ice blasting, grinder, scarifier, polycrystalline diamond cutter grinder, chemical removal, and heat torch. All removal methods were hand operated, including the water blasting, which was a lower pressure setup that used a wand. A total of 40 yellow paint lines 50 ft in length were applied to a concrete and an asphalt surface. Half of the lines were 12 mil thick, and the other half 20 mil. Evaluation criteria consisted of rate of removal, completeness of removal, and condition of the surface after removal (degree of scarring). The research results showed that the blasting and grinding techniques could remove most, if not all, of the markings. The shot blasting and grinding techniques scarred the PCC surface the most, and all removal techniques scarred the asphalt surface. Overall, the researchers found that the paint was most effectively removed with the chemical stripper and that image analysis could be a useful tool in quantifying marking removal (*19*).

RECOMMENDATIONS AND GUIDANCE

This chapter provided information on TxDOT's current pavement marking removal guidance and specification. Also provided is information on past research studies that can be used to improve TxDOT's practices. TxDOT's current specification governing marking removal (Item 677) and guidance provided in the *Pavement Marking Handbook* (*13*) can both be improved by considering the recommendations and best practices provided in NCHRP Report 759 (*14*). In addition to improvements in the aforementioned documents, new guidance documents could be developed to help specific in-field situations where pavement marking removal is problematic. These specific guidance documents would supplement Item 677 and the *Pavement Marking Handbook* by providing engineers with additional information to improve the quality of work zone pavement marking removal.

Based on this review of current TxDOT practice and existing literature, the following recommendations can be made:

- Update Item 677 to include Item 315, "Fog Seal." Including Item 315 will provide another means besides seal coat for correcting areas where scarring or ghost marking occur.
- The maximum scarring depth in Item 677 should be reduced from ¼ in. to 1/8 in. This requirement will hold contractors more accountable for damage caused to the pavement surface, which will result in shallower scars that are not as noticeable.
- The removal methods and descriptions in Item 677 should be updated to provide additional descriptive information about the removal techniques.
- Item 677 should reference the *Pavement Marking Handbook* for additional guidance.
- Item 677 should have a dedicated section on corrective actions that should occur if removal results in a confusing driving environment. This same information could be expanded upon in the *Pavement Marking Handbook*.
- The *Pavement Marking Handbook* section on pavement marking removal should be updated. Updates can include much of the referenced information from NCHRP Report 759. Tables showing the advantages and disadvantages for the various removal techniques would be useful to include. Updates could also include images of good and bad removal and a list of factors to consider when determining which removal method is best for a specific situation.
- The *Pavement Marking Handbook* should specifically address pavement markings, work zone markings, and final markings in areas where removal activities have occurred. These areas may require higher visibility markings, continuous markings,

or wider markings to help overcome the effects of ghost markings, scarring, and pavement discoloration or texture changes.

- A standalone guidance document for pavement marking removal could be developed in conjunction with updates to Item 677 and the *Pavement Marking Handbook*. The document could incorporate the results of Texas-specific field investigations of pavement marking removal across various situations.

CHAPTER 4: RRPM PRACTICES IN OTHER STATES

During the winter, snowfall amounts in some TxDOT districts requires the use of snowplows to remove the snow from the roadways. Surface-mounted RRPMs are removed by snowplows with steel blades since these RRPMs sit on top of the road surface (see Figure 2a). While steel-casting snowplowable RRPMs are available, they cost more per unit and may increase pavement maintenance, and durability and safety issues have been noted (see Figure 2b). Therefore, some states use surface-mounted RRPMs recessed in a groove cut into the pavement (see Figure 2c). Inlaid RRPMs are a special type of marker designed specifically for groove installation (see Figure 2d). In this activity, researchers reviewed the RRPM practices and specifications used in other states that deal with snow removal and developed recommendations for TxDOT.

(a) Surface-mounted RRPMs.

(b) Snowplowable RRPMs with Cast Metal Housing.

(c) Groove-Recessed RRPMs.

(d) Inlaid RRPMs.

Figure 2. Pavement Marker Types.

STATE OF THE PRACTICE

Researchers performed a literature review and reached out to state transportation agencies throughout the United States to gather information about their practices. While some information was available online, follow-up phone calls were made to verify the validity of the information. Through phone calls, researchers obtained information on the use of RRPMs from transportation agencies in 40 states, as shown in Figure 3.

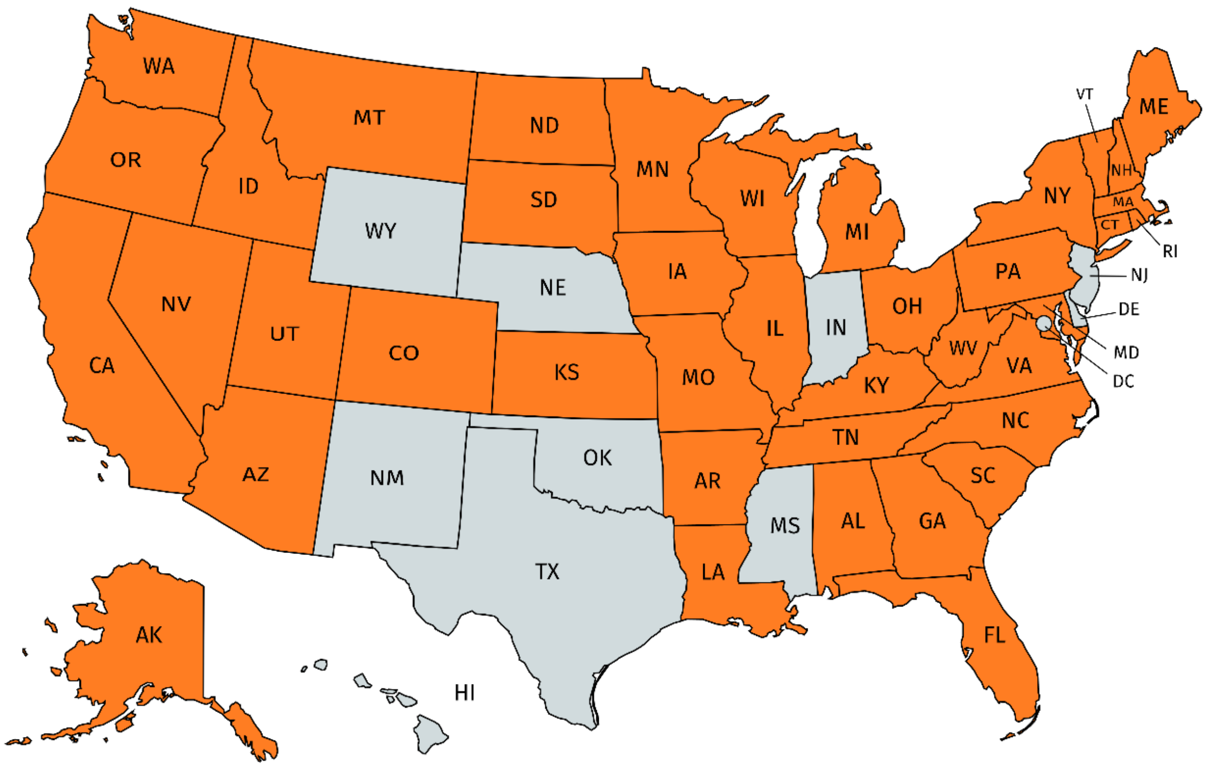


Figure 3. States Contacted for RRPM Practice Information.

States Not Using RRPMs

Of the 40 states contacted, 14 states (Connecticut, Idaho, Iowa, Kansas, Maine, Michigan, Minnesota, Montana, New Hampshire, New York, North Dakota, South Dakota, Vermont, and Wisconsin) do not use any type of RRPMs, primarily due to snowplowing activities. At least four of those states (Kansas, Maine, South Dakota, and Vermont) have opted to recess their striping instead of using RRPMs. Maine and Maryland reported that they restripe more frequently (i.e., annually) to keep markings in good condition.

Snowplowable Marker Experiences

Table 10 shows the 22 states that reported having experience with snowplowable RRPMs. Thirteen states reported that they used them in the past but have either discontinued their use or are eliminating their use over time through attrition, through overlays, and the like. Nine states reported that they currently use snowplowable RRPMs. Six states expressed a concern over liability issues associated with these RRPMs becoming dislodged and striking vehicles and/or their occupants. The remaining three states using the snowplowable RRPMs did not express any concern over their use.

Table 10. States with Snowplowable Marker Experiences.

State	Discontinued Use	Currently Using but with Concerns	Currently Using without Concerns
Arkansas	X		
Illinois			X
Kansas	X		
Kentucky		X	
Maine	X		
Maryland	X		
Massachusetts	X		
Missouri	X		
Nevada	X		
New Hampshire	X		
New York	X		
North Carolina		X	
North Dakota	X		
Ohio			X
Pennsylvania		X	
Rhode Island		X	
South Carolina	X		
Tennessee		X	
Utah	X		
Virginia			X
West Virginia		X	
Wisconsin	X		

Inlaid Marker Experiences

Five states reported have some experience with inlaid RRPMs (Illinois, Iowa, Kentucky, Missouri, and Utah). Illinois reported having limited installations of the inlaid RRPMs in Lake County, with no information on their effectiveness or durability. Iowa reported having a limited test area and found that they were not cost effective. Ultimately, they decided to do away with

RRPMs altogether. Kentucky is starting to use inlaid RRPMs as an alternative to the snowplowable type. As part of a research study performed by the University of Kentucky, 1,850 RRPMs were installed on Kentucky roadways and monitored during a variety of conditions. As shown in Figure 2, two RRPMs were placed in each groove. When a grade was present, water did not accumulate in the groove. In flat areas, water did accumulate in the groove, but the researchers found that only 2 percent of the grooves had water over both lenses and about 20 percent had water over one lens only. After one winter, only three of the RRPMs had missing lenses. Based on these findings, maintenance crews are no longer installing snowplowable RRPMs but using the inlaid RRPMs as replacements are needed. Missouri is field testing the inlaid RRPMs in the St. Louis area only. To date, the research has consisted only of driver opinions. The Missouri DOT published a special standard sheet for the use of inlaid RRPMs at entrance and exit ramps, but the sheet is only used at the discretion of the Traffic Division. While the inlaid RRPMs look promising, their maintenance costs, durability, measured visibility, and overall effectiveness have not yet been well-documented.

Groove-Recessed RRPMs Experiences

As shown in Figure 4, 13 states reported having some experience with groove-recessed RRPMs. Six states (Colorado, Georgia, Maine, Massachusetts, New Hampshire, and South Carolina), shown in red, field tested groove-recessed RRPMs and chose to discontinue their use.

In Colorado, the groove-recessed RRPMs were installed on a heavily traveled section of I-70 between Denver and the Rocky Mountain tourist areas. The Colorado DOT staff reported that their maintenance was problematic because they had to continually clean the grooves out. In addition, the RRPMs were visually ineffective during a snowstorm (a time in when they are needed most). Colorado DOT is now using internally illuminated LED RPMs and find that they are very effective during snowstorms.

The Georgia DOT reported it found visibility issues with the groove-recessed RRPMs and chose to simply replace any surface-mounted RRPMs as needed each year. It reported a significant cost savings over the cost of maintaining the groove-recessed RRPMs.

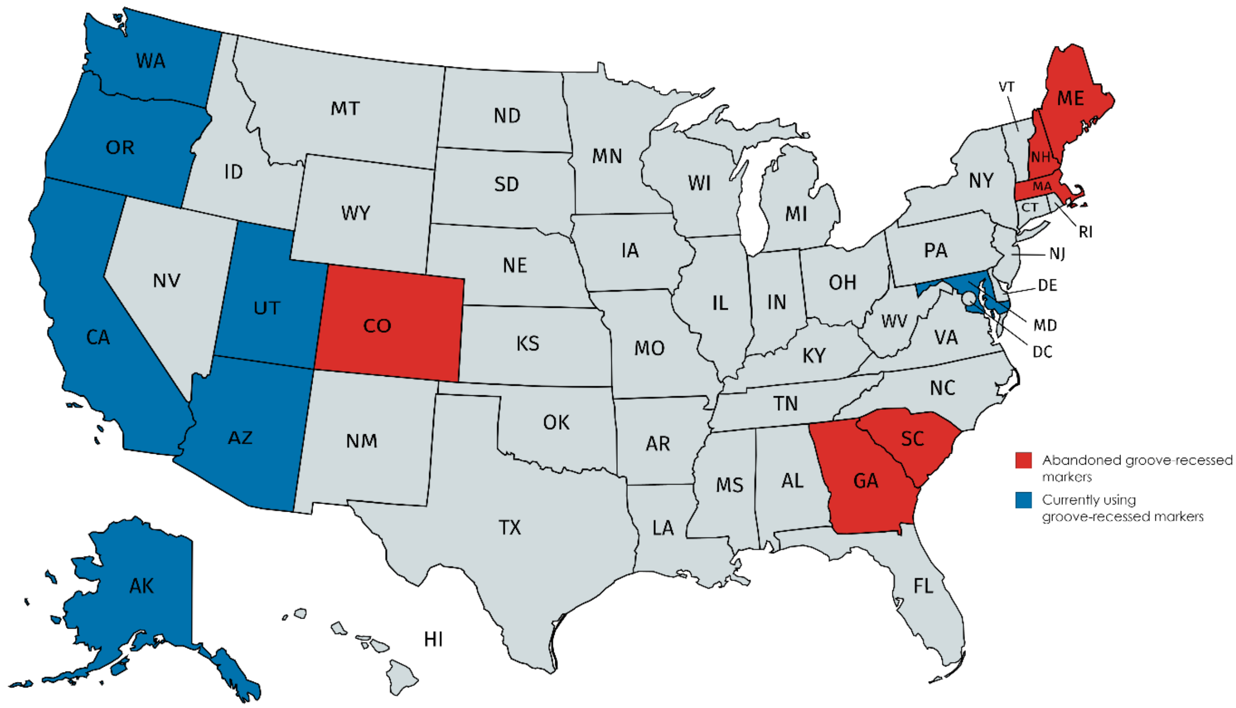


Figure 4. States with Groove-Recessed RRPM Experiences.

The Maine DOT also reported that it abandoned groove-recessed RRPMs due to ineffectiveness (primarily a lack of visibility) and began to use recessed polyurea pavement markings on interstates and other critical areas in need of improved delineation. It also reported that it restripes everything annually.

The Massachusetts DOT reported that it encountered durability issues, high loss rates, and poor visibility due to water, sand, salt, and debris in the groove of their groove-recessed RRPMs. Now it uses all-weather wet reflective tape that is 4 in. wide by 36 in. long and placed in a 125 mil groove in the pavement.

New Hampshire reported that it experimented with groove-recessed RRPMs and chose to discontinue their use. They found that water and dirt collected in the groove and visibility was significantly reduced.

Finally, South Carolina tried groove-recessed RRPMs after a lawsuit over a snowplowable marker. It found that the groove-recessed RRPMs were ineffective due to dirt and water accumulating in the grooves. Like Georgia, it now uses surface-mounted RRPMs and simply replace them each year. It also reported a significant cost savings over installing and maintaining the groove-recessed RRPMs.

Seven states (Alaska, Arizona, California, Maryland, Oregon, Utah, and Washington), shown in blue in Figure 4, are actively using groove-recessed RRPMs.

The Alaska Department of Transportation and Public Facilities (ADTPF) uses groove-recessed RRPMs in their Southcoast Region on selected resurfacing projects. They are typically replaced as needed on existing installations. While there are no published design criteria, they are generally considered for installation on major collectors and arterials that lack illumination and have average daily traffic greater than 1500 vehicles. Maintenance of the groove-recessed RRPMs is complicated given the types of materials that are laid down after a snowstorm. When properly installed, they are not damaged by snowplows but can become ground down through the action of traffic on gravel and sand. Despite these shortcomings, they were reported to work well in remote areas and on dark roadways. ADTPF has a standard drawing for groove-recessed RRPMs that can be found in Appendix B (*20*).

The Arizona DOT uses groove-recessed RRPMs only at ground elevations higher than 4000 ft. No formal assessment was documented, but their experience has been positive. Arizona DOT has a standard drawing for groove-recessed RRPMs that can be found in Appendix B (*21*).

The California Department of Transportation (Caltrans) uses groove-recessed RRPMs on select roadways in a few districts where snow is common in the winter months. There are no formal criteria for selecting installation locations for groove-recessed RRPMs; instead, this is decided at the district level and incorporated into reconstruction contracts. The groove-recessed RRPMs require minimal maintenance by Caltrans staff. The length of the groove was designed to allow for installation of a new marker in front of any damaged or missing RRPMs. However, regrinding of grooves is necessary if the roadway surface is chip sealed. In addition, old grooves can leave scarring on the pavement. Caltrans did not report any significant problems with dirt, sanding material, or water collecting in the groove. Average weighted price (from bid tabulations) for groove-recessed RRPMs was reported to be $6.75 each, while surface-mounted RRPMs were $3.10 each. The Caltrans standard drawing can be found in Appendix B (*22*).

Maryland Department of Transportation State Highway Administration (MDOT SHA) also uses groove-recessed RRPMs. The Maryland standard drawing can be found in Appendix B (*23*).

Oregon DOT began experimenting with groove-recessed RRPMs in the early 1980s and adopted an installation design based on Caltrans' standard. In 1999, the Oregon DOT design was changed to lengthen the groove to enable maintenance crews to simply add another marker instead of having to remove old non-functioning RRPMs or grind a new slot. More recently, other minor adjustments to the standard were made and are more thoroughly described in the Standard Drawing Report for TM517 dated July 1, 2015 (*24*). Their standard drawing can be found in Appendix B (*25*).

The Utah DOT is currently evaluating centerline groove-recessed RRPMs installed with the same method used by Arizona DOT. Utah DOT has four test beds across the state. In one test bed, it lost 25 percent of the devices in the first year; however, there were fewer losses in other locations. It anticipates using the groove-recessed RRPMs in the future, pending the results of the field testing. No formal documentation of the field testing has been published at this time. A standard drawing was not available.

The Washington State DOT uses groove-recessed RRPMs. Their experience indicates that passing traffic tends to keep the grooves free of water and debris. No placement guidance exists. Instead, they are installed at the discretion of their regional traffic engineers. Spacing is typically at 80-ft intervals, except on curves of 1500-ft or less radius, where they are spaced at 40-ft intervals. Historically, they last anywhere from two to four years. Washington State DOT replaces them every four years. Installation prices can vary from $3 to $9 each, depending on whether or not the installation is contracted or performed by state forces. Their standard drawing can be found in Appendix B (*26*).

CONCLUSIONS AND RECOMMENDATIONS

Information obtained during the state-of-the-practice revealed safety and durability concerns with snowplowable RRPMs. Inlaid RRPMs have not been sufficiently evaluated to determine their maintenance costs, durability, measured visibility, and overall effectiveness.

While groove-recessed RRPMs have been in use for quite some time, DOT experiences with them have been mixed. Almost half (six) of the 13 states who tried them eventually decided not to use them, with three of those states opting not to use any type of RRPMs. Two southern states (Georgia and South Carolina) realized a cost benefit when they opted to use surface-mounted RRPMs and replace them every year as needed.

Researchers attempted to compile elevation and average snowfall data for Texas and the seven states currently using groove-recessed RRPMs, but were unable to identify accurate snowfall data for locations where groove-recessed RRPMs are installed. In general, the states that are successfully using groove-recessed RRPMs have regions with mountainous terrain that has significantly higher elevations than Texas, with the exception of Maryland (which still gets significantly more snow than the Texas panhandle). It is likely that the amount of snowfall that must be managed in these states justifies the use of the groove-recessed RRPMs in terms of maintenance costs, durability, measured visibility, and overall effectiveness. Unfortunately, not enough data exist to make those comparisons.

CHAPTER 5: CURRENT USES AND EFFECTIVENESS OF SAFETY CORRIDORS

This chapter describes information obtained during a review of topics related to the concept of safety corridors. The following sections describe definitions of safety corridors, examples of previous or current safety corridors, potential uses of safety corridors, and documented effectiveness on accomplishing their intended purpose.

DEFINITION OF A SAFETY CORRIDOR

The term safety corridor can have different meanings depending on who is using the term and what its intended purpose is. While the specific details may change from one occurrence to another, common elements associated with safety corridors include:

- A stated purpose to improve safety on the corridor in question, which may be further described as one or more of these goals:
    - Reduce speeds.
    - Reduce crashes (or crash rates).
    - Reduce severity (e.g., number of injuries or fatalities) of crashes (or fatality rates).
- Increased enforcement within the corridor, either broadly stated or including an emphasis (such as on speeding or hazardous driving).
- Increased fines (typically double fines) for violations that occur within the corridor.
- Increased driver education.
- Specifically defined boundaries, which are typically indicated by special signing.

As an example, Pennsylvania defines a highway safety corridor as "the portion of a highway determined by a traffic study to be targeted for the application of signs, increased levels of enforcement and increased penalties specifically for the purpose of eliminating or reducing unsafe driver behaviors that are known to result in crashes and fatalities" (*27*).

USE OF SAFETY CORRIDORS

A review of recent reports, policies, and announcements indicates that safety corridors are currently being or have been used in at least 15 states:

- Alaska (*28*).
- Arizona (*29*).

- California (*30*).
- Florida (*30*).
- Kentucky (*30*).
- Minnesota (*30*).
- New Jersey (*31*, *32*).
- New Mexico (*33*).
- New York (*30*).
- Ohio (*30*, *34*).
- Oregon (*35*).
- Pennsylvania (*27*).
- Vermont (*36*).
- Virginia (*37*).
- Washington (*38*).

Identification of Corridors

While the details may vary, available information suggests that states have similar methods of identifying the corridors they ultimately designate as safety corridors. The selection process involves a review of traffic volume data, crash data, speed data, and any other data related to the purposes for which a safety corridor is being designated. For example, a safety corridor that is focused on behaviors related to impaired driving might emphasize a review of crash data and/or citations issued that includes drivers who were intoxicated or otherwise driving under the influence of alcohol or other drugs. This description from the Arizona DOT website provides a representative summary of the fundamentals of the selection process: "Safety Corridors were selected through a combination of statewide traffic crash data and law enforcement observations. All corridors have two things in common: a high number of severe and fatal crashes and the primary cause of these crashes is driver behavior (speeding, aggressive driving, impairment, and distracted driving). The Safety Corridors are reminders that these actions will not be tolerated" (*29*).

A corridor review may have specific criteria that must be met to grant a safety corridor designation, or the agency may decide to assign the designation to a set number of corridors that have the highest potential for improvement with the associated treatments. For example, the description by the Vermont Agency of Transportation states that it “identified four corridors where data indicates that a combination of high traffic volume, high speeds, and a high rate of crashes demands an increased level of enforcement” (*36*). The Virginia DOT, in contrast, describes a state statute that requires the following criteria be used in selecting a safety corridor: review of crash data, crash reports, type and volume of traffic, and engineering and traffic studies. To comply with that statute, Virginia DOT has defined the following criteria to identify candidate safety corridors on interstate highways (*37*):

- The crash frequency, weighted by severity, should be at least 50 percent more than the regional average for the highway system.
- The crash rate should be at least 25 percent more than the regional average for the highway system.
- The truck-involved crash rate should exceed the average crash rate for that region for all vehicles on the highway system.
- Enforcement capability.
- Roadway characteristics.

Some states include a corridor length criterion (e.g., minimum length of 2 mi, maximum length of 50 mi). A minimum length provides a threshold for rejecting a potential site that is not truly a corridor and could be considered for a spot treatment. A maximum length helps to ensure that the corridor has largely homogeneous characteristics throughout its length and is able to be realistically monitored.

The corridor review could be statewide or focused on select corridors that have been specifically submitted for consideration based on previous performance. A statewide review is obviously more comprehensive and helps ensure that the sites in most need of added attention are considered. However, a statewide review could be a challenging effort in Texas compared to states with fewer highway routes and fewer miles of roadway. Conversely, a focused review of selected sites is an easier process, but it includes the possibility that another site that meets the designation criteria is not included. The specifics of a selection process could be tailored to match the features of the available data and the databases in which they are stored.

Notification to the Public

After a corridor is selected to receive the safety corridor designation, the responsible agency must inform the public about the designation and what it means. Among states that have implemented safety corridors, this effort largely takes place through two methods: public information and on-site signage. Similar to public information methods on other transportation projects, safety corridor announcements can take place through press releases (an example of which is found in *39*) and through agency-organized events and resources.

In Alaska, a formal education/media campaign to promote safety corridors is typically divided into three parts: initial rollout, saturation media, and ongoing media. The initial rollout usually begins with the official signing and unveiling of a safety corridor by members of the DOT and other public officials. This event is designed to gain publicity for the safety corridor and make drivers aware of the campaign. Other aspects of the initial rollout that accompany the actual safety corridor signing include both television and radio advertisements. The saturation media campaign is an additional emphasis on publicity for the corridor during the two weeks prior and the two weeks after the designation of a safety corridor. Ongoing media efforts include weekly radio and television spots (*30*).

Arizona DOT has developed a summary flyer, shown in Figure 5, to describe what a safety corridor is, where they are located, and what they mean for drivers. The flyer is made available on their website for access at any time, but it can also be printed and distributed at public meetings. The flyer is full-color, produced in both English and Spanish, and includes examples of safety corridor signs that are installed at the designated sites.

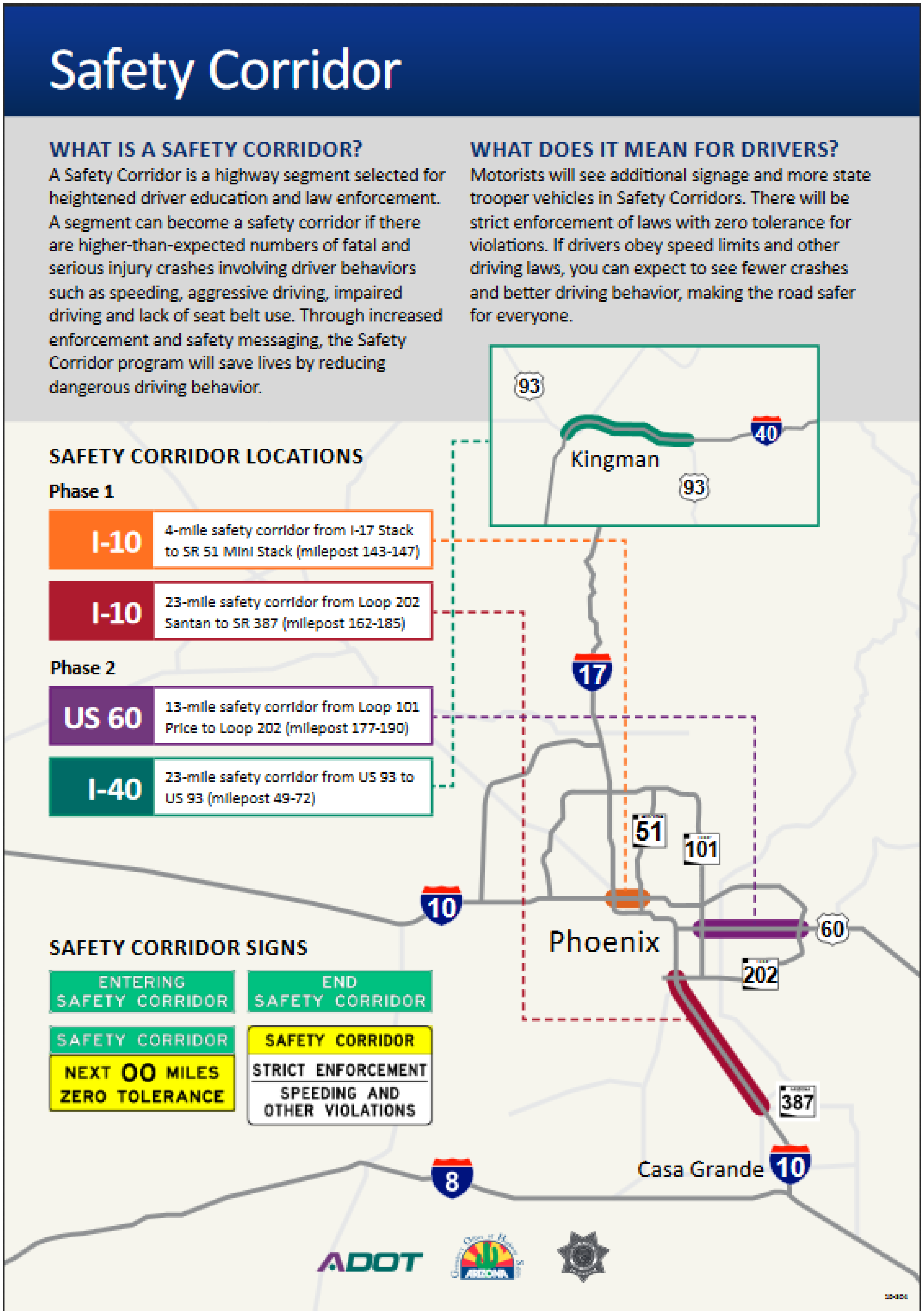
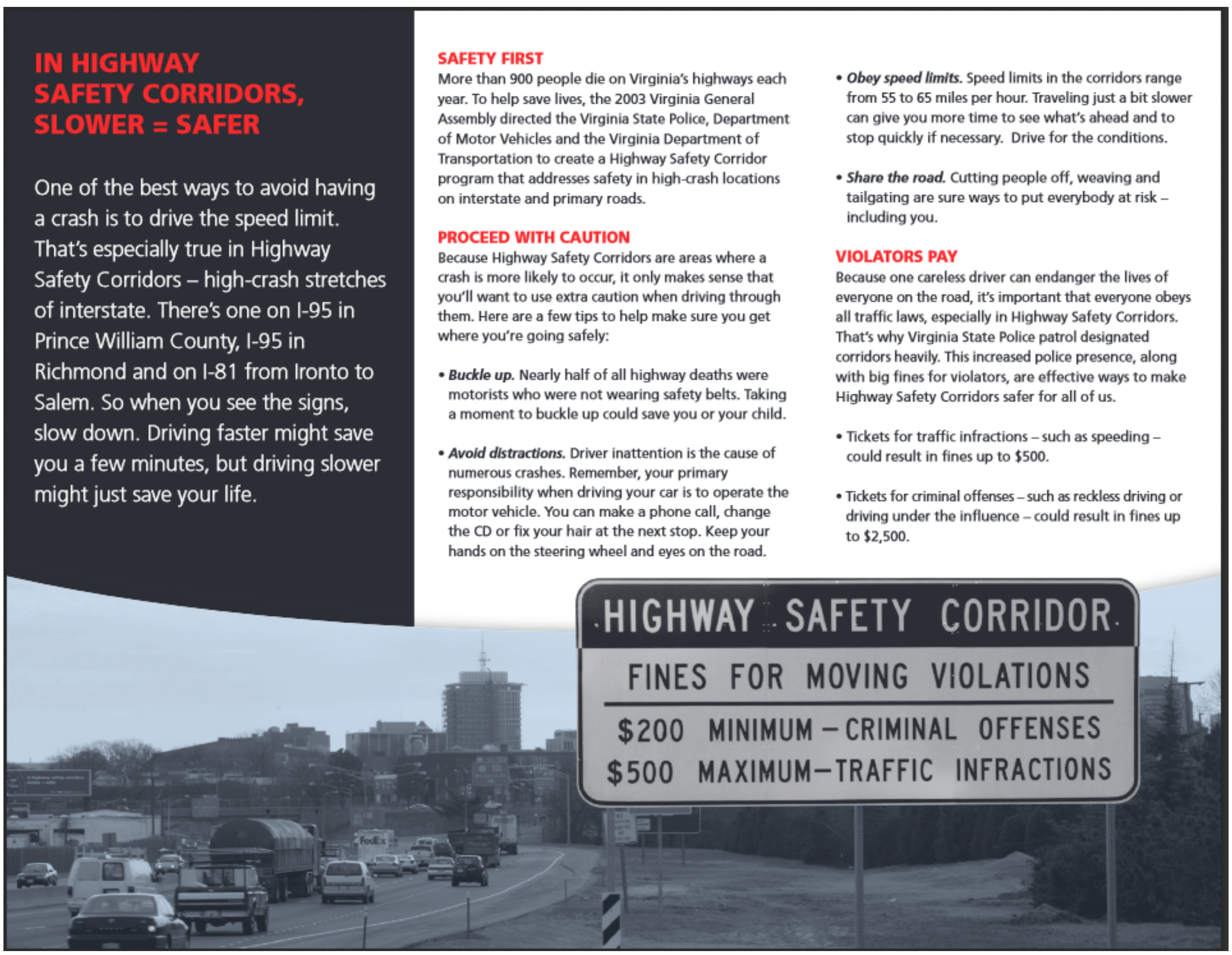


Figure 5. Arizona DOT Safety Corridor Summary Flyer (*29*).

Virginia DOT has produced a similar brochure (Figure 6 shows the second page of the brochure) that describes in some detail the location of each safety corridor, an explanation for why they are selected, and what drivers are expected to do while traveling through them. The brochure also summarizes the fine structure for violators, which is also featured on a sign that Virginia DOT uses within each corridor. As part of its selection criteria and policy, Virginia DOT also describes rules for public hearings prior to the selection of a safety corridor (*37*):

- The commissioner shall hold a minimum of one public hearing before any designation is implemented.
- The public hearing or hearings for a specific candidate safety corridor shall be held at least 30 days prior to the designation at a location as close to the proposed corridor as practical.



IN HIGHWAY SAFETY CORRIDORS, SLOWER = SAFER

One of the best ways to avoid having a crash is to drive the speed limit. That's especially true in Highway Safety Corridors – high-crash stretches of interstate. There's one on I-95 in Prince William County, I-95 in Richmond and on I-81 from Ironto to Salem. So when you see the signs, slow down. Driving faster might save you a few minutes, but driving slower might just save your life.

SAFETY FIRST

More than 900 people die on Virginia's highways each year. To help save lives, the 2003 Virginia General Assembly directed the Virginia State Police, Department of Motor Vehicles and the Virginia Department of Transportation to create a Highway Safety Corridor program that addresses safety in high-crash locations on interstate and primary roads.

PROCEED WITH CAUTION

Because Highway Safety Corridors are areas where a crash is more likely to occur, it only makes sense that you'll want to use extra caution when driving through them. Here are a few tips to help make sure you get where you're going safely:

- ***Buckle up.*** Nearly half of all highway deaths were motorists who were not wearing safety belts. Taking a moment to buckle up could save you or your child.
- ***Avoid distractions.*** Driver inattention is the cause of numerous crashes. Remember, your primary responsibility when driving your car is to operate the motor vehicle. You can make a phone call, change the CD or fix your hair at the next stop. Keep your hands on the steering wheel and eyes on the road.
- ***Obey speed limits.*** Speed limits in the corridors range from 55 to 65 miles per hour. Traveling just a bit slower can give you more time to see what's ahead and to stop quickly if necessary. Drive for the conditions.
- ***Share the road.*** Cutting people off, weaving and tailgating are sure ways to put everybody at risk – including you.

VIOLATORS PAY

Because one careless driver can endanger the lives of everyone on the road, it's important that everyone obeys all traffic laws, especially in Highway Safety Corridors. That's why Virginia State Police patrol designated corridors heavily. This increased police presence, along with big fines for violators, are effective ways to make Highway Safety Corridors safer for all of us.

- Tickets for traffic infractions – such as speeding – could result in fines up to $500.
- Tickets for criminal offenses – such as reckless driving or driving under the influence – could result in fines up to $2,500.

Figure 6. Second Page of Virginia DOT Safety Corridor Brochure (*37*).

Education efforts for the SR 14 Safety Corridor in Washington included (*30*):

- A project kickoff media campaign.
- A "Designate A Driver" holiday campaign at local bars and restaurants.
- "Heed the Speed on Hwy. 14" signs.
- Public awareness messages on the back of trucks that travel on SR 14.
- Commercial vehicle educational materials and air fresheners handed out at weigh stations.
- A project wrap-up and celebration.

Like other segments with special operating conditions (e.g., school zones and work zones), the boundaries of a safety corridor must be identified with signs for drivers to know that they are entering and exiting the zone and that there are unique considerations while driving in that zone. The *Manual on Uniform Traffic Control Devices* does not currently contain signs specific to safety corridors, so the states that use safety corridors develop their own signs that are tailored to the conditions in that state. Examples of signs are shown in Figure 5 and Figure 6. Signs from other states show similar information, such as the sign from Alaska (see Figure 7), and the sign from New Jersey (see Figure 8). Signs for safety corridors are developed based on the purpose of each corridor, the associated behavior(s) that are the focus of the corridor, and the state law or statute that governs the conditions and requirements each corridor must meet.

Figure 7. Alaska Safety Corridor Sign (*30*).

Figure 8. New Jersey Safe Corridor Sign (*32*).

Disposition of Fines

The fines for traffic violations in safety corridors are generally higher than the fines for the same violations in other locations. In many states, the fines are doubled for the violations that the safety corridor is intended to reduce (e.g., speeding). The applicable state law or statute describes the details of the fine structure, as well as the disposition of those fines when they are collected. Some states prescribe that the additional portion of the fine (i.e., the cost of the fine above the normal cost for that violation elsewhere in the state) goes into a fund that is restricted to be used for safety-related treatments. In other states, the entirety of the fine may go into a special fund, while still other states may use a different distribution. In New Jersey (*31*), monies collected from enforcement activities within safety corridors are deposited in a Highway Safety Fund established by the New Jersey DOT. The department has developed a grant program, consistent with the requirements of applicable legislation, to fund local law enforcement agencies that have a safety corridor within their municipal boundaries for enforcement efforts within these corridors. This grant program identifies the following eligible uses for which these local law enforcement agencies may apply:

- Procurement of equipment as follows:
  - Radar units.
  - Crash data collection systems (hardware and software).
  - GPS units.
  - Surveillance devices such as cameras and video equipment.

    - Protective vests.
    - Communications equipment.
- Salaries and overtime directly attributed to the enforcement activities of Safe Corridor locations.
- Programs, projects, or initiatives that support one or more of the emphasis areas outlined in the New Jersey Comprehensive Strategic Highway Safety Plan. At the time the New Jersey *Report on Safe Corridors* (*31*) was written, the then-current emphasis areas were as follows:
    - Aggressive Driving.
    - Impaired Driving.
    - Young Drivers.
    - Older Drivers.
    - Intersection Improvement.
    - Roadway Departure.
    - Driver Safety Awareness.
    - Pedestrian, Bicycles, Rail, and Vehicular Conflicts.

In other states that also use non-enforcement strategies, the funds from increased fines may be used for engineering improvements (e.g., improved guardrails or pavement markings), education initiatives (e.g., outreach on roadway safety to specific communities or road user groups), or emergency services (e.g., supplemental funding to trauma units that serve people injured in crashes). Regardless of the purpose(s) for which the fines are used, it is important to document how many citations are written in safety corridors and account for the funds associated with those fines to enable a proper evaluation of the results of the corridor and an audit of the funding.

PURPOSE OF SAFETY CORRIDORS

States have varying purposes for their safety corridor programs, but in general, they tend to be used as solutions for addressing high-crash locations. The primary measure of effectiveness may be expressed in terms of number (or frequency) of crashes, crash rate (e.g., crashes per mile of roadway, crashes per 100 million vehicle-mi traveled), number of injuries or fatalities, or number of truck crashes. The emphasis of the safety corridor then is described as targeting the activities or behaviors that have been identified as the causes of those crashes. Speeding is a common target of safety corridors, so the corridor treatment typically involves increased enforcement of the posted speed limit (see Figure 9). Other common (and somewhat related) safety corridor targets include aggressive driving, seat belt use, distracted driving, and impaired driving. Vermont (*36*) includes all those behaviors and activities in their safety corridor program.

Figure 9. Illustration of Speed Enforcement in Vermont (*36*).

While crash reduction is generally the primary purpose of a safety corridor, a safety corridor can be designated for a specific purpose. In early 2018, Ohio DOT unveiled their first Distracted Driving Safety Corridor (*34*) to focus on reducing the behaviors associated with distracted driving that lead to crashes. Supporting data indicated a high number of crashes involving distracted driving and over 2700 distracted driving violations in a 26-month period in the two counties in which the corridor is located. Based on their description, Ohio DOT will place signage alerting motorists when they enter and leave the corridor and informing them that it is a high enforcement area. Signs will also be placed throughout the corridor reminding motorists of the dangers of distracted driving. Examples of signs for this corridor are shown in Figure 10. Other violations (e.g., speeding, impaired driving, improper seat belt use) will still be enforced.

Figure 10. Sample Signs for Ohio's Distracted Driving Safety Corridor (*34*).

DOCUMENTATION OF RESULTS

Regardless of the purpose of a safety corridor, the responsible agency must track the relevant measures of effectiveness to determine whether the stated purpose has been achieved. Many of the states included in this review have stated their procedures for evaluating the effectiveness of safety corridors, though the details vary and not all of the results of those evaluations are made readily available to the public.

Vermont's Agency of Transportation uses the five-year crash and enforcement history to develop a baseline to track the effectiveness of safety corridors. When available, equipment is also used to collect one to two weeks of speed data. Throughout the duration of the safety corridor, crash, enforcement, and speed data are collected and analyzed. These data are utilized to determine whether the crash frequency and severity were impacted, as well as to determine the influence on speed trends. Finally, partner agencies collectively determine the level of enforcement activity needed going forward in the safety corridor (*36*).

All of New Jersey's safety corridors are located in urban areas, so the evaluation process is different from most states. Specifically, officials mentioned that many crash types are exacerbated by congestion and access management problems, and their typical engineering countermeasures include the following: improved signal timing and coordination, updated signing and striping, maintenance issues, and pedestrian safety improvements. The New Jersey DOT analyzes fatal, injury, property damage only, and total crashes to identify crash reductions from previous years. This analysis is conducted approximately every three years using the same criteria used for the selection of the safety corridor. If the safety corridor does not meet the initial criteria, it may be decommissioned. Otherwise, safety improvement efforts in the corridor will continue. Initially, New Jersey implemented 13 safety corridors. For these corridors, there was about a 7 percent decrease in both injury and total crashes (*30*).

Virginia DOT (*37*) has shared crash data for three highway safety corridors on their website. The provided data show the crash histories of all three sites for four years prior to their safety corridor designation and 10 to 11 years after the designation. For each site, the number of total crashes (and some subsets of crashes) appear to decline early after the designation was made but have risen in the most recent years. Details on volume levels or other variables that would add context to the crash numbers are not provided with the crash data tables, one of which is shown in Figure 11. More details on the safety corridor program in Virginia have been described in a series of reports and papers by Fontaine and Read, such as "Evaluation of Highway Safety Corridors" (*40*).

I-81 Salem Highway Safety Corridor: Years beginning January 13
(Northbound and Southbound mileposts 127 to 42)

	Before Designation				After Highway Safety Corridor Designation										
					Yr 1	Yr 2	Yr 3	Yr 4	Yr 5	Yr 6	Yr 7	Yr 8	Yr 9	Yr 10	Yr 11
Crash Severity	00-01	01-02	02-03	03-04	04-05	05-06	06-07	07-08	08-09	09-10	10-11	11-12	12-13	13-14	14-15
Property Damage Only	82	116	105	143	144	108	112	126	96	94	96	105	108	107	152
Injury	53	43	61	65	70	43	50	45	42	41	50	33	42	38	39
Fatal	0	0	0	0	0	1	2	1	0	0	0	3	2	1	0
Annual Total Crashes	135	159	166	208	214	152	164	172	138	135	146	141	152	146	191
Fatal + Injury Crashes	53	43	61	65	70	44	52	46	42	41	50	36	44	39	39

Figure 11. Crash Data from I-81 Safety Corridor in Virginia (*37*).

Additional summaries of evaluations conducted in various states are provided in a synthesis on safety corridors compiled by Nemmers et al. (*30*). One such summary described results from the SR 14 Safety Corridor in Washington. The SR 14 Safety Corridor is a 15-mi two-lane rural road that follows the Columbia River Gorge in southwest Washington. State and local officials determined the top three collision causes to be exceeding safe speeds, crossing the centerline, and driving under the influence of alcohol. The leading collision types were hitting fixed objects, hitting wildlife, and vehicle overturns. Engineering countermeasures included:

- Installing centerline rumble strips throughout the entire corridor.
- Marking the road with corridor signs.
- Updating signs along the corridor.
- Improving pedestrian warning information for drivers at a nearby state park.
- Conducting a speed study in the corridor.
- Installing road condition warning signs using a highway advisory radio system.

Enforcement targeted excessive speeding, following too closely, improper passing, and DUI violations. The Washington State Patrol and the county sheriff's office reported a 55 percent increase in DUI arrests, a 103 percent increase in speeding contacts, a 158 percent increase in total contacts, and a 110 percent increase in traffic warnings. The safety corridor project lasted two years, and results indicated a 65 percent decrease in fatal and disabling injury crashes on SR 14 compared to three years prior to implementation. In addition, total collisions decreased by 19 percent, alcohol-related collisions declined 57 percent, excessive speeding (the number one cause of crashes) decreased 37 percent, and hitting fixed objects (the number one collision type) was reduced by 17 percent.

Several states have prescribed procedures for terminating a safety corridor designation following a review of the relevant data (*30*). In Ohio, after countermeasures have been installed for a predetermined length of time, a simple before-and-after crash count comparison combined with an EB approach is used to analyze the corridor's countermeasures' effectiveness. Reviewed annually, Ohio decommissions a safety corridor if a decline in the fatal crash statistics used in corridor selection occurs that causes the roadway to drop below the top 5 percent statewide. In New Jersey, approximately every three years the safety corridors are re-analyzed using the same criteria used for selection, and if the corridor does not meet those criteria, it may be decommissioned; otherwise, further efforts and improvements will continue.

Researchers who made the initial safety corridor designation lead Oregon's decommissioning process, and decommission is considered if any one of the following criteria is met (*30*):

- The three-year average fatal plus serious injury crash rate is at or below 100 percent compared to the three-year average for similar roadways.
- Any of the remaining designation criteria are not met.
- Minimum requirements within safety corridor program guidelines are not being performed.
- A continued lack of activity or investment in the safety corridor.

However, a local stakeholder group may adopt the safety corridor once it is decommissioned, assuming that the group provides meaningful local investment into improving the safety of the roadway.

LESSONS LEARNED

After compiling the information from 13 states' efforts on safety corridors, Nemmers et al. (*30*) described common characteristics and good practices of the examples studied. This process led to a list of recommendations, which are summarized below.

- Multidisciplinary: A multidisciplinary approach should be used. Most states include engineering, education, enforcement, and emergency medical providers (4E approach). Most states also agreed that there was not a single cause for the higher crash frequencies along particular stretches of highway and consequently believed that a group of solutions needed to be considered.
- Limited Number: Limit the number of active corridors at one time; too many become ineffective. Pilot corridors should be developed first. The range of active safety corridors per state at any given time was between 3 and 12.
- Crash Data: Agencies should consistently use data on crashes, injuries, and fatalities (both frequencies and rates) for selection, evaluation, and decommissioning of safety corridors. A crash rate that was 10 percent greater than the statewide average for similar roadways was found to be a common threshold for designating a safety corridor.

- Champion: An agency that has a statewide champion for safety corridors improves the potential for the program to be successful. A champion has the responsibility of guiding the selection of appropriate corridors, maintaining uniformity in the program, and identifying and distributing available funding.
- Safety Action Plan: In conjunction with the first recommendation, a multidisciplinary task force should develop a corridor Safety Action Plan, and the task force should meet regularly for continual review and monitoring of the plan and strategies.
- Legislation: Different states have different rules and laws related to safety corridors, but specific legislation can be valuable in establishing consistent criteria for defining safety corridors and providing the authority to initiate increased fines. Legislation provides the basis for law enforcement personnel to conduct their activities, which can lead to improvements in the desired measures of driver performance.
- Special Signing: Implementation of a safety corridor should require special signing. Typical messages include "Safety Corridor—Fines Doubled," "Enhanced Speed Limits," and "Lights on for Safety."
- Road Safety Audits: The responsible agency should conduct a Road Safety Audit or another type of detailed, multidisciplinary safety review when a new safety corridor is implemented to improve the likelihood of a comprehensive and potentially successful effort.
- Low-Cost Engineering: Safety corridor strategies typically include only low-cost engineering improvements, such as signing upgrades or centerline and edge line rumble stripes/strips. These improvements can be valuable in reducing common crash causes, such as run-off-road crashes. A safety corridor does not have to include complex or costly treatments to be successful.
- Length: A safety corridor program should not establish a subjectively determined length of safety corridors because the length can vary from one corridor to another, depending on corridor needs and characteristics. Whatever the length of the corridor, the responsible agency should define a corridor that has homogeneous characteristics throughout.

- Decommissioning: The agency should have a defined process for decommissioning a safety corridor after an improved safety measure is achieved. This practice improves the efficiency of the overall program and allows available funds to be more readily applied to other corridors where the need is greater.
- Selection Criteria and Measures of Effectiveness: The agency should use statistically rigorous corridor selection criteria and methods for analyzing measures of effectiveness to improve the ability of the program to produce results that are effective and supported by relevant data.
- Before-and-After Data: To support statistically rigorous methods, agencies need to collect the appropriate comprehensive before-and-after data, as well as drivers' response to the safety corridor activities. Most states in Nemmers et al. review had limited after data. The safety corridor program needs to provide the resources to collect the necessary data for the appropriate length of time.

CHAPTER 6: WRONG-WAY DRIVING FORUM

The WWD event data compiled by researchers in several regions in Texas have proven invaluable for identifying problem areas and examining the potential for both near- and long-term study of WWD countermeasures (*41*, *42*). Continued oversight and coordination of ongoing activities, as well as new investigations and evaluations, is critical for the reliability of the evaluations, the ability to compare findings across the state, and the sharing of lessons learned. As part of this project, researchers organized a peer-exchange for TxDOT and other agencies to discuss technologies used to detect and mitigate WWD maneuvers in Texas and across the United States. The half-day forum was held immediately following the 3rd Annual Texas A&M Transportation Technology Conference in Bryan, Texas, on May 9, 2018. Table 11 contains the agenda. About 50 people representing TxDOT, TTI, Southwest Research Institute, Harris County Toll Road Authority, Central Texas Regional Mobility Authority, the Federal Highway Administration (FHWA), Arizona DOT, Wisconsin DOT, Florida DOT, Iowa DOT, New York State Thruway, various consulting firms, and technology manufacturers attended.

Table 11. WWD Forum Agenda.

Time	Agenda Item	Speaker(s)
12:00 to 12:30 p.m.	Box Lunches	None
12:30 to 12:45 p.m.	Welcome and Introductions	Michael Chacon (TxDOT) Melisa Finley (TTI)
12:45 to 2:15 p.m.	Panel on Active Sign and Pavement Markings Systems	Eric Ferron (FHWA) John Gianotti (TxDOT) Stacey Pierce (Wisconsin DOT) Raj Ponnaluri (Florida DOT)
2:15 to 2:30 p.m.	Break	None
2:30 to 3:00 p.m.	Arizona DOT Wrong-Way Driving Detection and Warning System Pilot Deployment	Brent Cain (Arizona DOT)
3:00 to 3:45 p.m.	Open Discussion on Wrong-Way Driving Traffic Management Center Procedures and Coordination with Police	Brian Fariello (TxDOT) John Gianotti (TxDOT)
3:45 to 4:15 p.m.	TxDOT Connected Vehicle Wrong-Way Driving System	Melisa Finley (TTI)
4:15 to 4:45 p.m.	Open Discussion on Other Technologies	Melisa Finley (TTI)
4:45 to 5:00 p.m.	Closing Session	Melisa Finley (TTI)

CHAPTER 7: PEDESTRIAN CRASHES ON HIGH-SPEED ROADS

This chapter summarizes findings from recent research on pedestrian crashes, especially those crashes on high-speed arterials and freeways. In particular, this chapter:

- Describes countermeasures for reducing the number and severity of those crashes.
- Summarizes available documentation on the effectiveness of those countermeasures.
- Highlights selected tools and resources for choosing appropriate treatments.
- Provides examples of lessons learned in previous implementations of those treatments.
- Presents the methodology used to identify cluster of pedestrian crashes on high-speed roads.
- Describes observations from cities on what may be contributing to pedestrian crashes on high-speed roads.

COUNTERMEASURES FOR PEDESTRIAN CRASHES ON HIGH-SPEED ROADS

Hudson et al. (*43*) conducted a study to investigate the causes and factors that contribute to pedestrian fatalities on very high-speed roadways in Texas. Researchers conducted a survey of 20 states to learn what they have done in terms of engineering, education, enforcement, and evaluation to address pedestrian safety on controlled- or limited-access urban interstate, freeway, and expressway main lanes where posted speed limits are 55 mph or higher. The design of the survey was based on a literature review that identified factors that correlated with pedestrian fatality rates, motivations for pedestrians entering high-speed roadways, and countermeasures that were implemented to reduce fatalities or protect pedestrians.

The Hudson report described pedestrians involved in crashes on high-speed roadways in two categories, based on definitions from Johnson (*44*): intentional pedestrians and unintended pedestrians. The term intentional pedestrians refers to persons entering controlled-access, high-speed roadways on purpose, such as crossing the interstate as a shortcut to destinations. The term unintended pedestrians refers to persons who exit a vehicle on the roadway, such as when repairing a flat tire on the roadside, assisting another stranded motorist, or being involved in a crash; in many cases, the reason the pedestrian was on the highway was unknown.

The report further described countermeasures designed for pedestrian safety on high-speed roadways as not prevalent in the existing literature. Based on surveys and studies, researchers identified suggestions to restrict pedestrian activity on interstate highways. Generally, those suggestions were divided into five categories: educating pedestrians, building barriers to discourage pedestrian travel, accommodating pedestrians, warning drivers, and fining pedestrians.

Survey respondents reported being aware of pedestrian safety concerns on the main lanes of high-speed, controlled-access highways. Eighty percent responded that a law or policy that prohibits pedestrian access on controlled-access highways exists in their states. Policies and practices aimed at unintended pedestrians were more frequently cited than those policies and practices addressing intentional pedestrians. The survey respondents highlighted existing practices such as the construction of overpasses/underpasses, installation of fences along rights of way or medians, and use of roadside assistance programs (see Table 12).

Table 12. Summary of Countermeasures Credited for Improving and/or Maintaining Low Pedestrian Crashes on High-Speed Roadways from (*43*).

Practices	Pros	Cons	Implementation
Underpasses/Overpasses	Keeps pedestrians from exposing themselves to traffic. Has a high potential to reduce crashes if pedestrians use them. Can be multi-functional.	Usage could be low. Construction cost could be an issue. Crime safety can be an issue.	Locate along logical pedestrian routes. Connect with pedestrian infrastructure. Inviting design.
Barriers and Fences	Can prevent pedestrians from trespassing to some extent.	Can be easily traversed sometimes.	Serve as channelization tool where alternative safe routes exist.
Lighting	Increases visibility at night.	Increased electricity cost.	Consider adaptive lighting.
Signing	Warns drivers.	May induce pedestrians.	NA
Shoulder Width and Design	Provides space for emergency vehicles, broken-down vehicles.	High construction cost.	NA
Move-Over Laws	Avoids conflicts between vehicle and unintended pedestrians.	The effectiveness relies on education and enforcement.	Focus on young, older, and African American drivers. Use explicit yet reasonable provisions and appropriate qualifying language to support enforcement. Get support from affected agencies.
Collision Clearance Laws	Reduces possibility of secondary crashes.	Drivers may worry about liability.	Educate to ensure drivers are aware of laws.
Roadside Assistance Program	Reduces possibility of secondary crashes.	Implementation cost may be an issue.	Coordinate between agencies for increased effectiveness.

A previous investigation of pedestrian crashes in Texas on Project 0-6702 (*45*) provided background for the Hudson study. The 0-6702 study was tasked with investigating pedestrian crashes on all types of Texas roadways and evaluating the effectiveness of selected countermeasures. In that study, researchers found that 21 percent of all fatal TxDOT-reportable pedestrian crashes occurred on freeways, leading to a recommendation to conduct additional research into how to address pedestrian crashes, especially freeway crashes. As part of that study, researchers reviewed the literature on available treatments and their effectiveness in reducing pedestrian crashes, injuries, and fatalities. They classified treatments into broad categories of engineering, education, and enforcement; although the review of treatments considered roadways of all types, several treatments they described are applicable to high-speed roadways.

Engineering treatments identified in the 0-6702 study (*45*) were subdivided into traffic control devices and geometric design features. Most of the treatments in the traffic control devices category focused on locations such as marked crosswalks and signalized intersections, which are not as common on high-speed roadways as on low-speed roadways. Even so, some treatments are applicable on high-speed roads, particularly in combination. For example, marked crosswalks are generally not recommended on high-speed roads without additional treatments (e.g., beacons or traffic signals) to supplement them (*46*). Traffic control device treatments identified in 0-6702 that have applicability for high-speed roads that are not access-controlled include:

- Advance yield line and sign: pavement markings placed 30 to 50 ft upstream of a crosswalk, often accompanied by YIELD or YIELD HERE TO PEDESTRIAN signs.
- Pedestrian-activated flashing beacons at pedestrian crossings—at the pedestrian crossing, on the side of the roadway, and/or overhead; in advance of the pedestrian crossing, both overhead and on the side of the roadway.
- Rectangular rapid-flashing beacons (RRFBs)—at the pedestrian crossing (see Figure 12), on the side of the roadway, and optionally overhead, flashing in an eye-catching sequence to draw drivers' attention to the sign and the need to yield to a waiting pedestrian.

Figure 12. RRFB Installed on Roadside at School Crossing on 45-mph Roadway.

Geometric design treatments identified in 0-6702 (*45*) that can be beneficial on high-speed roads include the following:

- Median barriers—barriers in the median encourage pedestrian crossings at crosswalks by discouraging them at undesirable locations, and they are commonly used on freeways and limited-access highways to separate the two directions of vehicle traffic.
- Roadside and sidewalk barriers—based on a similar principle as median barriers, they prevent or discourage pedestrians from entering the roadway at undesirable locations, and they also provide a useful guide to pedestrians with visual disabilities.
- Overpasses and underpasses—pedestrian overpasses (bridges, see Figure 13) and underpasses (tunnels) allow pedestrians and bicyclists to cross streets while avoiding potential conflicts with vehicles.
- Median refuge islands—where crossing is permitted, median refuge islands simplify the street-crossing task by permitting pedestrians to make vehicle gap judgments one direction at a time.

Figure 13. Pedestrian Overpass on I-25 in Denver, CO.

Project 0-6702 also discussed potential education and enforcement treatments. The effectiveness of those treatments is often measured in different ways than engineering treatments; for example, an education treatment may be evaluated by measuring the program's ability to improve user knowledge, measuring a program's ability to change user behavior, or by looking at a program's ability to reduce crashes. To be effective, an education treatment must answer the user's primary question, "Is it worth changing my behavior?" Education treatments described in 0-6702 (*45*) included:

- Education of traffic officers.
- Public awareness campaigns.
- Public involvement workshops.
- Curriculum-based education.
- Media-based education.
- One-time instruction.
- Skills-based training.
- Virtual reality.
- WalkSafe.
- Non-English translation of education materials.

One way of evaluating the effectiveness of an enforcement treatment is by measuring the program's ability to increase compliance with the vehicle code, which includes laws pertaining to pedestrian and motor vehicle right of way. Another is by looking at an enforcement treatment's ability to reduce crashes. The enforcement types and strategies highlighted in 0-6702 (*45*) were:

- Driver and pedestrian-vehicle code awareness.
- Police officer vehicle code awareness.
- Targeted routine enforcement.
- High-visibility enforcement.
- Staged crossings with decoy pedestrians (police officers).
- Automated enforcement.
- Education materials in lieu of citations.
- Citations for pedestrian right-of-way violations.
- Fines for pedestrian right-of-way violations.
- Prosecution of pedestrian right-of-way violations.
- Citations after a period of enforcement using education materials.

Carter and Council (*47*) provided summary tables of countermeasures for pedestrian crashes in rural areas. They categorized crashes as "walking along roadway," "pedestrian failed to yield, midblock," "midblock dart/dash," "disabled vehicle related," "pedestrian failed to yield, intersection," and "crossing expressway." The summary table for "crossing expressway" crashes is provided in Table 13 as an example. Their full list of countermeasures for all crash types included:

- Add paved shoulder.
- Add sidewalks.
- Improve roadway lighting.
- Improve signing.
- Use speed monitoring trailers.
- Educate pedestrians and drivers.
- Increase police enforcement.
- Add curb ramps.
- Narrow the roadway by restriping.
- Relocate street furniture.

- Improve school zone pedestrian accommodations.
- Utilize traffic calming measures.
- Add or enhance crosswalks.
- Install pedestrian signals.
- Provide school crossing guard.
- Restrict on-street parking.
- Provide motorist assistance.
- Install fence or barrier.
- Install pedestrian overpass/underpass.

Table 13. Countermeasures for Crossing Expressway Rural Pedestrian Crashes from (*47*).

Countermeasure	Potential Safety Effectiveness	Feasibility for Rural Areas	Discussion
Improve Roadway Lighting	High	Medium (needs targeting)	Crashes of this type occur frequently on dark roadways. Adding or improving lighting will improve visibility of both motorists and pedestrians and is likely to reduce this type of crash. This treatment would be most feasible if targeted to more urbanized rural areas and/or freeways adjacent to development.
Install Fence or Barrier	High	Medium (needs targeting)	A fence or barrier would prevent pedestrians from accessing the freeway from adjacent land. However, most rural freeways are adjacent to undeveloped land, so this treatment may not be as effective as it would be in urban areas. It could be targeted to "rural" freeways in the more urbanized areas where higher pedestrian volume is expected.
Install Pedestrian Overpass/ Underpass	High	Low (needs targeting)	This treatment should be targeted to locations where there are "generators" (e.g., housing units) on one side of the freeway and "attractors" (e.g., businesses) on the other.
Increase Police Enforcement	Medium	Medium	Pedestrian alcohol consumption is a greatly overrepresented factor in this crash type. Police restriction of "drunk walking" (before the pedestrian accesses the freeway) and enforcement of pedestrian restrictions (once the pedestrian is on the freeway) would likely reduce these crashes.
Provide Motorist Assistance	Medium	Medium (needs targeting)	If the pedestrian is crossing the freeway due to a disabled vehicle, a motorist assistance program would decrease crashes by getting disabled vehicles fixed or towed more quickly. However, the widespread and low volume nature of many rural roads would make such a program financially infeasible on all but the most major rural roads.

The *PEDSAFE Handbook* (*48*) describes seven categories of countermeasures for roadways of all types. Some specific countermeasures have more applicability to high-speed roadways than others, but the categories and some example treatments are listed as follows:

1. Pedestrian facility design (e.g., sidewalks, curb ramps, marked crosswalks, transit stop treatments, roadway lighting improvements, and street furniture).
2. Roadway design (e.g., bicycle lane installation, lane narrowing, and installation of pedestrian refuge areas such as raised medians).
3. Intersection design (e.g., pedestrian considerations in roundabouts and right-turn lane design).

4. Traffic calming.
5. Traffic management (e.g., closure of intersections and diversion of vehicular traffic).
6. Signals and signs (e.g., traffic control signals, pedestrian hybrid beacons, pedestrian countdown signals, blank-out signs, and in-roadway lighting).
7. Other measures (e.g., advance stop lines).

PROVEN EFFECTIVENESS OF COUNTERMEASURES

Traffic Control Devices

Project 0-6702 (*45*) conducted a before-and-after field study at five treatment sites, including two RRFB sites on roads with a speed limit of 40 mph or above. The purpose of the study was to identify the changes in driver yielding and selected pedestrian behaviors resulting from installing these treatments at previously untreated crosswalks. For the two higher-speed sites (one with a posted speed limit of 40 mph and one with 45 mph), rates of drivers yielding to crossing pedestrians showed a noticeable improvement, as shown in Table 14. At the 40-mph site (GA-19), yielding rates increased nearly 80 percentage points, from less than 20 percent to more than 90 percent. The 45-mph site (FR-01) had pre-treatment yielding rates higher than the 40-mph site, but post-treatment yielding rates still improved by more than 40 percentage points.

Table 14. Driver Yielding at Before-and-After Study Sites from (*45*).

Site	Period	Total Crossing Events	Yielding Vehicles			Non-Yielding Vehicles			Yielding Rates (%)		
			Near	Far	Total	Near	Far	Total	Near	Far	Total
FR-01	Before	64	62	29	91	94	55	149	40	35	38
	After	75	119	103	222	30	14	44	80	88	83
GA-19	Before	70	34	52	86	317	261	578	10	17	13
	After	65	135	130	265	13	10	23	91	93	92

An expanded study (*49*) that analyzed data from 0-6702 and multiple other studies concluded that RRFBs led to similar results at 15 40-mph sites and nine 45-mph sites, with post-treatment yielding rates of 78 percent and 74 percent, respectively.

Studies by Van Houten and others have demonstrated the effectiveness of advance yield lines and YIELD HERE TO PEDESTRIAN signs (*50*, *51*, *52*). This research found a reduction in motor vehicle-pedestrian conflicts and an increase in motorists yielding to pedestrians at uncontrolled approaches with multilane crosswalks. The documented findings are for crosswalks with and without amber flashing beacons. Additionally, Van Houten and Malenfant demonstrated that signs with markings are more effective than signs without markings (*51*). In a 2001 study, Van Houten et al. showed advance yield lines with YIELD HERE TO PEDESTRIAN signs reduce vehicle-pedestrian conflicts by 67 to 87 percent; the study also found an increase in the distance between the yielding vehicles and the pedestrians (*52*).

Overhead flashing beacons appear to have the greatest visibility to motorists, particularly when used at, or in advance of, the pedestrian crossing. Many installations have used both overhead and side-mounted beacons. In general, the effectiveness of flashing beacons may be limited on high-speed or high-volume arterial streets. For example, one study showed driver yielding behavior ranges from 30 to 76 percent (with the median values falling in the 50 percent range); however, the evaluations did not contain enough information to attribute yielding values to specific road characteristics (*53, 54, 55*, *56*). The field studies reported in Transit Cooperative Research Program (TCRP) Report 112/NCHRP Report 562 (*46*) found a similar range of driver yielding values (25 to 73 percent), with the average value for all flashing beacons at 58 percent. Within the TCRP/NCHRP findings, researchers found (on arterial streets) traffic volumes have a statistically significant effect on driver yielding behavior.

Van Winkle and Neal evaluated the use of pedestrian-actuated beacons and crosswalk flashers in Chattanooga, Tennessee (*54*). The installation of the crosswalk flashers was a compromise solution for a group of senior citizens who wanted a traffic signal to assist them in crossing a minor arterial street with a speed limit of 40 mph. City staff conducted a before-and-after study in 1987 and then a follow-up data collection in 2000. City staff collected data pertaining to the percentage of drivers yielding or slowing down at the pedestrian crosswalk. The 1987 data showed driver yielding improved from 11 to 52 percent in the eastbound direction and from 6 to 32 percent in the westbound direction. The 2000 data indicated a sustained long-term improvement; the yielding percentages were 55 percent in the eastbound direction and 45 percent in the westbound direction. The authors attributed the success of the flashers to pedestrian actuation.

Geometric Design Treatments

Campbell et al. (*57*) discussed findings from studies on the effectiveness of median barriers as pedestrian crossing safety treatments. As part of a larger study on pedestrian countermeasures, median fence barriers were installed at two sites: one in Washington, D.C., with a 4-ft fence, and one in New York City with a 6-ft fence (*58*). At one site, the median fence barrier had two gaps, each located at an intersecting minor street. After installation of the barrier, researchers interviewed pedestrians to gauge their reactions to the treatment. The findings were:

- Regarding crosswalk use, 61 percent of the pedestrians identified the barrier as the reason for using the crosswalk.
- When asked whether the barrier affected the manner in which they crossed the street, 52 percent stated it had no effect and 48 percent indicated the only effect was to force them to cross at the intersection.
- Of those pedestrians who were crossing midblock before the installation, 61 percent did so out of convenience, with about half of them indicating they would use the crosswalk only if midblock traffic volumes were very heavy.
- After installation of the fence, 32 percent of the 22 pedestrians who previously made midblock crossings stated inconvenience as the major factor, with high turning volume at the intersection a close second factor (23 percent).
- Older pedestrians were generally concerned with turning traffic at intersections, and many cited recent crash experiences as a concern.
- Almost one-quarter of those pedestrians interviewed indicated they had walked along the median to the end of the barrier, or an opening, before completing the crossing.
- While merchants at a control site indicated they did not anticipate much effect from a median barrier, 58 percent of those pedestrians at the experimental sites indicated the barrier was discouraging customers from shopping on both sides of the street.
- Most residents accepted the barrier; only 7 percent wanted it removed, with a few complaining about inconvenience and unsightly appearance.

As part of an analysis of freeway pedestrian crashes, Knoblauch et al. (*59*) attempted to estimate the maximum national impact of right-of-way fencing (example shown in Figure 14) and/or median barriers on freeway crashes if these pedestrian barriers were employed and were completely effective in controlling crashes deemed preventable by the treatment. The researchers estimated that 14 percent of freeway pedestrian crashes were susceptible to this countermeasure. An analysis of the crash types and the contributing factors suggested that such fencing and barriers could address between 160 and 222 of these crashes nationwide per year.

Figure 14. Example of Pedestrian Barrier Fence along Edge of Right of Way (Source: http://www.triadfabs.com/product/pedestrian-guard-rails).

Campbell et al. (*57*) also discussed several studies of grade separation treatments. In Tokyo, Japan, researchers analyzed reported pedestrian crashes for 6 months before and 6 months after the installation of pedestrian overpasses at 31 locations (*60*). The overall results are shown in Table 15. The table shows data for 656-ft sections and 328-ft sections on either side of each site (converted from metric). Crashes related to the treatment (pedestrian crossing crashes) decreased after installation of the overpasses; however, non-related crashes increased by 23 percent on the 656-ft sections. Additionally, there was a greater reduction in daytime pedestrian collisions than nighttime collisions.

Table 15. Comparison of Crashes before and after Installation of Pedestrian Overpasses in Tokyo from (*57*).

Type of Crash	656-ft sections			328-ft sections		
	Before	After	Reduction	Before	After	Reduction
Related crashes	2.16	0.32	85.1%	1.81	0.16	91.1%
Non-related crashes	2.26	2.77	−22.9%	1.65	1.87	−13.7%
Total	4.42	3.09	29.9%	3.46	2.03	41.1%

Treatments from Multiple Categories

Alluri et al. (*61*) provided a summary table of selected countermeasures from the seven categories listed in the *PEDSAFE Handbook*, along with results from previous evaluations that produced crash modification factors (CMFs). That table is reproduced in this document as Table 16.

Liu et al. (*62*) conducted an evaluation of the effectiveness of transverse rumble strips on reducing vehicle speeds and crashes at pedestrian crosswalks on rural roads in China. Based on crash data from 366 sites, researchers conducted an observational before-after study of crashes using the EB method and a comparison group, and they concluded that transverse rumble strips may reduce expected crash frequency at pedestrian crosswalks by 25 percent. They also collected speed data at 12 sites. Analysis of that data led researchers to conclude that transverse rumble strips significantly reduce vehicle speeds near pedestrian crosswalks on rural roads with posted speed limits of 60 km/h (37 mph) and 80 km/h (50 mph). They found the following speed reductions:

- On 60-km/h roads:
  - Mean speed declined 9.2 km/h (5.7 mph).
  - 85th percentile speed declined 9.1 km/h (5.6 mph).
- On 80-km/h roads:
  - Mean speed declined 11.9 km/h (7.4 mph).
  - 85th percentile speed declined 12.0 km/h (7.5 mph).

Table 16. Common Pedestrian Countermeasures and Corresponding CMFs from (*61*).

Category	Countermeasure	Crash Type	Crash Severity	CMF	Source
Intersection Design	Convert unsignalized intersection to roundabout	Ped	Fatal/Injury	0.73	De Brabander and Vereeck (2009)
	Convert intersection to roundabout	Ped	All	0.11	Schoon and Van Minnen (1994)
Roadway Design	Install pedestrian overpass	Ped	Fatal/Injury	0.10	Gan et al. (2005)
	Install raised median	Ped	All	0.75	Gan et al. (2005)
	Install raised median (marked crosswalk)	Ped	All	0.54	Zegeer and Seiderman (2001)
	Install raised median (unmarked crosswalk)	Ped	All	0.61	Elvik and Vaa (2004)
	Install refuge island	Ped	All	0.44	ITE (2004)
	Bicycle lanes (veh w/ped from right)	Ped	All	0.90	Jensen (2008)
	Bicycle lanes (veh w/ped from left)	Ped	All	1.05	Jensen (2008)
Signs and Signals	Permit right-turn on red (New York)	Ped	All	1.43	Bahar et al. (2007b)
	Permit right-turn on red (New Orleans)	Ped	All	1.81	Bahar et al. (2007b)
	Permit right-turn on red (Ohio)	Ped	All	1.57	Bahar et al. (2007b)
	Permit right-turn on red (Wisconsin)	Ped	All	2.08	Bahar et al. (2007b)
	Prohibit left turn	Ped	All	0.90	Gan et al. (2005)
	Install pedestrian signals	Ped	All	0.47	Gan et al. (2005)
	Modify signal phasing	Ped	All	0.95	ITE (2004)
	Install pedestrian countdown signal heads	Ped	Fatal/Injury	0.75	Markowitz et al. (2006)
	Add exclusive pedestrian phasing	Ped	All	0.66	ITE (2004)
	Install HAWK	Ped	All	0.31	Fitzpatrick and Park (2010)
	Restrict parking near intersection	Ped	All	0.70	Gan et al. (2005)
Traffic Calming	Install speed humps	Ped	All	0.95	Elvik and Vaa (2004)
	Install raised pedestrian crossing	Ped	All	0.92	Elvik and Vaa (2004)
	Install raised intersection	Ped	All	1.05	Elvik and Vaa (2004)
Pedestrian Facility Design	Install sidewalks and walkways	Ped	All	0.25	Gan et al. (2005)
	Install marked crosswalks (minor intersection)	Ped	All	0.35	Haleem and Abdel-Aty (2012)
	Improve lighting at intersection	Ped	Fatal	0.22	Elvik and Vaa (2004)
	Improve lighting at intersection	Ped	Injury	0.58	Elvik and Vaa (2004)

Dunckel et al. (*63*) conducted a GIS-based analysis of pedestrian crashes in Montgomery County, Maryland, to identify 10 areas with high numbers of pedestrian crashes. Researchers targeted these 10 high incidence areas (HIAs) with a 3E approach (engineering, education, and enforcement programs) to create a more pedestrian-friendly, walkable environment. They conducted pedestrian road safety audits to determine the most effective engineering improvements for each area, subsequently implementing treatments such as countdown pedestrian signals, lighting upgrades, sidewalk improvements, median fencing, midblock pedestrian crossings with high-intensity beacons, and bus stop and shelter consolidation. Demographic analysis grouped the HIAs together to create more effective education campaigns, and community members were involved in order to reach a wider audience. Enforcement efforts targeted pedestrians and drivers in the HIAs with warnings and citations for those individuals who violated pedestrian laws. Similar methodologies were used to target HIAs near schools as part of the initiative's Safe Routes to School program. Between 2009 and 2012, researchers reported pedestrian collisions in the treated HIAs dropped 43 percent, pedestrian fatalities countywide dropped 38 percent from 2008 to 2012, and pedestrian collisions in a subset of the Safe Routes to School areas dropped 79 percent.

Pécheux et al. (*64*) conducted a long-term evaluation of 18 pedestrian safety countermeasures (or combination of countermeasures) for FHWA in Las Vegas, Nevada; Miami-Dade County, Florida; and San Francisco, California. The study methodology consisted of a two-phase study. Phase I involved a detailed analysis of pedestrian crashes, the selection of appropriate countermeasures, the development of implementation and evaluation plans, and collection and analysis of baseline data. Phase II involved the actual implementation and assessment of the impacts of the countermeasures identified in Phase I. The project included self-evaluations conducted by the field teams in each city, as well as an independent national evaluation and cross-cutting study conducted by an independent contractor. The objectives of the evaluations were to assess the safety and mobility impacts of the pedestrian safety countermeasures selected for deployment. The evaluations involved collecting and analyzing quantitative data related to the safety and mobility impacts of the countermeasures. They classified the countermeasures in one of the following four categories of effectiveness in changing behaviors related to pedestrian safety: high effectiveness, moderate effectiveness, low effectiveness, or effectiveness depends on application. The classification of each countermeasure (based on evaluations at both high-speed and low-speed sites) is as follows:

- High effectiveness (seven countermeasures):
    - Leading pedestrian interval.
    - Pedestrian countdown signals.
    - In-street pedestrian signs.
    - Activated flashing beacons.
    - RRFBs.
    - Call buttons that provide feedback to pedestrians to confirm the press of the button.

- o Danish offset (see Figure 15) combined with high-visibility crosswalk, advance yield markings, and YIELD HERE TO PEDESTRIANS signs.
- Moderate effectiveness (four countermeasures):
  - o Electronic No Turn on Red (NTOR) sign.
  - o Prohibition of permissive left turns.
  - o Portable speed trailers.
  - o Automated pedestrian detection (to activate or extend pedestrian crossing phase).
- Low effectiveness (five countermeasures):
  - o High-visibility crosswalks.
  - o Advance yield markings.
  - o LOOK pavement stencils.
  - o TURNING TRAFFIC YIELD TO PEDESTRIANS signs.
  - o Pedestrian zone signs.
- Effectiveness depends on application (two countermeasures):
  - o Median refuge island.
  - o Dynamic lighting.

Figure 15. Danish Offset Crosswalk Used in Las Vegas (*64*).

TOOLS TO IDENTIFY POTENTIAL COUNTERMEASURES

Various resources exist to help practitioners identify options for potential countermeasures for pedestrian crashes. One such tool that has received widespread use is the *Guidelines for Pedestrian Crossing Treatments*, published as Appendix A in NCHRP Report 562/TCRP Report 112 (*46*). Quantitative procedures in the guidelines use key input variables (e.g., pedestrian volume, street-crossing width, and traffic volume) to recommend one of four possible crossing treatment categories:

- Marked crosswalk.
- Enhanced, high-visibility, or "active when present" traffic control device.
- Red signal or beacon device.
- Conventional traffic control signal.

The guidelines include supporting information, examples, and pictures of traffic control devices for these treatment categories. Researchers and several external traffic engineers tested the guidelines on actual crossing locations to refine the guidelines for accuracy. The results of these tests indicated that the guidelines provide appropriate recommendations of pedestrian treatments that substantially agree with engineering judgment. The guidelines in the report provide printed worksheets that can be used to manually input the necessary data and make calculations to generate a recommended treatment, following the process shown in Figure 16. A supplemental spreadsheet tool automates the calculations and provides a graphical output that displays the recommended treatment and thresholds for other treatment categories for the given conditions; Figure 17 shows an example of the spreadsheet's graphical output.

FHWA developed a tool that considers pedestrian crashes and targeted solutions (*65*). The tool, named the Systemic Safety Project Selection Tool by its creators, presents a step-by-step process to conduct systematic safety planning to identify highway safety improvement projects for widespread implementation on a particular system of road. Example crash types include roadway departure crashes, head-on crashes, and crashes involving vulnerable road users. The systematic approach involves modifications that are widely implemented to address roadway features correlated with severe crash types.

The systematic approach itself is not a tool but a process that uses risk to drive action. There are three components: planning, balance of funding, and evaluation. These components are intended to be iterative and easy to apply to a variety of systems, locations, and crash types (*66*). Within the planning component there are four steps, as follows:

1. Identify crash types and risk factors.
2. Screen and prioritize locations.
3. Select appropriate countermeasures.
4. Prioritize projects.

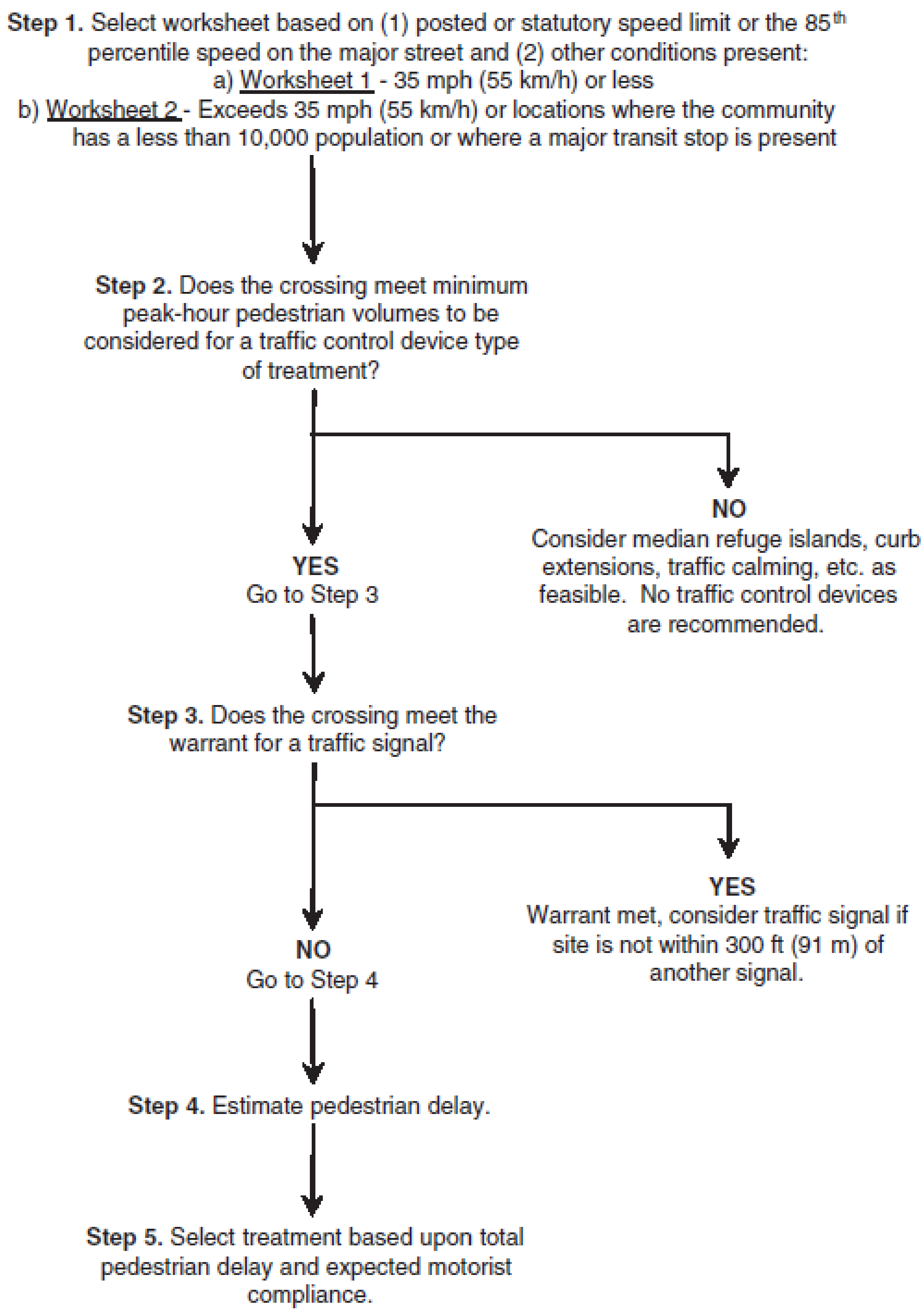


Figure 16. Flowchart for Guidelines for Pedestrian Crossing Treatments from (*46*).

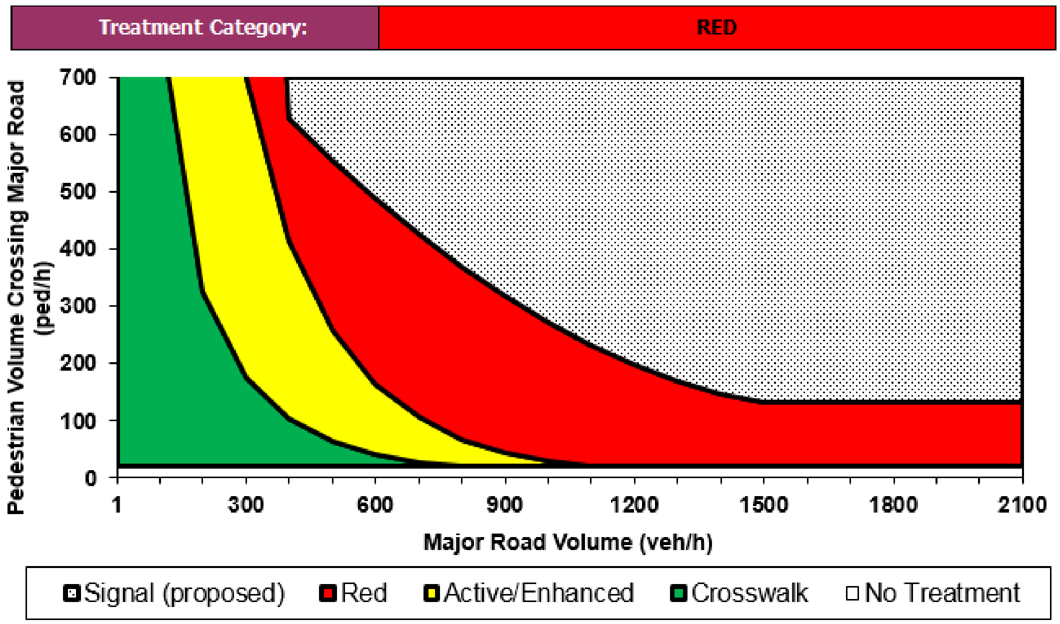


Figure 17. Graphical Display of Results from Spreadsheet Tool from (*46*).

These steps require a data management component, which is a collection of processes to facilitate data renewal and integration. System-wide crash analysis is required for identifying target crash types and risk factors. Questions to be asked include where are the crashes located, what is the geometry, and what is the behavior of the pedestrian? Doing a risk assessment is necessary so that the analyst is able to identify candidate locations that are more at risk than others. Countermeasures should be low-cost so that their implementation can be widespread, stretching the dollars as far as possible across the study area. Therefore, selecting low-cost solutions having the most benefit will likely offer the most rewards and will provide a balance of funding for the second component of the systematic approach.

The Minnesota Department of Transportation (MnDOT) used the systematic approach in its efforts to address safety. MnDOT first applied the approach to its county road safety plans. In its rural counties, road departure crashes were the biggest problem, while in its metropolitan counties, there were high pedestrian and bicyclist crashes. However, there was no single place where these crashes accumulated. MnDOT personnel looked at the characteristics of the crashes and places with similar characteristics instead of focusing on a few locations where two to three severe crashes occurred in a year. They used the Minnesota Crash Mapping Analysis Tool to assist them in this process. A pilot project helped them to prioritize countermeasures and create a decision tree (see Figure 18) to help identify low-cost, proactive projects.

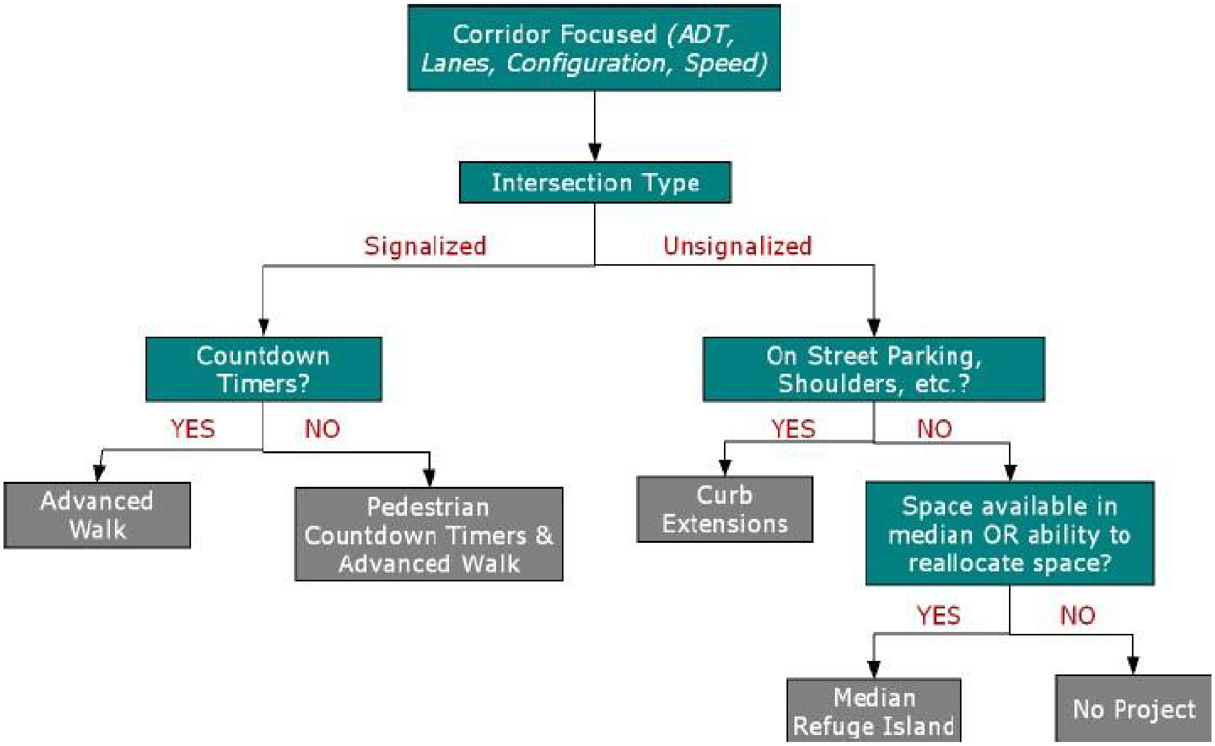


Figure 18. MnDOT Project Development Decision Tree from (*66*).

TxDOT Project 0-6702 (*45*) also used a decision-tree method to explore the TxDOT Crash Record Information System database to identify characteristics of crashes involving pedestrians in Texas. Researchers identified and analyzed 34,620 TxDOT-reportable pedestrian crashes over the 5-year period of 2007–2011 to find the significant factors influencing severity of crashes involving pedestrians in Texas that may be difficult to identify using traditional exploratory analyses. The results of the analysis led researchers to conclude that light condition, road class, traffic control, right shoulder width, involvement of a commercial vehicle, pedestrian age, and the manner in which the vehicle(s) were moving prior to the first harmful event were critical in classifying the injury severity of pedestrian crashes, with road class and light condition as the most important variables in predicting crash severity. Identifying common factors in crashes to predict where they will occur helps to generate suggestions for appropriate countermeasures to treat the sites with the greatest risk factors.

Blackburn et al. (*67*) developed an FHWA *Guide for Improving Pedestrian Safety at Uncontrolled Crossing Locations* that provides guidance to agencies for documenting conditions at crossing locations and selecting appropriate countermeasures. The document was developed in the context of FHWA's Safe Transportation for Every Pedestrian program, which focused on five specific countermeasures:

1. Crosswalk visibility enhancements (e.g., high-visibility crosswalk markings, parking restriction on crosswalk approach, improved lighting, advance YIELD HERE TO [STOP HERE FOR] PEDESTRIANS sign and yield [stop] line, IN-STREET PEDESTRIAN CROSSING sign, and curb extension).
2. Raised crosswalk.
3. Pedestrian refuge island.
4. Pedestrian hybrid beacon.
5. Road diet.

Like the aforementioned Alluri study (*61*), the FHWA guide does not contain results from a specific evaluation conducted by its authors, but it does describe safety benefits for the five countermeasures reported in other studies, and the guide also includes best practices for identifying locations and installing countermeasures at uncontrolled pedestrian crossing locations. Also similar to the Alluri study, Blackburn et al. provided a summary table of reported CMFs and crash reduction factors (CRFs), which is reproduced here as Table 17.

Table 17. Summary Table of CRFs and CMFs for Countermeasures in (*67*).

Countermeasure	CRF	CMF	Basis	Reference
Crosswalk visibility enhancement[1]	—	—	—	—
Advance STOP/YIELD signs and markings	25%	0.75	Pedestrian crashes[2]	Zegeer, et. al. 2017
Add overhead lighting	23%	0.77	Total injury crashes	Harkey, et. al. 2008
High-visibility marking[3]	48%	0.52	Pedestrian crashes	Chen, et. al., 2012
High-visibility markings (school zone)[3]	37%	0.63	Pedestrian crashes	Feldman, et. al. 2010
Parking restriction on crosswalk approach	30%	0.70	Pedestrian crashes	Gan, et. al., 2005
In-street Pedestrian Crossing sign	UNK	UNK	N/A	N/A
Curb extension	UNK	UNK	N/A	N/A
Raised crosswalk (speed tables)	45%	0.55	Pedestrian crashes	Elvik, et. al., 2004
	30%	0.70	Vehicle crashes	
Pedestrian refuge island	32%	0.68	Pedestrian crashes	Zegeer, et. al., 2017
PHB	55%	0.45	Pedestrian crashes	Zegeer, et. al., 2017
Road Diet – Urban area	19%	0.81	Total crashes	Pawlovich, et. al., 2006
Road Diet – Suburban area	47%	0.53	Total crashes	Persaud, et. al., 2010

[1]This category of countermeasure includes treatments which may improve the visibility between the motorist and the crossing pedestrian.
[2]Refers to pedestrian street crossing crashes, and does not include pedestrians walking along the road crashes or "unusual" crash types.
[3]The effects of high-visibility pavement markings (e.g., ladder, continental crosswalk markings) in the "after" period is compared to pedestrian crashes with parallel line markings in the "before" period.

LESSONS LEARNED ON SELECTION/IMPLEMENTATION OF COUNTERMEASURES

At the end of the Hudson report (*43*), researchers discussed best practices, opportunities for future research, and recommendations for increasing pedestrian safety on high-speed, controlled-access roadways. Their analysis of countermeasures to address pedestrian safety on high-speed roadways suggested that some countermeasures were promising but may require improvements to be effective (e.g., designing overpasses or underpasses that are easily accessible and inviting for pedestrians; fences or barriers can be used to guide pedestrian crossing behavior but must be made so that pedestrians cannot climb or otherwise circumvent them).

In the shorter term, they concluded, effective education and enforcement efforts may be critical to successful implementation of existing practices. Education and enforcement were commonly mentioned in the survey responses as tools for managing pedestrian safety on controlled-access highways. According to their literature review, different groups were not equally aware of existing laws and programs, and they recommended that more effective education programs need to be developed to focus on hard-to-reach and vulnerable groups. Additional suggestions (*43*) for future efforts to increase understanding of pedestrian safety issues on high-speed, controlled-access roadways and to improve mitigation efforts included:

- Expand Move-Over Laws.
- Evaluate Intentional and Unintended Pedestrian Activity Independently.
- Increase Data Collection, Evaluation, and Monitoring of Practices.
- Research and Develop Guidelines for Pedestrian Crossing Opportunities along Urban Interstates.

In addition to their evaluations of various countermeasures, Pécheux et al. (*64*) documented some lessons learned during the project, which they shared to help other agencies considering similar evaluations in the future. The major steps in their project included:

- Establishing and maintaining a multi-agency pedestrian safety team to oversee and guide the project.
- Identifying pedestrian safety and mobility problems, including potential contributing factors to crashes.
- Selecting pedestrian safety countermeasures corresponding to the problems identified.
- Obtaining funding and support for pedestrian safety improvements.
- Procuring, deploying, and maintaining the countermeasures.
- Evaluating the effectiveness of the countermeasures.

General lessons learned (*64*) included the following:

- Assemble a diverse set of project partners to address the range of issues that might arise during the study.
- Implement (from project kickoff) regular communication and participation mechanisms for project partners.
- Use various methods/sources to understand problems and to determine causes of crashes at prominent pedestrian crash locations.
- Begin the program by implementing low-cost countermeasures for the greatest potential of widespread use.
- Pursue various funding sources for the pedestrian safety program.

- Do not underestimate the complexity of procurement.
- Budget ample time for deployment and coordinate with the appropriate jurisdictions.
- Consider how the timing of countermeasure deployment may impact the experimental design and evaluation.
- Consider the unique aspects of collecting and reducing pedestrian safety data.

Countermeasure-specific lessons learned (*64*) included the following:

- Strategically place in-street pedestrian signs to reduce the chance of them being hit by vehicles and to maximize their effectiveness.
- Consider the technical issues surrounding the use of automated pedestrian detection and activated flashing beacons.
- Translate public service messages into multiple languages to conduct a successful outreach to non-English speaking populations.
- Be prepared to demonstrate to concerned traffic engineers that the electronic NTOR sign will not significantly disrupt traffic progression along a corridor. Work with the local electric utility and vendors to make sure everything is in place for success.

Pedestrian overpasses (bridges) and underpasses (tunnels) allow pedestrians and bicyclists to cross streets while avoiding potential conflicts with vehicles (*68*). Because they are expensive to construct, agencies should reserve grade-separated crossings for locations with high crossing demand and where the risks of crossing the roadway are high. Ideally, overpasses and underpasses should take advantage of the topography of a site; grade separations are less expensive to construct and more likely to be used if they can help pedestrians avoid going up and down slopes, ramps, and steps.

The effectiveness of pedestrian overpasses and underpasses depends on their level of use by pedestrians. A study by Moore and Older found use of overpasses and underpasses depended on walking distances and convenience of the facility (*57*, *69*). They defined a convenience measure (R) as the ratio of the time to cross the street on an overpass divided by the time to cross at street level. The researchers found around 95 percent of pedestrians will use an overpass if the walking time is the same, or better than, the crossing time at street level (i.e., $R \leq 1$). However, if crossing the overpass takes 50 percent longer than crossing at street level ($R = 1.5$), almost no one will use the overpass. Usage of pedestrian underpasses was not as high as overpasses with similar values of R.

When designing grade-separated crossings, agencies should consider accessibility. Researchers asked a panel of people with disabilities to comment on accessibility issues after using three pedestrian overpasses in San Francisco, California (*57, 70*). They identified nine major elements that create a barrier or hazard to users with disabilities:

- Lack of adequate railings to protect pedestrians from drop-offs on overpass approaches.
- Greater than acceptable cross slopes.
- No level area at the terminals of the ramps on which to stop wheelchairs before entering the street.
- Lack of level resting areas on spiral bridge ramps.
- Railings difficult to grasp for wheelchair users.
- Lack of sight distance to opposing pedestrian flow on spiral ramps.
- Use of maze-like barriers to slow bicyclists on bridge approaches that create a barrier to those individuals who use wheelchairs or who are visually impaired.
- Lack of sound screening on the bridge to permit people with visual impairments to hear oncoming pedestrian traffic and otherwise more easily detect direction and avoid potential conflicts.

METHODOLOGY TO IDENTIFY CLUSTER OF PEDESTRIAN CRASHES ON HIGH-SPEED ROADS

Researchers considered various approaches to identify sites with potential for pedestrian safety improvements. As a reference to inform this process, researchers used a recently published FHWA guideline document (*71*). The following figure from that document (see Figure 19) summarizes the steps of this process.

Regarding the approach selected, researchers focused on crash data as the core of the identification of pedestrian crashes. Researchers considered other pieces of information, such as the information in the RHiNo database. However, many crash-relevant elements from that database are already included in the CRIS database.

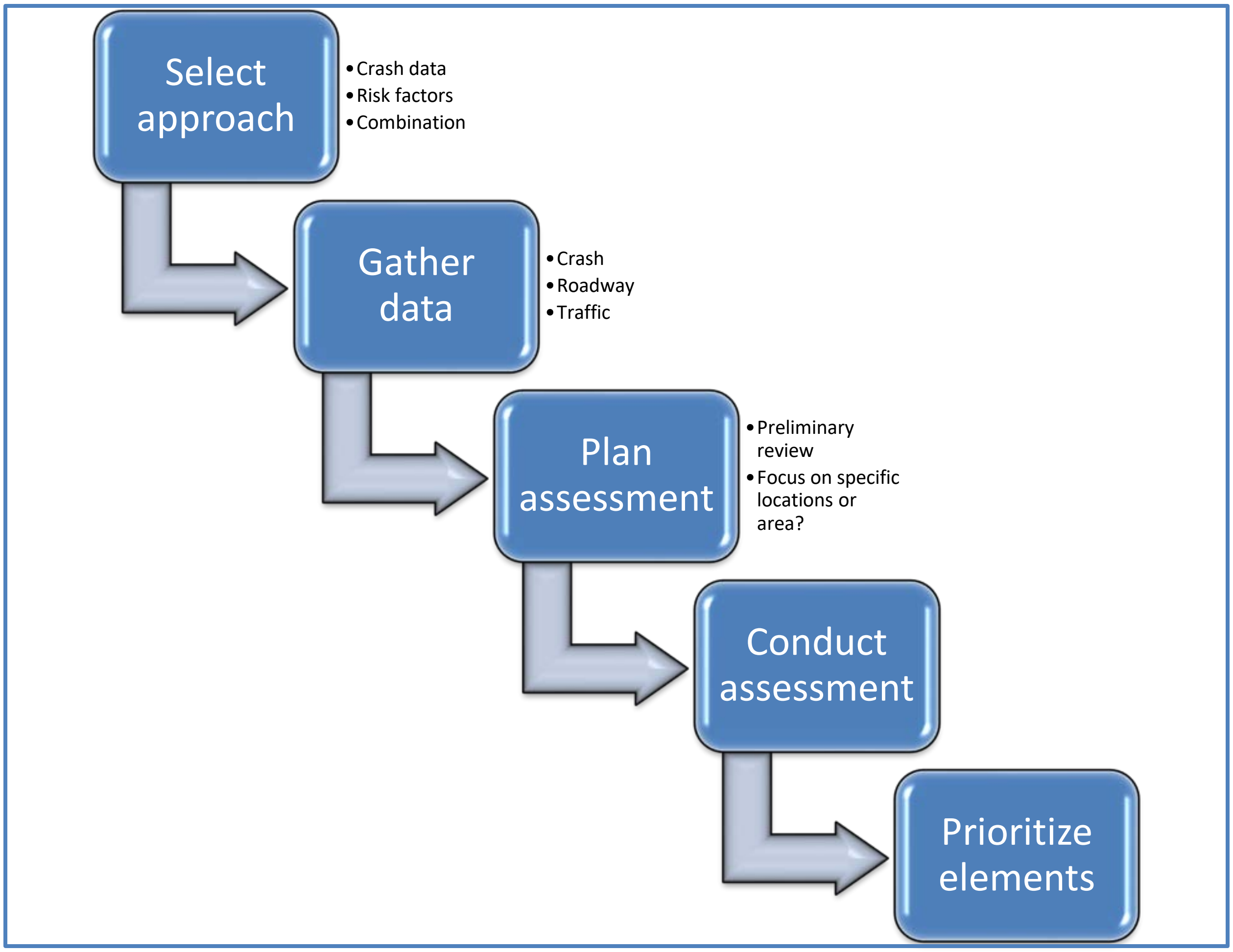


Figure 19. Steps within Process To Identify High Pedestrian Crash Locations (*71*).

Crash Data Characteristics

In Texas, crash data come from multiple sources, including TxDOT, state highway patrol, other public agencies, and emergency medical services. The data are coded and stored into a relational database structure (CRIS database) with separate files (called tables) for the crash, unit, and person information. These tables are linked through identifier fields. TxDOT undergoes a process of quality control of the data before making the final version available for use. These control checks address inconsistencies or omissions (as submitted by the investigating law enforcement agency), assigns final coordinates to crashes, and supplements or enhances the crash report based on a review of the crash narrative. Researchers used codes in CRIS to identify pedestrian crashes statewide at high-speed locations for the analysis.

Period of Analysis

Considering that pedestrian crashes are rare among crashes (rare events themselves), researchers elected to analyze six years of crash data. Even for such a relative long period of analysis, it was anticipated that the vast majority of crashes would be found in isolation, given the rarity and the size of the Texas roadway network.

Geographic Location of High-Speed Pedestrian Crashes

Researchers identified an initial number of 30,483 pedestrian-vehicle crashes for the period 2012–2017 in Texas. Figure 20 shows the density of all pedestrian crashes identified for the period of analysis. Next, a filter was applied to focus on high-speed roads, defined as being roads where the variable RepSL is 40 mph or above. Among these roads, the number of pedestrian high-speed crashes for targeted analysis was found to be 10,640 out of the 30,483 total pedestrian crashes.

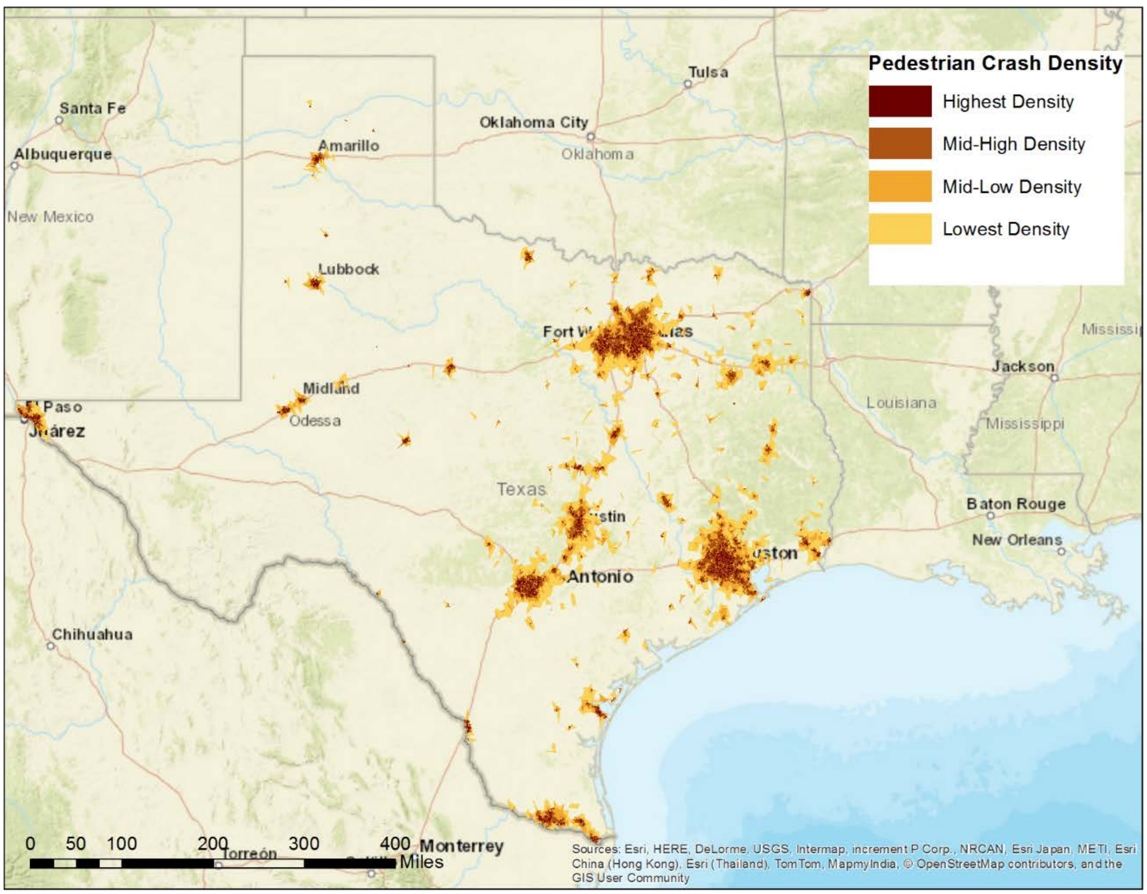


Figure 20. Pedestrian Crash Locations in Texas.

Clustering Analysis

Researchers elected to use cluster analysis techniques to investigate locations of higher crash occurrences. The rationale to use these methods is that little can be said about a location that only experienced one or two pedestrian crashes in six years. Furthermore, the number of locations with such a small number of crashes is expectedly the vast majority of locations in the state. On the other hand, if a location has a steady yearly occurrence (1 or 2 crashes every year), that location would be a strong candidate to be considered for countermeasures, excluding other considerations. However, it is critical to define the limits of a site to continue to implement this rationale. A decision must be made about what threshold should define the clusters, which in turn, should define the sites to study. Past research on safety at signalized intersections has suggested the use of a 300-ft threshold (*72*). However, this research explored various thresholds because pedestrian crashes should expectedly exhibit different characteristics than vehicle-to-vehicle crashes found in that work.

Initial Analysis and Selection of Cluster Threshold

Researchers first defined clusters at a 100-ft threshold and found that the 10,640 crashes are then grouped in 10,420 clusters of crashes. Using this threshold implies that the largest distance between two adjacent pedestrian crashes is 200 ft. However, having 10,640 crashes grouped in 10,420 clusters indicates very little clustering (1.02 crashes per cluster). Researchers repeated the exercise with a threshold of 250 ft and found that there were 8,236 clusters of crashes. This exercise implies that 500 ft is the maximum distance between two adjacent crashes.

Researchers repeated the exercise once more with a threshold of 150 ft (which produced clusters of adjacent crashes within 300 ft of each other at the most). This process produced a very similar set of 8,766 clusters averaging 1.21 crashes per cluster that was not too different from the results of using a 250-ft threshold. Given these results, clustering of crashes occurred between thresholds of 100 ft and 150 ft, and it does not change much when increasing the threshold from 150 ft to 250 ft. For that reason, researchers elected to work with a threshold of 150 ft for the cluster analysis.

After performing the cluster analysis, researchers identified 31 locations with clusters that had between 7 and 19 crashes in the 6-year period. When investigating the resulting clusters, researchers identified the corresponding locations as either intersections, corridors, or a combination of the two. The following sections describe further investigations at these 31 locations.

OBSERVATIONS ON CONTRIBUTIONS TO PEDESTRIAN CRASHES ON HIGH-SPEED ROADS

Crash Narrative Review

Researchers reviewed all the crash report narratives for the 31 clusters described previously to preliminarily identify common characteristics of crashes, potential trends, and possible countermeasures. After reading all the crash report narratives for the crashes at these clusters, along with considering the street names provided in the report, researchers believed that there were three clusters where some or all of the crashes were not at the coordinates indicated by CRIS or that the crashes occurred on two different roads. One of these clusters had some of the crashes on the freeway that was passing under the arterial. When the crashes were separated, the number of crashes would not have passed the minimum criteria of seven crashes to be considered a cluster. For one of the sites, roughly half of its crashes appears to be at a nearby intersection with similar street names to the CRIS location. For the remaining cluster, all of the crashes appear to have been assigned to a different location approximately 1.25 mi away from the location that was identified by street names. Researchers set aside those three sites and focused their efforts on the remaining 28 sites.

Observations from Crash Narrative Review

The review of the narratives provides some insights into why the pedestrian was present on the high-speed road and the actions of the pedestrian. For the 284 crashes reviewed, slightly more than half occurred on a segment, with the remaining 45 percent occurring at an intersection. The crashes were evenly split between daytime and nighttime/dawn/dusk conditions. The pedestrian was struck by a vehicle going straight in most cases (63 percent), with 20 percent involving vehicles turning left and 14 percent involving vehicles turning right. Three of the crashes involved a U-turn lane, and the movement of the vehicle was unknown for the remaining 2 crashes (1 percent).

Researchers assigned the pedestrian as either intended or unintended based upon the information available in the narrative along with an estimate of why the pedestrian was present. An unintended pedestrian reflects the situation where the individual was not intending to walk or cross a street. Table 18 shows the distribution of reasons that the pedestrian was present. In most cases, the person was intentionally crossing the high-speed roadway. For the entire group of pedestrian crashes, 3 percent of the crashes involved an unintended pedestrian, 11 percent could not be determined, and 86 percent were intentional pedestrians. Those crashes involving unintentional pedestrians included those pedestrians who were retrieving items from the road or were standing on the side of the road or in the median when a vehicle ran off the road.

Table 18. Why Was Pedestrian Present?

Why Was Pedestrian Present?	**Not an Unintended Pedestrian**		**Unknown**		**Unintended Pedestrian**		**Total**	
	Num	**%**	**Num**	**%**	**Num**	**%**	**Num**	**%**
Crossing roadway	209	85%	17	53%	1	14%	227	80%
Fleeing police/ chasing car	2	1%		0%	1	14%	3	1%
Other	9	4%		0%		0%	9	3%
Retrieving items from road	2	1%		0%	2	29%	4	1%
Sleeping/laying down	1	0%	1	3%		0%	2	1%
Stalled vehicle		0%		0%	1	14%	1	0%
Standing in traffic	2	1%		0%		0%	2	1%
Standing on median, shoulder, or off the road	3	1%		0%	2	29%	5	2%
Unknown	2	1%	7	22%		0%	9	3%
Walking along the sidewalk or roadside	11	4%		0%		0%	11	4%
Walking in traffic	4	2%	5	16%		0%	9	3%
Walking on shoulder		0%	2	6%		0%	2	1%
Total	**245**	**100%**	**32**	**100%**	**7**	**100%**	**284**	**100%**

Observations from Site Review

A common feature at most of the corridors and intersections containing the 28 clusters was one or more bus stops near or within the cluster. This coincidence suggests a connection between pedestrians who use public transit and pedestrians at greater risk of being involved in a crash. Transit agencies vary from place to place on their criteria for establishing a bus stop; some include a great deal of detail on the surrounding area (including available pedestrian facilities), while others do not. Regardless of the process used to establish a bus stop, that process should ideally consider the presence of continuous sidewalks to nearby pedestrian generators and the presence of adjacent crosswalks to provide a common point for crossing pedestrians to use when preparing to cross the street.

All the sites contained crashes in which a pedestrian was struck by a motor vehicle while crossing the street outside of a crosswalk. In some cases, this occurrence was a result of pedestrians moving between vehicles that were stopped for a red signal when the signal changed to green. The more common instances involved pedestrians who were crossing from one commercial property to another or between residential and commercial areas. In the latter category of crashes, many of the pedestrians were struck while in a two-way left-turn lane, suggesting that a median refuge island could be useful in preventing future crashes of a similar nature.

In examining other occurrences related to commercial properties, researchers reviewed a noticeable number of crashes with pedestrians who were struck while walking on the sidewalk. While some were struck by a vehicle that was out of control and left the roadway (perhaps when a driver was intoxicated), other pedestrians were struck by a vehicle entering or (more commonly) exiting a driveway to a commercial property. A frequent scenario for exiting drivers was that they looked left to check for oncoming vehicles and failed to notice the pedestrian approaching from their right before proceeding through the driveway. Access management measures, such as reducing the number of driveways, can help to reduce pedestrian exposure to these types of crashes. A different kind of access management would apply to a small number of corridor sites that have essentially no defined driveways, but rather a mountable curb or no curb adjacent to a series of contiguous commercial properties. These sites also may have no formal sidewalk, though a wide paved surface similar to a shoulder lane might provide additional buffer between a pedestrian and the traffic on the adjoining roadway. Installation of a formal curb with sidewalk and buffer would provide a dedicated pedestrian path at these locations.

The selection of sites had at least half of their crashes occur during nighttime hours, dawn, or dusk. This frequency indicates that either installation of new roadway lighting or a review of existing lighting would be beneficial for these sites.

Some intersection sites had a high number of pedestrian crashes within the crosswalk, where pedestrians were struck by a left-turning vehicle. A review of street-level images from

Google Earth indicates that some of those intersections appear to have protected left-turn phasing, but others have protected/permitted or permitted-only left turns. A formal review of left-turn phasing at these intersections and introduction of protected-only left turns for some approaches would reduce the likelihood of pedestrians being struck by drivers who did not see a crossing pedestrian while concentrating their view on searching for an acceptable left-turn gap. Similarly, a leading pedestrian interval could also give pedestrians a head start on entering the intersection and increasing their visibility before left-turning vehicles begin their turning movements.

The review of crash narratives also revealed a notable number of crashes with vehicles turning right on red or using a free-flow right-turn lane. In the former category, drivers typically did not notice the pedestrian on their right that was preparing to cross the street because they were looking left for oncoming vehicles. Outreach/education efforts or supplemental signing at such intersections could be beneficial treatments to help drivers develop a consistent habit to thoroughly check their surroundings. In the latter category, drivers may also be looking to their left as they travel through the right-turn lane to make sure they have a suitable gap in traffic to merge, and speeds in free-flow right-turn lanes can increase the risk of serious injury to pedestrians compared to the right-turn-on-red condition. Recent design guidelines for dedicated right-turn lanes recommend tighter turning radii to reduce turning speeds in conjunction with marked crosswalks and adequate pedestrian refuge in the island between the right-turn lane and the through lanes. An example of a traditional free-flow right-turn lane compared to the preferred design is shown in Figure 21; the smaller radii and adjusted approach angle also make it easier for drivers to look to their left for approaching vehicles because the head-turn angle is reduced.

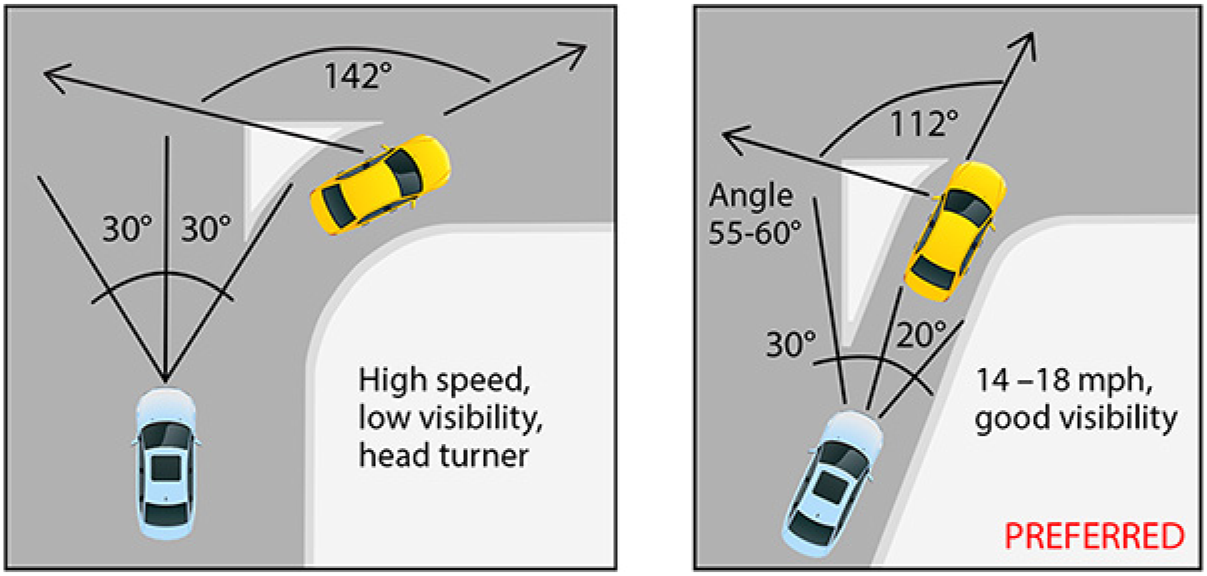


Figure 21. Traditional (Left) and Preferred (Right) Right-Turn Channelization Design.

Survey

Researchers contacted practitioners in each of the metropolitan areas that contained one or more of the crash clusters of interest and sent practitioners a predetermined list of survey questions to ask them for additional insights about the characteristics of those sites, potential pedestrian generators, possible causes for crashes, and countermeasures that they had either implemented or considered. Not all of the practitioner surveys have been completed, but those surveys that have been returned to date tend to support the above findings in identifying the types of crashes that are occurring and possible causes for them. Possible countermeasures that practitioners have considered or suggested for selected sites include:

- Pedestrian refuge islands.
- Moving bus stops closer to intersections.
- Reducing the number of travel lanes to shorten crossing distances.
- Using pedestrian hybrid beacons at the otherwise uncontrolled crosswalks.

SUMMARY

Efforts within this task can be combined to generate insights into potential solutions that could improve conditions for pedestrians at locations identified as having safety concerns. Preliminary reviews of the pedestrian crashes on Texas high-speed roads produced several observations. In many locations, the occurrence of a crash involving a pedestrian is the result of a series of unfortunate events. For example, the presence of dark (nighttime) conditions, nearby sources for alcohol, high volume of turning traffic, and high operating speed on the roadway does not necessarily mean that there will be many crashes; however, when these elements are combined, a greater chance can exist that a pedestrian crossing the street could be involved in a collision. There are some locations, however, where the lack of sidewalks or pedestrian refuge along with the need for better access management may be contributing to a large number of pedestrian crashes.

APPENDIX A: STEPS OF THE EMPIRICAL BAYES PROCEDURE EMPLOYED IN THE ANALYSIS OF THE TXDOTATLANTA DISTRICT NIGHTTIME CRASH DATA

Step 1. Develop an SPF and estimate the regression coefficients and a NB dispersion parameter (k) using data from the reference group.

Step 2. Estimate the expected number of crashes $E(\kappa_{it})$ for each year (t) in the before period at each treatment site using the SPF developed in Step 1 multiplied by α_f (the ratio of nighttime crashes and daytime crashes on segments where wet-weather pavement markings were not installed) as follows:

$\hat{E}(\kappa_{it}) = \alpha_f \hat{\mu}_{it}$ where $\hat{\mu}_{it}$ is the mean crash frequency estimated from the SPF developed based on the daytime crashes.

Step 3. Compute the sum of the annual SPF predictions during the before period at each treatment site by summing $E(\kappa_{it})$ for before years:

$$P_i = \sum_{t=1}^{t_{0i}-1} \hat{E}(\kappa_{it})$$

where t_{0i} denotes the year during which the countermeasure was installed at site i.

Step 4. Obtain an estimate of the expected number of crashes (M_i) before implementation of the countermeasure at each treatment site and an estimate of variance of M_i. The estimate M_i is given by combining the sum of the annual SPF predictions during the before period (P_i) with the total count of crashes during the before period, as follows:

$$M_i = w_i P_i + (1 - w_i) K_i$$

where K_i is the total crash counts during the before period at site i and the weight w_i is given by:

$$w_i = \frac{1}{1 + kP_i}$$

where k is the estimated dispersion parameter of the NB regression model developed in Step 1. An estimated variance of M_i is given by:

$$V\hat{a}r(M_i) = (1 - w_i) M_i .$$

Step 5. Determine SPF predictions $\hat{E}\left(\kappa_{iy}\right)$ for each year in the after period at each treatment site, and compute C_i, the ratio of the sum of the annual SPF predictions for the after period (Q_i) and the sum of the annual SPF predictions for the before period (P_i):

$$C_i = \frac{\sum_{t=t_{0i}+1}^{T} \hat{E}\left(\kappa_{iy}\right)}{\sum_{t=1}^{t_{0i}-1} \hat{E}\left(\kappa_{it}\right)} = \frac{Q_i}{P_i}.$$

Step 6. Obtain the predicted crashes ($\hat{\pi}_i$) and its estimated variance during the after period that would have occurred without implementing the countermeasure. The predicted crashes ($\hat{\pi}_i$) are given by:

$$\hat{\pi}_i = C_i M_i$$

The estimated variance of $\hat{\pi}_i$ is given by:

$$V\hat{a}r\left(\hat{\pi}_i\right) = C_i^2 V\hat{a}r\left(M_i\right) = C_i^2\left(1-w_i\right)M_i.$$

Step 7. Compute the sum of the predicted crashes over all sites in a treatment group of interest and its estimated variance by:

$$\hat{\pi} = \sum_{i=1}^{I} \hat{\pi}_i$$

$$V\hat{a}r\left(\hat{\pi}\right) = \sum_{i=1}^{I} V\hat{a}r\left(\hat{\pi}_i\right)$$

where I is the total number of sites in a treatment group of interest.

Step 8. Compute the sum of the observed crashes over all sites in a treatment group of interest by:

$$L = \sum_{i=1}^{I} L_i$$

where L_i is the total crash counts during the after period at site *i*.

Step 9. The index of effectiveness of the countermeasure is estimated by:

$$\hat{\theta} = \frac{L}{\hat{\pi}\left(1+\mathrm{var}\left(\hat{\pi}\right)/\hat{\pi}^2\right)}.$$

The percent change in the number of crashes at site *i* is given by $100\left(1-\hat{\theta}\right)$. If $\hat{\theta}$ is less than 1, then the countermeasure has a positive effect on safety.

Step 10. Compute the estimated variance and standard error of the index of effectiveness and the approximate 95 percent confidence interval for θ. The estimated variance and standard error of the index of effectiveness are given by:

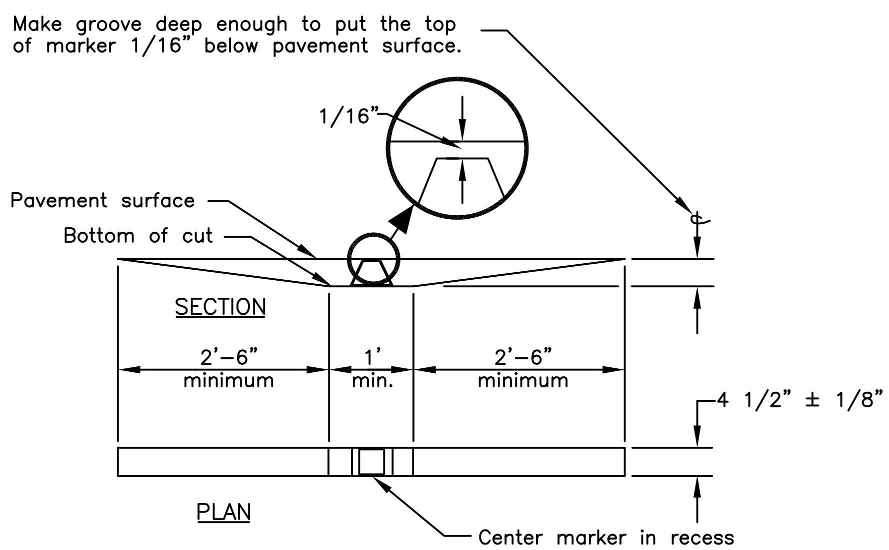
$$V\hat{a}r\left(\hat{\theta}\right)=\hat{\theta}^2\frac{\left(1/L+V\hat{a}r\left(\hat{\pi}\right)/\hat{\pi}^2\right)}{\left(1+V\hat{a}r\left(\hat{\pi}\right)/\hat{\pi}^2\right)^2}$$

$$s.e.\left(\hat{\theta}\right)=\sqrt{V\hat{a}r\left(\hat{\theta}\right)}$$

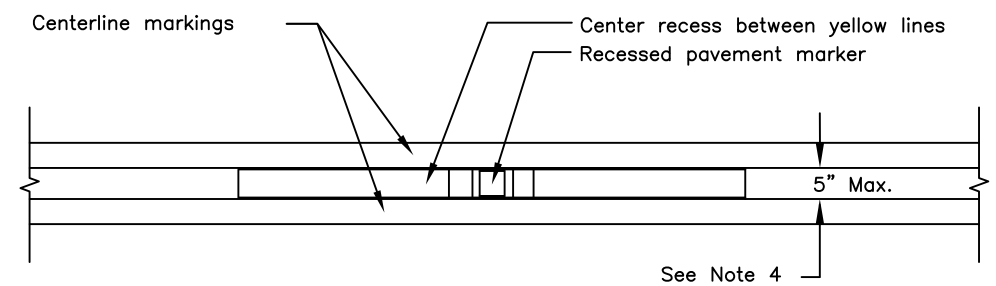
The approximate 95 percent confidence interval for θ is given by adding and subtracting $1.96\, s.e.\left(\hat{\theta}\right)$ from $\hat{\theta}$. If the confidence interval contains the value 1, then no statistically significant effect has been observed. This value does not mean that a safety effect does not exist, so all indices that were estimated are reported in this paper to show a complete picture of safety effects. A confidence interval placed below 1 (i.e., the upper limit of the interval is less than 1) implies that the countermeasure has a significant positive effect (i.e., a reduction in crashes) on safety. The confidence interval placed above 1 (i.e., the lower limit of the interval is greater than 1) implies that the countermeasure has a significant negative effect (i.e., an increase in crashes) on safety.

APPENDIX B: GROOVE-RECESSED RRPM STANDARDS

T-06.00



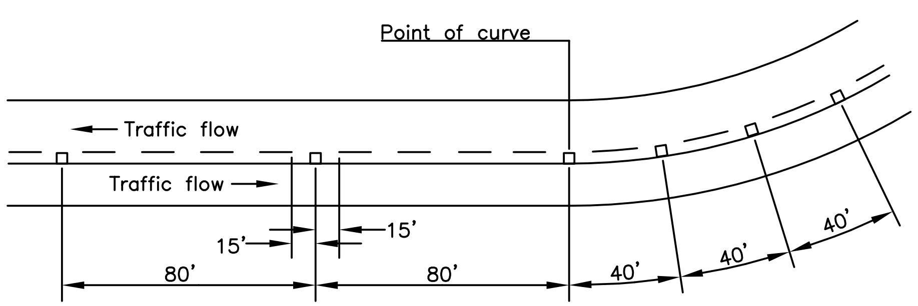
RECESSED PAVEMENT MARKER SLOT



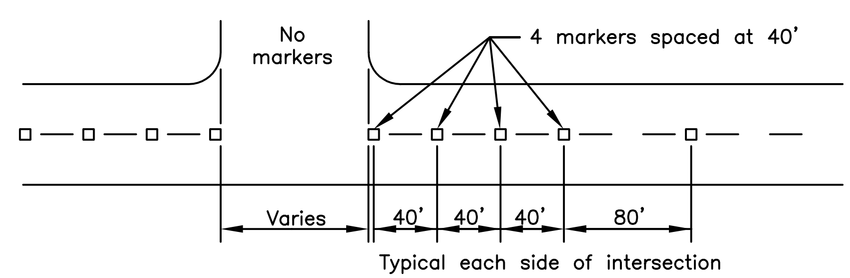
RECESSED PAVEMENT MARKERS WITH DOUBLE CENTERLINE INSTALLATION

GENERAL NOTES

1. Install recessed pavement markers spaced at 80' on tangent sections of roadway and on curves with a radius greater than 1,600'.
2. Install recessed pavement markers spaced at 40' on curves with a radius 1,600' or less.
3. Install recessed pavement markers between the lines on sections with double lines (either broken or solid.)
4. Increase the distance between yellow painted lines from the standard 3" up to a maximum of 5" to minimize paint overspray onto the marker.
5. Install recessed pavement markers on the centerline of the line, midpoint between stripe segments on sections with single broken lines.
6. Install reflectors of the same color as the pavement markings they supplement, except when red reflectors are specified on the departure side of markers on one-way roads to warn motorists they are going the wrong way.
7. Unless otherwise specified on one-way roads, reflectors are required only on the approaching traffic side of markers. In these cases, the 2'-6" taper may be omitted on the departure side.



RECESSED PAVEMENT MARKERS ON CURVES WITH A RADIUS LESS THAN 1,600'



RECESSED PAVEMENT MARKERS AT INTERSECTION APPROACHES

REVISIONS		
Date	Description	By

Sheet 1 of 1

State of Alaska
Department of Transportation
& Public Facilities

RECESSED PAVEMENT MARKERS

APPROVED

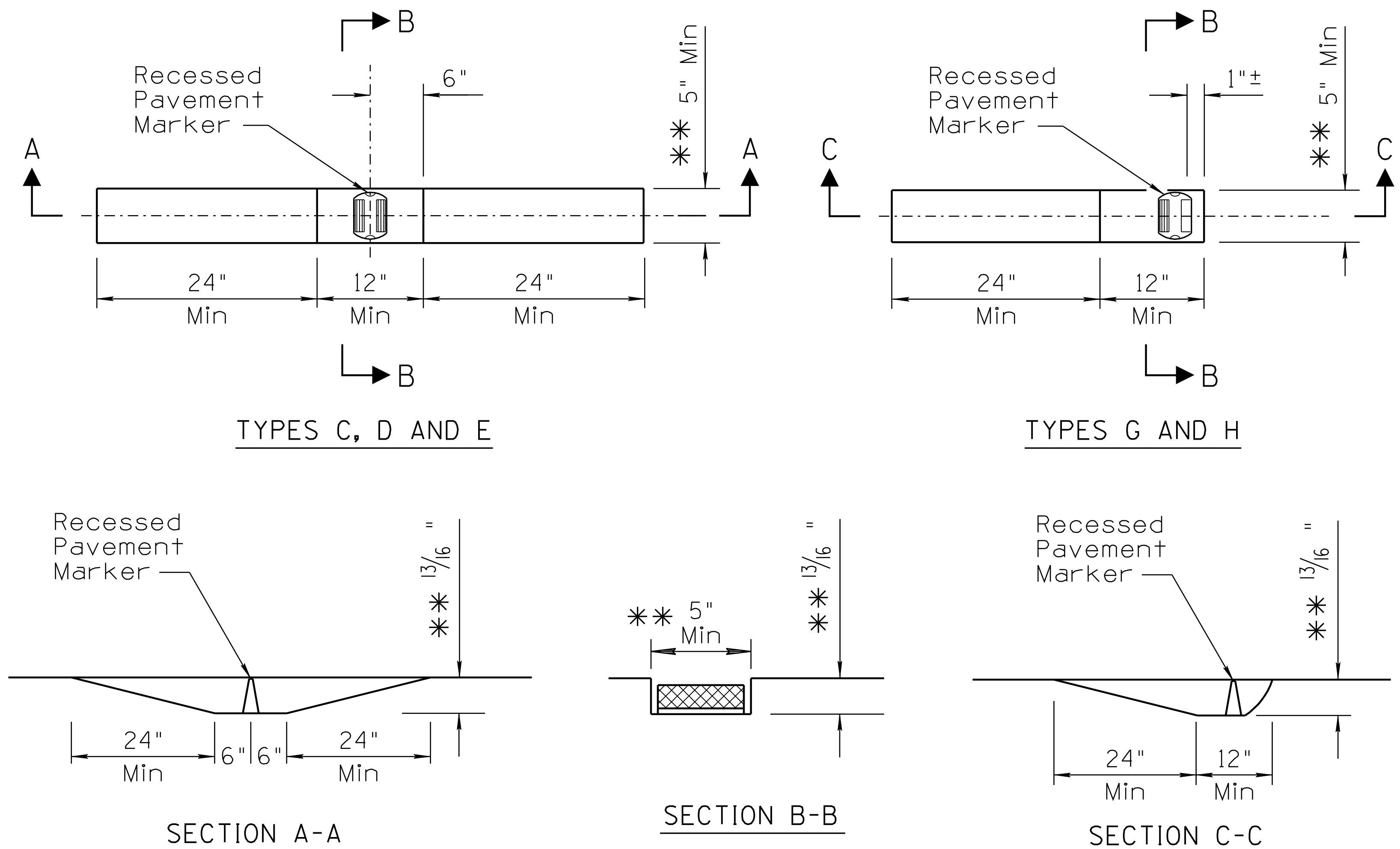
Date 3/28/03

T-06.00

NOTES:

1. Shape of marker shown is for information only. The actual configuration of markers can vary including the shape and type of reflecting surface as long as it fits within the standard recessed groove.
2. See Standard Drawing M-19 for types and dimensions of pavement markers.

**3. Depth and width of groove may be adjusted slightly to fit physical dimensions of marker selected if approved in advance by the Traffic Engineering Group.



RECESSING GROOVE DETAILS

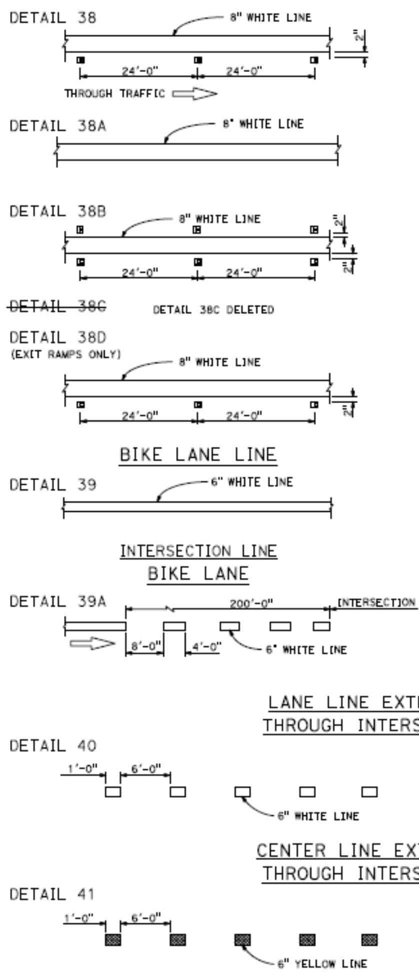
NOT TO SCALE

NO	DESCRIPTION OF REVISIONS	MADE BY	DATE
1	RE-ISSUE	L. LOPEZ	2/02
2	ADDED TYPE E RECESSED PAVEMENT MARKER	L. LOPEZ	6/08
3	REVISED DRAWING AND NOTES, NEW BORDER, CHANGED TEXT TO UPPER AND LOWER CASE.	L. LOPEZ	6/14
4			

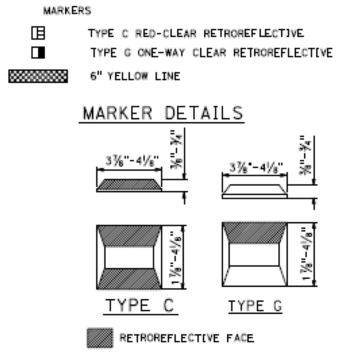
DESIGN APPROVED SIGNATURES	ARIZONA DEPARTMENT OF TRANSPORTATION INTERMODAL TRANSPORTATION DIVISION TRAFFIC SIGNING & MARKING STANDARD DRAWINGS	REVISION 6/14
		DRAWING NO. M-18
APPROVED FOR DISTRIBUTION ON FILE	RECESSED PAVEMENT MARKER DETAILS	SHEET NO. 1 OF 1

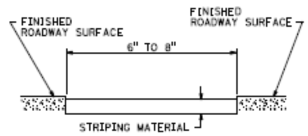
10:51:49 AM 6/5/2014 V:\Traffic\Dev\tr_dev\english_stds\sign_mark\current_stds\M-18.dgn

CHANNELIZING LINE



LEGEND





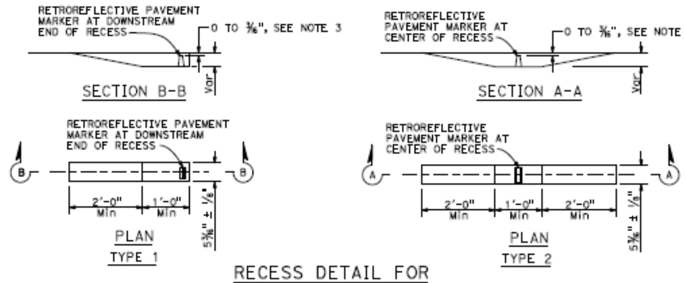
DETAIL FOR RECESSED TRAFFIC STRIPE

See Notes A and B.

RECESSED NOTES:

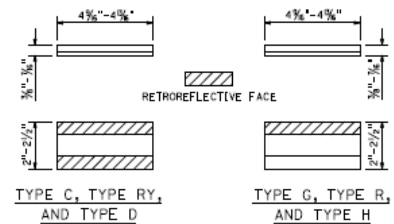
A. See typical traffic line details for pavement marking patterns.

B. See standard specifications for recess depth and recess striping material thickness.



RECESS DETAIL FOR RETROREFLECTIVE PAVEMENT MARKER

See Note 4



RETROREFLECTIVE PAVEMENT MARKER FOR RECESSED INSTALLATION

See Notes 1 and 2.

RECESSED MARKER NOTES:

1. See typical traffic line details for marker patterns to be used with recessed pavement markers.
2. The retroreflective pavement markers shown for recessed installations are not to be used for non-recessed installations.
3. The top of pavement markers installed in recesses shall be 0 to ⅜" below the pavement surface.
4. Use Type 1 recess for pavement markers with one-way retroreflective face. Use Type 2 recess for pavement markers with two-way retroreflective face.

STATE OF CALIFORNIA
DEPARTMENT OF TRANSPORTATION

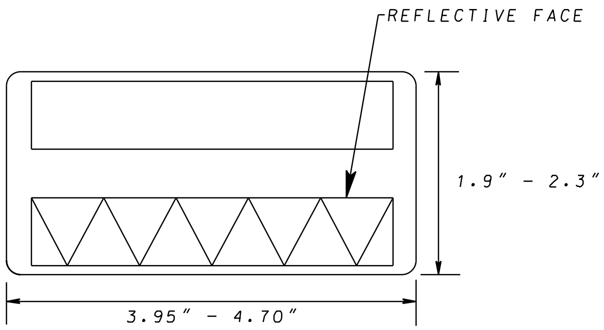
PAVEMENT MARKERS AND TRAFFIC LINES TYPICAL DETAILS

NO SCALE

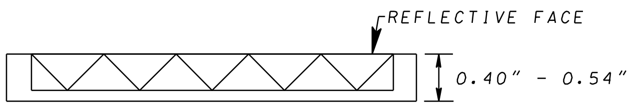
RSP A20D DATED OCTOBER 19, 2018 SUPERSEDES STANDARD PLAN A20D DATED MAY 31, 2018 - PAGE 15 OF THE STANDARD PLANS BOOK DATED 2018.

REVISED STANDARD PLAN RSP A20D

2018 REVISED STANDARD PLAN RSP A20D



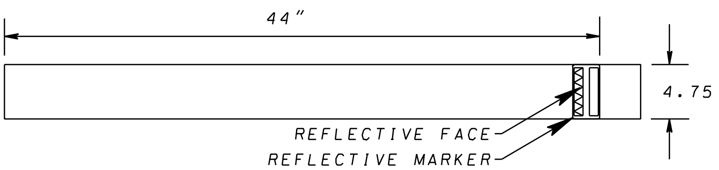
REFLECTIVE MARKER – PLAN VIEW



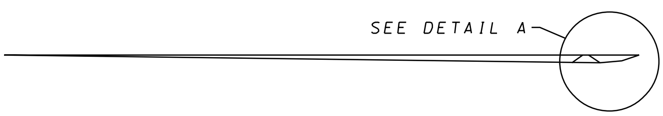
REFLECTIVE MARKER – FRONT VIEW

INSTALLATION

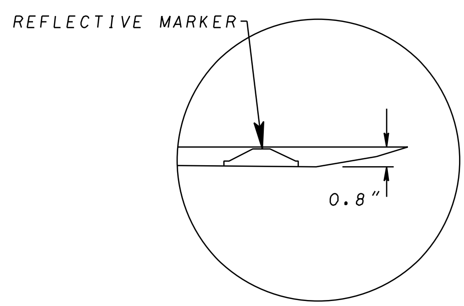
1. THE GROOVE SHALL BE CUT AS SHOWN.
2. THE CUT PATTERN SHALL BE CLEANED, AND DRIED BY COMPRESSED AIR BEFORE PLACING THE ADHESIVE. THE ADHESIVE SHALL BE PLACED PER THE MANUFACTURERS RECOMMENDATIONS.
3. EPOXY ADHESIVE SHALL BE INSTALLED DURING WEATHER CONDITIONS CONSISTENT WITH MANUFACTURERS RECOMMENDATIONS.
4. REFLECTIVE MARKER SHALL BE INSTALLED PER MANUFACTURERS RECOMMENDATIONS AND SHALL BE SELECTED FROM THE QUALIFIED PRODUCTS LIST (OPL).
5. THE MARKER SHALL BE PROTECTED FROM TRAFFIC UNTIL THE ADHESIVE HAS PROPERLY HARDENED.



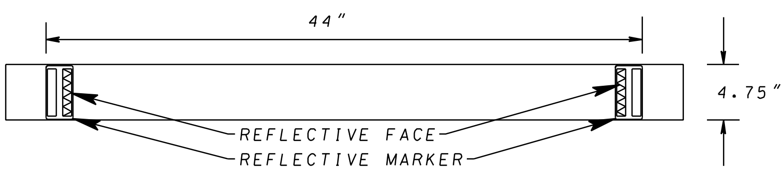
ONE WAY PAVEMENT GROOVE – PLAN VIEW



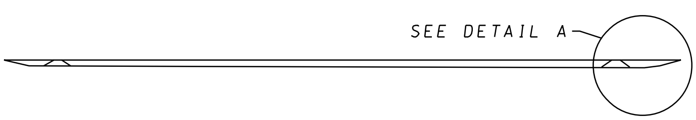
ONE WAY PAVEMENT GROOVE – SIDE VIEW



DETAIL A



TWO WAY PAVEMENT GROOVE – PLAN VIEW



TWO WAY PAVEMENT GROOVE – SIDE VIEW

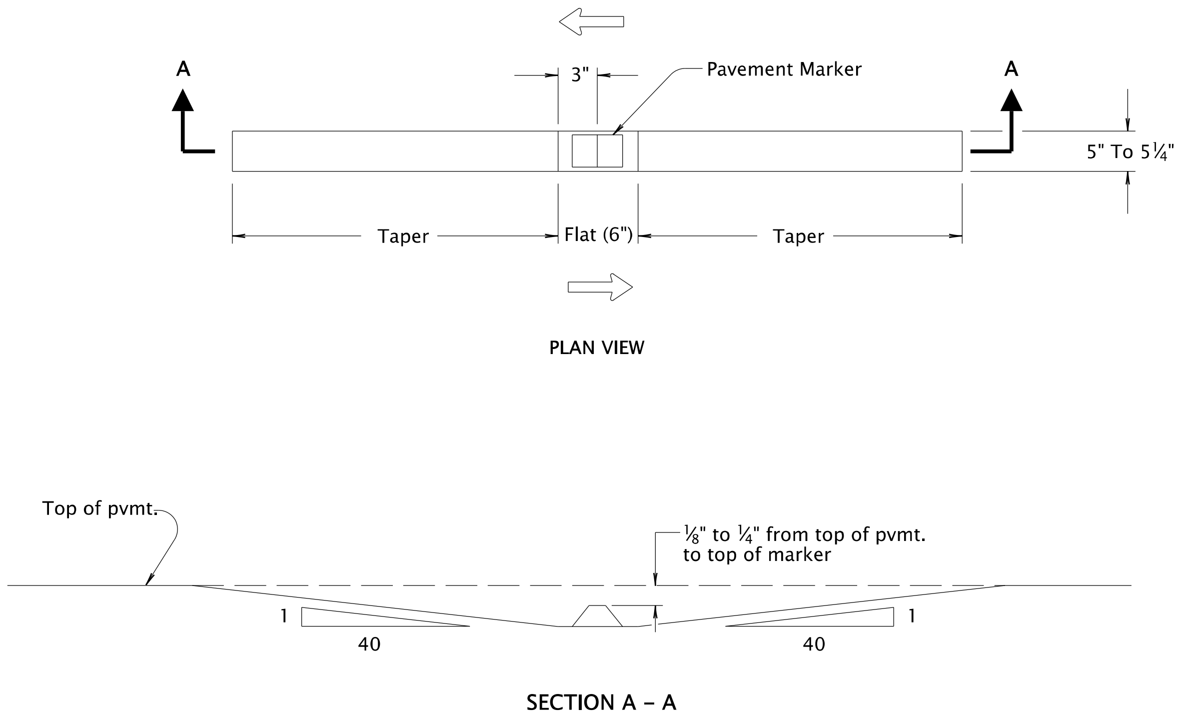
SPECIFICATION 558	CATEGORY CODE ITEMS	
APPROVED	DIRECTOR – OFFICE OF TRAFFIC AND SAFETY	
SHA State Highway Administration	APPROVAL • SHA REVISIONS	APPROVAL • FEDERAL HIGHWAY ADMINISTRATION
	APPROVAL 02-05-14	APPROVAL 01-14-14
	REVISED	REVISED
	REVISED	REVISED
	REVISED	REVISED

Maryland Department of Transportation
STATE HIGHWAY ADMINISTRATION
STANDARDS FOR HIGHWAYS AND INCIDENTAL STRUCTURES

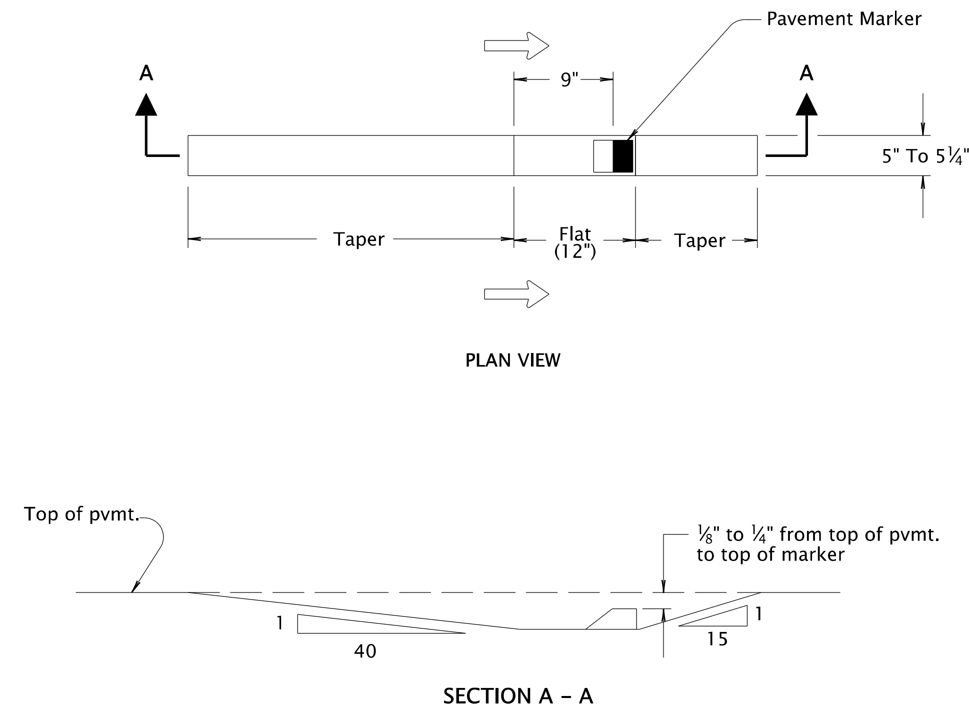
RECESSED PAVEMENT MARKERS

STANDARD NO. MD 558.01

tm517.dgn 01-09-2018



BI-DIRECTIONAL RECESSED PAVEMENT MARKER DETAIL



MONO-DIRECTIONAL RECESSED PAVEMENT MARKER DETAIL

LEGEND

Direction of Travel

Bi-directional yellow marker reflects yellow both left and right in this symbol

Mono-directional crystal white marker reflects white to the left in this symbol

To be accompanied by Standard Dwg. Nos. TM502 and TM515

CALC. BOOK NO. N/A

BASELINE REPORT DATE 07/01/2015

NOTE: All material and workmanship shall be in accordance with the current Oregon Standard Specifications.

The selection and use of this Standard Drawing, while designed in accordance with generally accepted engineering principles and practices, is the sole responsibility of the user and should not be used without consulting a Registered Professional Engineer.

OREGON STANDARD DRAWINGS

RECESSED PAVEMENT MARKERS

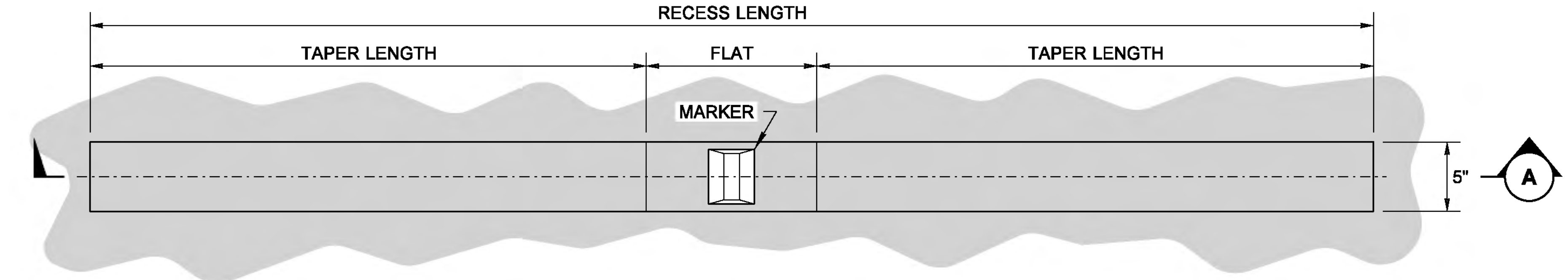
2018

DATE	REVISION DESCRIPTION

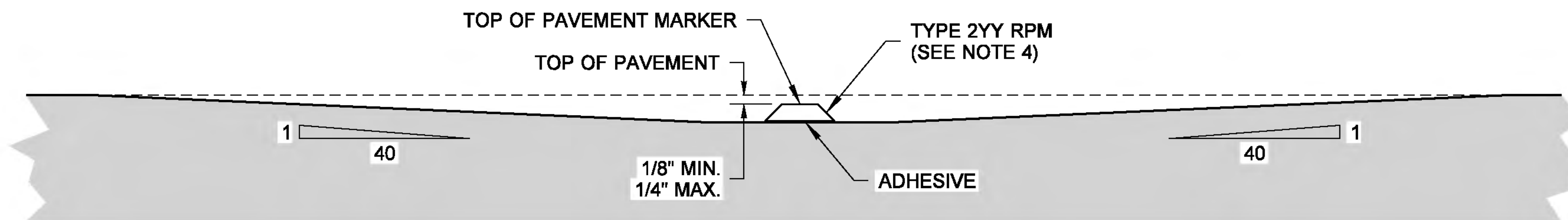
TM517

Effective Date: June 01, 2018 - November 30, 2018

DRAWN BY: COLBY FLETCHER



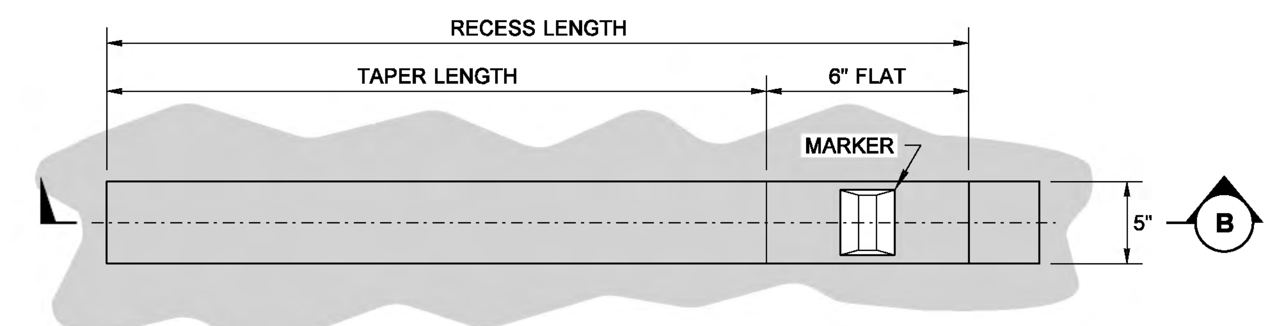
PLAN VIEW



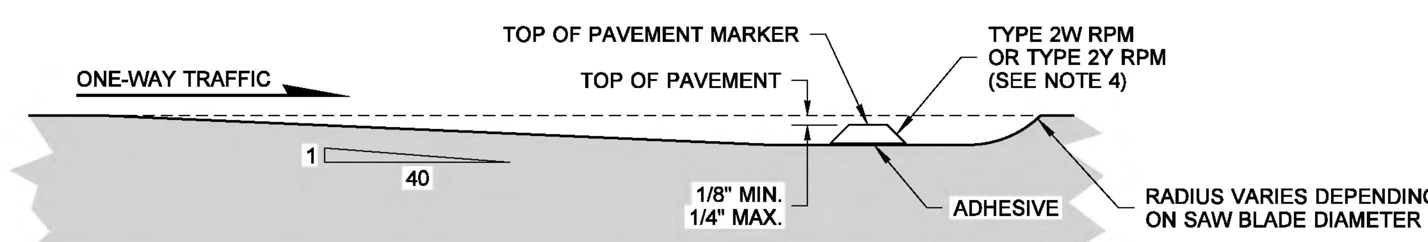
SECTION (A)

TWO-WAY ROADWAY RECESSED PAVEMENT MARKER DETAILS

FOR USE WHERE SPECIFIED IN CONTRACT



PLAN VIEW



SECTION (B)

ONE-WAY ROADWAY RECESSED PAVEMENT MARKER DETAILS

FOR USE WHERE SPECIFIED IN CONTRACT

LONGITUDINAL MARKING SUPPLEMENT WITH RAISED PAVEMENT MARKERS
STANDARD PLAN M-20.30-04

SHEET 2 OF 2 SHEETS

APPROVED FOR PUBLICATION

STATE DESIGN ENGINEER

Washington State Department of Transportation

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