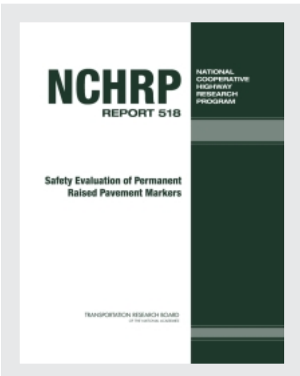


# Safety Evaluation of Permanent Raised Pavement Markers

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

# NCHRP REPORT 518

# Safety Evaluation of Permanent Raised Pavement Markers


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# FOREWORD

*By Charles W. Niessner*
*Staff Officer*
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This report presents the findings of a research project to evaluate the safety performance of snowplowable permanent raised pavement markers (PRPMs) on two-lane roadways and four-lane freeways. An analytical engineering procedure relying on safety performance functions or crash prediction models for roadways with and without PRPMs was developed to determine the potential cost-effectiveness of implementing PRPMs at a location. The report will be of particular interest to traffic engineers with responsibility for installing and maintaining pavement marking systems.

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PRPMs were introduced for centerline and skip line application as a traffic safety measure to provide more positive guidance for drivers in inclement weather and low-light conditions. These devices have been popular with highway agencies and have been widely used as supplemental delineation treatments to improve driver preview distances.

Studies in New York, Texas, and Pennsylvania have raised concerns about the relationship between PRPMs and crash rates. Specifically, the studies conducted in Texas and Pennsylvania indicated potential negative safety effects of these devices. These studies pertained to single jurisdictions only, and their results were questioned because of some identified data and methodological difficulties. In general, there have been few comprehensive and conclusive studies performed that quantify the safety effects of PRPMs.

Under NCHRP Project 5-17, "Safety Evaluation of Permanent Raised Pavement Markers," iTRANS Consulting, Ltd., undertook research to quantify the safety effects of PRPMs and to develop guidelines for their use. This study gathered data in six states (Illinois, Missouri, New Jersey, New York, Pennsylvania, and Wisconsin) to evaluate the safety performance of snowplowable PRPMs at nonintersection locations along two-lane roadways, four-lane expressways, and four-lane freeways.

Safety performance functions (or crash prediction models) were developed for various crash types: total, fatal and injury, nighttime, nighttime fatal and injury, daytime, daytime fatal and injury, wet weather, dry weather, and guidance-related. These safety performance functions (SPFs) served as a statistical tool to determine the overall effectiveness of PRPMs for particular crash types at the treatment locations.

Further disaggregate analysis, using regression techniques, investigated the relationship between the effect of PRPMs on nighttime crashes and various roadway, traffic, and PRPM design factors. The purpose of this disaggregate analysis was to determine some of the specific conditions under which PRPMs are effective or not in reducing crashes. The analysis showed the following:

- The nonselective implementation of PRPMs on two-lane roadways, overall, does not significantly reduce total or nighttime crashes, nor does it significantly increase these crash types. At locations where PRPMs were implemented on the basis of selective policies (i.e., poor crash history, among other criteria), the analyses produced mixed results. Positive effects were found in New York for total and nighttime crashes where PRPMs were installed at locations selected on the basis of the wet weather nighttime crash history. Similar safety effects were not found in Pennsylvania, where PRPMs were implemented at locations selected on the basis of total nighttime crash history. The analysis results have also revealed that selective implementation of PRPMs requires a careful consideration of traffic volumes and roadway geometry (i.e., degree of curvature). At low volumes (annual average daily traffic [AADT] < 5,000 veh/day), PRPMs can in fact be associated with a negative effect, which is magnified by the presence of sharp curvature. For example, for PRPMs installed on roadways with AADTs ranging between 5,000 and 15,000 veh/day and with a degree of curvature greater than 3.5, an increase of nighttime crashes of 26 percent can be estimated from the model.

- Overall, the installation of PRPMs at noninterchange locations on four-lane freeways showed neither a positive nor a negative overall safety effect on total and nighttime crashes. However, some significant reductions were recorded for wet weather crashes at those locations on four-lane freeways, and there are indications that PRPMs are only effective in reducing nighttime crashes where the AADT exceeds 20,000 veh/day.
- Because of data-intrinsic constraints, it was not viable to perform a sound safety assessment of the effect of PRPMs on four-lane expressways.

The results obtained from the disaggregate analyses were used to develop guidelines for the use of snowplowable PRPMs for two-lane roadways and four-lane freeways. The guidelines are based on a two-step procedure. First, the expected safety benefit after the installation of PRPMs is determined in relation to the expected reduction in future nighttime crashes. Second, a positive expected safety effect is followed by an analytical engineering procedure relying on safety performance functions or crash prediction models for roads with and without PRPMs to determine the potential cost-effectiveness of implementing PRPMs at a location. The guidelines are discussed in the context of the present "Manual on Uniform Traffic Control Devices" (MUTCD), and modifications are proposed for future editions.

# CONTENTS

# SAFETY EVALUATION OF PERMANENT RAISED PAVEMENT MARKERS


## SUMMARY

### S.1 BACKGROUND AND OBJECTIVE

Permanent raised pavement markers (PRPMs) are delineation devices that are often used to improve preview distances and guidance for drivers in inclement weather and low-light conditions. Recent studies in New York, Texas, and Pennsylvania have raised concerns about the safety effects of PRPMs after potential negative side effects were reported. These studies pertained to single jurisdictions only, and their results were questioned because of some identified data and methodological difficulties. NCHRP Project 5-17 responds to the need to use state-of-the-art analytical methods and extensive data to comprehensively assess the safety effects of PRPMs and to identify critical design parameters. The primary objectives of NCHRP Project 5-17, as presented in the project statement, are "to assess the safety effects of permanent raised pavement markers (PRPMs) and to develop guidelines for their use."

An empirical Bayesian before-and-after safety evaluation methodology was selected to address methodological issues and challenges associated with previous efforts undertaken to evaluate PRPMs. The methodological issues and challenges (e.g., regression to the mean and traffic volume changes) were identified during a comprehensive literature review of previous PRPM evaluation studies. In total, 29 states were surveyed by iTRANS and assessed for possible inclusion in the study. Six states were selected on the basis of their ability to provide the necessary crash, traffic volume, roadway attribute, and PRPM installation data required to perform the evaluation study. This study gathered data to evaluate the effects of snowplowable PRPMs on nonintersection crashes on a representative sample of two-lane roadways, four-lane expressways, and four-lane freeways in the states of Illinois, Missouri, Pennsylvania, New York, Wisconsin, and New Jersey. Because of data-intrinsic constraints that were proved impossible to overcome despite all efforts by the research team, it was not viable to perform a sound safety assessment of the effect of PRPMs on four-lane expressways.

### S.2 STUDY METHODOLOGY

Safety performance functions (or crash prediction models) were developed for various crash types: total, fatal and injury, nighttime, nighttime fatal and injury, daytime,

daytime fatal and injury, wet weather, dry weather, and guidance-related. These safety performance functions (SPFs) served as a statistical tool to determine the overall effectiveness of PRPMs for particular crash types at the PRPM treatment locations.

Further disaggregate analysis, using regression techniques, investigated the relationship between the effect of PRPMs on nighttime crashes and various roadway, traffic, and PRPM design factors. The purpose of this disaggregate analysis was to determine some of the specific conditions under which PRPMs are effective in reducing crashes or vice versa.

### S.3 DISCUSSION OF RESULTS

The analysis showed that the nonselective implementation of PRPMs on two-lane roadways, overall, does not significantly reduce total or nighttime crashes, nor does it significantly increase these crash types. On the other hand, for those locations where PRPMs were implemented on the basis of selective policies (i.e., poor crash history, among other criteria), the analyses produced mixed results. Positive effects were found in New York for total and nighttime crashes where PRPMs were installed at locations selected on the basis of the wet weather nighttime crash history. Similar safety effects were not found in Pennsylvania, where PRPMs were implemented at locations selected on the basis of total nighttime crash history. The analysis results have also revealed that selective implementation of PRPMs requires a careful consideration of traffic volumes and roadway geometry (degree of curvature). At low volumes (where the annual average daily traffic [AADT] is less than 5,000 vehicles per day [veh/day]), PRPMs can in fact be associated with a negative effect, which is magnified by the presence of sharp curvature. For example, for PRPMs installed on roadways with AADTs ranging between 5,000 and 15,000 veh/day and with a degree of curvature greater than 3.5, an increase of nighttime crashes of 26 percent can be estimated from the model.

Overall, the installation of PRPMs at noninterchange locations on four-lane freeways showed neither a positive nor a negative overall safety effect on total and nighttime crashes. However, some significant reductions were recorded for wet weather crashes at locations on four-lane freeways, and there are indications that PRPMs are only effective in reducing *nighttime* crashes where the AADT exceeds 20,000 veh/day.

The results from the disaggregate analyses were used to develop guidelines for the use of snowplowable PRPMs for two-lane roadways and four-lane freeways. The guidelines are based on a two-step procedure. First, the expected safety benefit after the installation of PRPMs is determined in relation to the expected reduction in future nighttime crashes. Second, a positive expected safety effect is followed by an analytical engineering procedure relying on safety performance functions or crash prediction models for roads with and without PRPMs to determine the potential cost-effectiveness of implementing PRPMs at a location. The guidelines were discussed in the context of the present "Manual on Uniform Traffic Control Devices" (MUTCD), and modifications are proposed for future editions.

CHAPTER 1

# INTRODUCTION

Fifty-seven percent of the 37,795 fatal crashes in the United States during 2001 occurred on two-lane undivided highways, compared with just 6.1 percent of fatal crashes that occurred on four-lane divided highways (*1*). Over one-third of the fatal crashes on two-lane undivided highways and 27 percent of the fatal crashes on four-lane divided highways occurred during dark or unlighted conditions. The majority of those crashes involved only one vehicle. Any safety measure that has the potential to increase visibility and assist drivers in staying within their lanes should therefore be given serious consideration.

Pavement markings and other delineation devices provide drivers with information about their position within their own lane and information about which lanes are available for their use, especially at night. In addition, delineation devices provide the driver with a preview of upcoming changes in the roadway geometry, including curves, lane drops, narrowing, the start and end of passing zones, crosswalks, and intersections. Permanent raised pavement markers (PRPMs) are delineation devices that are often used for centerline, lane divider line, and, more rarely, edgeline applications to improve preview distances and guidance for drivers in inclement weather and low-light conditions.

Recent studies in New York, Texas, and Pennsylvania, which are discussed in Chapter 2, have raised concerns about the safety effects of PRPMs after potential negative side effects were reported. These studies are among the few that have been performed to date to determine the effect of PRPMs on highway safety. These studies pertained to single jurisdictions only, and their results were questionable because of some data and methodological difficulties. NCHRP Project 5-17 responded to the need to use state-of-the-art analytical methods and comprehensive data to assess the safety effects of PRPMs and to identify critical design parameters. The primary objectives of NCHRP Project 5-17, as presented in the project statement, were "to assess the safety effects of permanent raised pavement markers (PRPMs) and to develop guidelines for their use."

To achieve these objectives, data related to snowplowable PRPM, nonintersection locations along two-lane roadways, four-lane divided expressways, and four-lane freeways roadways from six U.S. states (Illinois, Missouri, Pennsylvania, New York, Wisconsin, and New Jersey) were collected, aiming to undertake a statistically defendable analysis of their crash experience.

The six states were selected after undertaking a detailed survey of PRPM implementation practices and an assessment of data availability (to support a safety evaluation of PRPMs) in 29 U.S. states with known PRPM installations.

A review of literature pertaining to past research on the safety effect of PRPMs and a survey of current PRPM implementation practices were undertaken during the first quarter of 2002. The literature review identified critical design parameters, data requirements, methodological issues, and challenges. These were carefully studied before the formulation and implementation of the study design.

A literature review of the human factor issues pertaining to PRPMs was executed. The knowledge from these past research studies was used in the interpretation of the safety evaluation results and the development of PRPM implementation guidelines.

Two types of safety data analyses were performed: (1) a composite analysis that determined the overall effect of PRPMs, by state, for a number of different crash types (e.g., nighttime, wet weather, and guidance) and (2) a disaggregate analysis that investigated the relationships between the safety effect of PRPMs on nighttime crashes and a number of critical roadway, traffic, and PRPM design parameters. The results of these analyses were used to develop, in combination with human factors considerations, a comprehensive set of guidelines for the application of PRPMs, as well as an engineering procedure for estimating the anticipated cost-effectiveness of PRPMs at a particular location.

The body of this report has been structured into six additional chapters: the findings from the review of the PRPM-related literature and jurisdictional practices (Chapter 2), data collection and preparation (Chapter 3), safety impact analysis of PRPM installations (Chapter 4), a discussion of study results (Chapter 5), guidelines for the use of snowplowable PRPMs (Chapter 6), and study conclusions (Chapter 7).

CHAPTER 2

# REVIEW OF PRPM-RELATED LITERATURE AND JURISDICTIONAL PRACTICES

This chapter summarizes (1) the findings of a literature review of studies related to PRPMs and (2) the state of the practice according to state departments of transportation (DOTs) that responded to the iTRANS survey. Three sections make up this chapter. First, an overview of current PRPM guidelines and practices is provided. This overview is followed by a section that critically reviews the knowledge about the safety effect of PRPMs. The section also assesses methodological problems and issues arising from past research. This assessment sets the stage for the design of the current evaluation study. The third section reviews the human factors issues studied in past research efforts that may become relevant to the interpretation of the study results and formulation of guidelines for PRPM implementation.

## 2.1 OVERVIEW OF PRPM CURRENT PRACTICES

PRPMs were developed to provide delineation over a wider range of environmental conditions than could be achieved with standard pavement marking materials. Retroreflective PRPMs provide a clear, definitive outline of pavement markings even under adverse visibility conditions such as rain, fog, and darkness. Standard paint lines are ineffective during rainy conditions because rain often accumulates on the painted markings, thus reducing the retroreflectivity of the paint, whereas the raised pavement markers stand above the pooled water (*2*). Nonsnowplowable PRPMs are also effective in providing a "wake up call" for the driver who wanders out of the travel lane. The wake up call is created by the vehicle vibration and audible tone when crossing over the PRPMs. Currently, there are many types and models of pavement markers on the market, including both retroreflective and nonretroreflective types. PRPMs are developed with a variety of configurations and characteristics. Some markers are wedge shaped, and some are round or oval. Markers are available with and without replaceable retroreflective inserts, and the variations are numerous. Commercially available markers vary in all aspects, such as size, shape, composition, and capabilities. Snowplowable markers have also been developed to reduce the vulnerability of the marker to snowplow activity. In general, there are two main types of PRPMs: retroreflective and nonretroreflective. In addition, there are two subcategories of retroreflective PRPMs: conventional raised nonsnowplowable pavement markers and snowplowable pavement markers. Snowplowable markers can be either raised or recessed.

### 2.1.1 Nonretroreflective PRPMs

Nonretroreflective raised pavement markers, such as convex buttons, are made of plastic, ceramic, or aluminum. Nonretroreflective raised pavement markers are often used, in conjunction with retroreflective PRPMs, as an alternative to painted markings. The "Manual on Uniform Traffic Control Devices" (MUTCD) (*3*) provides guidelines on the spacing requirements of nonretroreflective PRPMs when used as a replacement to painted markings. The "Roadway Delineation Practices Handbook" (*2*) indicates that the nonretroreflective PRPMs will provide daytime visibility and the retroreflective PRPMs the nighttime visibility.

### 2.1.2 Retroreflective PRPMs

There are two types of retroreflectors: prismatic (also called cube-corner) and spherical lens (*4*). The marker that is most commonly installed today is the wedge-shaped, cube-corner retroreflector. Prismatic retroreflectors are manufactured with different face designs, and spherical lens retroreflectors are manufactured with different glass bead types. Changing either the face design or the glass bead type in retroreflectors can be expected to give different results for daytime and nighttime delineation. References such as ASTM F923-00 (*4*), the "Roadway Delineation Practices Handbook" (*2*), and the "Guidelines for the Use of Raised Pavement Markers" (*5*) provide guidance in the selection of appropriate markers.

The American Society for Testing and Materials (ASTM) has produced the following standard specifications:

- ASTM D 4383, "Standard Specification for Plowable, Raised Retroreflective Pavement Markers" (*6*), and
- ASTM D 4280, "Standard Specification for Extended Life Type, Nonplowable, Prismatic, Raised Retroreflective Pavement Markers" (*7*).

These specifications provide the performance requirements for pavement markers in terms of the coefficient of luminous intensity before abrasion, abrasion resistance, color, lens impact strength, adhesive bond strength, compressive strength, and ramp hardness of holders. These specifications also provide guidelines on how to test the performance of pavement markers.

Many states have developed special provisions and standard specifications for pavement markers that are generally based on the above ASTM specifications. While the ASTM specifications provide minimum and maximum values, state guidelines tend to identify more precise values that fall within the ranges of acceptable values specified in the ASTM guidelines.

For example, ASTM D 4383 specifies that the installed height of the casting shall not exceed 0.43 in. (10.9 mm) and shall not be less than 0.06 in. (1.5 mm) above the road surface, while the guidelines for the state of Illinois specify that the height should be 0.3 in. (7.6 mm) and the guidelines for the state of Maryland specify a maximum height of 0.25 in. (6.4 mm).

#### *2.1.2.1 Snowplowable Pavement Markers*

In the United States, there are two types of snowplowable pavement markers: raised and recessed. According to the iTRANS state surveys and literature reviews, recessed markers are not as popular as raised markers are. Some of the states that have installed or are currently installing recessed markers are Kansas, Maine, Maryland, Oregon, Virginia, West Virginia, and Pennsylvania. These states, with the exception of Oregon, also install raised snowplowable pavement markers. Illinois, Indiana, Massachusetts, Michigan, New York, Ohio, and Wisconsin almost exclusively use raised snowplowable markers.

Hofmann and Dunning (*8*) found that, although recessed snowplowable markers last on average 12 months longer than raised snowplowable pavement markers, they do not perform as well as raised markers. This finding confirms Endres's (*9*) conclusion that raised pavement markers out-perform recessed markers under dry and wet weather conditions.

A variety of problems are associated with recessed markers because the collection of debris, rain, and snow in the recessed slots obscure the reflective surface of the markers. Pigman and Agent (*10*) evaluated the performance of recessed snowplowable markers by observing the marker's visibility during snow and ice conditions. It was found that following snowplow operations, the groove retained snow and ice. However, because of the passing traffic, the snow and ice melted and the water was swept away in a short period of time. Pigman and Agent observed that vehicle tires cleansed the top third of the marker, but the bottom portion remained obscured. It was concluded that although nighttime visibility was reduced, the recessed markers remained visible.

Some states have evaluated the performance of recessed markers. The state of Maine ceased the installation of recessed markers because when the recessed grooves become filled with snow and ice, the markers are ineffective. Investigations by the Pennsylvania DOT (PennDOT) found that recessed markers on downgrades are not as visible as recessed markers on inclines if water accumulates in the recessed slots. As a result, PennDOT has decided to stop the installation of recessed markers on its roadways.

#### *2.1.2.2 Nonsnowplowable Pavement Markers*

Raised nonsnowplowable markers are used extensively in states where snowfall is not a concern, such as Texas and California. Other states—such as Illinois, New Jersey, Oregon, Michigan, Maryland, and Massachusetts—use only snowplowable pavement markers.

### 2.1.3 Implementation Criteria and Maintenance Procedures

States extensively use the MUTCD (*3*) and FHWA's "Roadway Delineation Practices Handbook" (*2*) as guides for the implementation of PRPMs. The MUTCD mainly provides guidelines on the desired spacing of PRPMs, while the "Roadway Delineation Practices Handbook" also provides general guidelines on PRPM colors, materials, installation, and maintenance procedures. The "Roadway Delineation Practices Handbook" provides guidelines on the desired layout of PRPMs for various roadway infrastructure elements (e.g., curves, intersections, and tangents ramps) on different roadway types (e.g., two-lane roadways, four-lane undivided roadways, and four-lane divided roadways). According to these guidelines, the spacing between consecutive PRPMs on tangents should be 80 ft (24 m). For horizontal curves between 3 and 15 degrees, a spacing of 40 ft (12 m) is recommended. For curves greater than 15 degrees, the recommended spacing is 20 ft (6 m). It is not recommended that centerline and edgeline PRPMs be used together because this may create confusion on some sharp curves. Most states, in accordance with these guidelines, install one two-way yellow marker on the centerline of two-lane roadways only. In some states, such as Illinois and Pennsylvania, a group of two markers can be used on the centerline of high-volume, high-speed, two-lane roads. On divided multilane facilities, the most common practice in the iTRANS states surveyed during this current research study is to install one-way white PRPMs on the lane lines only. An exception is New Jersey, where PRPMs are also installed on the left edgelines of multilane facilities.

States have developed PRPM installation criteria. In the states of Ohio, Texas, and California, PRPMs are installed nonselectively on all state-maintained highways. Other states—such as Maryland, Massachusetts, Wisconsin, Pennsylvania, Illinois, Indiana and Kansas—have a combination of selective and nonselective implementation practices. PRPMs are implemented nonselectively on certain roadway types, such as freeways, and selectively on other roadway types on the basis of one or more of the following parameters:

- Roadway type,
- Traffic volume,
- Illumination,
- Safety record,
- Speed limits, and
- Horizontal curves.

For example, Maryland implements PRPMs nonselectively on all Interstate highways and other freeways. Maryland, Massachusetts, and Wisconsin use the speed limit of a roadway as a primary criterion for deciding where to implement PRPMs. In Maryland, PRPMs are implemented on all two-lane roadways that have a speed limit exceeding 45 mph (72 km/h), irrespective of the traffic volume. In Massachusetts, PRPMs are installed on undivided roadways that have a speed limit of 50 mph (80 km/h) or greater. In Wisconsin, PRPMs are installed on all roadways that have a speed limit of more than 65 mph (100 km/h), which includes all multilane freeway facilities.

Missouri, Pennsylvania, and Massachusetts implement PRPMs on all freeways. Michigan's PRPM guidelines recommend implementation on all freeways that lack roadway illumination.

The criteria for implementing PRPMs in Illinois, Indiana, and Kansas relate to traffic volume thresholds for different roadway types. PRPMs are only installed on roadways where the average daily traffic (ADT) volumes exceed these thresholds. Table 2-1 provides a summary of the traffic volume thresholds for different roadway types.

The majority of surveyed states implement PRPMs at locations with actual or potentially poor safety records. In Maryland, PRPMs are implemented where the crash rate for "correctable" guidance-related crashes is significantly higher than the statewide average on similar road types. In Indiana, site selection for the implementation of PRPMs is based primarily on the need for additional alignment delineation in areas of frequent inclement weather (e.g., fog, smoke, and rain); low roadway illumination; and evidence of vehicles leaving the roadway, such as excessive wear of pavement markings or excessive skid marks. In Michigan, PRPMs are installed only on nonfreeways where there is a concentration of crashes and only after other countermeasures such as signing, pavement markings, and roadside delineation (e.g., chevrons and post-mounted delineators) have been unsuccessful in improving the safety of the locations.

Illinois and Maryland install PRPMs at horizontal curves where it is necessary for motorists to decrease their travel speed by more than 10 mph (16 km/h) in order to traverse the curve safely.

Some states implement PRPMs at other cross-section elements. For example, Illinois installs PRPMs at lane reduction transitions; freeway gores; rural left-turn lanes; and two-way, left-turn lanes. Maryland has detailed standard design drawings for PRPM installations at one-lane bridges; intersection approaches; two-way, left-turn lanes; left-turn lanes; acceleration lanes; deceleration lanes; and lane transitions.

One of the primary maintenance problems with retroreflective PRPMs is maintaining the reflectivity level. The reflectivity retention of retroreflective PRPMs tends to depend mostly on cumulative vehicular exposure since the time of installation (*11*). A study by Ullman (*12*) evaluated several models of corner-cube reflectors for factors such as volume of vehicle exposure, degradation in reflectivity, damage, and missing percentages. The "Roadway Delineation Practices Handbook" (*2*) states that it is difficult to precisely predict the service life of retroreflective PRPMs.

In response to the iTRANS state practices survey, some states provided information on their PRPM maintenance practices. Pennsylvania and Ohio replace PRPM lenses on a fixed 2-year and 3-year cycle, respectively. In some states, the replacement cycle depends on the roadway type and traffic volume. Table 2-2 shows the PRPM replacement cycle for Indiana. Texas provides guidelines for when to schedule the maintenance of PRPMs based on the results of a nighttime test inspection (Table 2-3). The replacement cycle of PRPMs in Texas, based on ADT volumes, is summarized in Table 2-4. Colorado and Iowa removed all existing PRPMs and interrupted any future installations because of the high maintenance costs.

**TABLE 2-1 PRPM guidelines based on traffic volume for different roadway types (source: iTRANS state practices survey)**

| State | Guidelines for rural two-lane roadways | Guidelines for multilane roadways |
|---|---|---|
| Illinois | ADT > 2,500 veh/day | ADT > 10,000 veh/day |
| Indiana | ADT > 2,500 veh/day | ADT > 6,000 veh/day |
| Kansas | ADT > 3000 veh/day and TADT > 450 veh/day | |

ADT = Average daily traffic (both directions).
TADT = Truck average daily traffic.

**TABLE 2-2 PRPM replacement cycle for the state of Indiana**

| Number of lanes | ADT (veh/day) | Replacement cycle (years) |
|---|---|---|
| Two | Fewer than 5,000 | 4 |
| | 5,000 to 15,000 | 3 |
| | More than 15,000 | 2 |
| Four or more | Fewer than 10,000 | 4 |
| | 10,000 to 30,000 | 3 |
| | 30,000 to 75,000 | 2 |
| | More than 75,000* | 2 |

* These roadways should be inspected at least once each year.

## 2.2 REVIEW AND ASSESSMENT OF KNOWLEDGE ABOUT THE SAFETY EFFECT OF PRPMS

This section critically reviews literature before summarizing any methodological problems arising from past research. The literature review focuses on the relatively few studies that have been conducted from about 1980 to date, since older studies are less likely to be relevant in terms of findings and methodologies employed.

### 2.2.1 Review of Literature

Seven evaluation studies were reviewed and are summarized herein.

The first study to be reviewed was undertaken by Wright et al. (*13*). This study evaluated the safety effects of reflective raised pavement markers in Georgia. From 1976 to 1978, the Georgia DOT installed reflectorized pavement markers (both raised and recessed markers) on the centerlines of 662 horizontal curves, all of which were in excess of 6 degrees of curvature. At some locations, warning signs, chevron markers, or other delineation devices that were intended to provide guidance to drivers were also installed. These additional devices may have affected the analysis's results. For each curve studied, the location, length, degree of curvature, year of installation, ADT by year, and annual crash frequency by type (single-vehicle or other) and time of day (day or night; daytime: 6:00 a.m. to 5:59 p.m.) were collected. Locations were monitored 200 ft (61 m) in both directions beyond the curve in the belief that curve-related, single-vehicle crashes often take place beyond the end points of curves.

**TABLE 2-3 When to schedule PRPM system maintenance for the state of Texas (based on nighttime inspection)**

| For markers spaced at… | Maintenance should be scheduled as soon as possible if… |
|---|---|
| 80 ft (24 m) | Fewer than two markers are visible |
| 40 ft (12 m) | Three or fewer markers are visible |

**TABLE 2-4 Suggested replacement cycles for PRPMs for the state of Texas**

| ADT (veh/day) | Replacement cycle (years) |
|---|---|
| More than 50,000 | 1 |
| More than or equal to 10,000 | 2–3 |
| Fewer than 10,000 | 3–4 |

The study examined the change in nighttime crashes (from 6:00 p.m. to 5:59 a.m.) and used daytime crashes at the same sites as a control group. In the crash data from 1975 to 1980, there were 223 before-installation crashes and 391 after-installation crashes at the selected sites. For approximately 68 percent of the sites, no crashes were reported for the 6 years of data analyzed. A log-linear model was fit to the data stratified by the year of installation, daytime-versus-nighttime crashes, and before-versus-after installation time period. Overall, nighttime crashes were estimated to have been reduced by 22 percent compared with daytime crashes at the same sites.

A disaggregate analysis by year of installation revealed that sites modified in 1976 and 1977 had reductions of 33 percent and 32 percent, respectively. However, sites modified in 1978 showed a 53-percent *increase* in nighttime crashes, an effect that could not be explained. Perhaps sites most worthy of PRPM installation, and therefore most likely to yield safety benefits, were treated earlier in the program. Single-vehicle crashes were estimated to have been reduced by 12 percent more than other nighttime crash types were. These reductions were found to be independent of ADT and curvature, although it should be remembered that all curves had at least 6 degrees of curvature.

Kugle et al. (*11*) collected 2 years of before data and 2 years of after data at 469 Texas locations varying in length from 0.2 to 24.5 miles (0.32 to 39.4 km). PRPMs were installed between 1977 and 1979. Sixty-five percent of the locations were on two-lane roads; 33 percent on four-lane roads; and the remaining on three-, five-, or six-lane roads. Seventeen sites were subsequently omitted from analysis because they were resurfaced after PRPM installation, which would likely have influenced crash risk. Crashes were subclassified for analysis by wet weather/dry weather, daytime/nighttime, and fatal/injury/property-damage-only (PDO). Comparison of wet-versus-dry crashes excluded conditions such as muddy and snowy, but these crashes were included in the total nighttime-versus-daytime analysis. Daytime crashes included daytime, dawn, and dusk crashes, while nighttime crashes included crashes with and without street lighting present. Crash types potentially affected by PRPMs—namely head-on, sideswipe, and run-off-road—were identified for a separate analysis. In addition, ADT and the number of wet weather days were recorded for each location during the analysis periods. Three evaluation methods were used and are described below.

The first evaluation method involves calculating the cross-product ratio as an overall measure of effectiveness. This method aggregates data from all sites and does not consider noncrash factors, such as ADT. The cross-product ratio measures the relative change in the crash type of interest compared with a control group of crashes believed not to be affected by the measure of interest. The control group can therefore be used to control for factors such as changes in ADT and other changes over time that affect crash risk. Nighttime crashes were compared with daytime crashes and wet weather crashes compared with dry weather crashes. Using nighttime-versus-daytime crashes for illustration, the cross-product ratio, $T$, is calculated as

$$T = \frac{x_{11}x_{22}}{x_{12}x_{21}} \qquad (2\text{-}1)$$

Where

$x_{11}$ = Crashes in the after period during nighttime,
$x_{12}$ = Crashes in the before period during nighttime,
$x_{21}$ = Crashes in the after period during daylight, and
$x_{22}$ = Crashes in the before period during daylight.

The change in crash frequency due to treatment is estimated as

$$\text{Percent Change} = 100(T - 1) \qquad (2\text{-}2)$$

The second method, called Gart's procedure, calculates the cross-product ratio at each individual location and weights each estimate by the total number of crashes at each site for a weighted average estimate of treatment effectiveness. This allows the higher-crash locations to exert more influence on the estimated effectiveness.

The third method uses logistic regression, which can include the influence of factors other than the PRPMs in the estimation of effectiveness. The probability of an individual location experiencing a nighttime crash is modeled as a function of time (before or after installation), ADT, and number of lanes. This procedure provides an estimate of effectiveness adjusted for site differences in ADT and number of lanes. Kugle et al.'s analysis of wet weather crashes also included the number of wet weather days as a variable in the model (*11*).

The results of the three methods provided different numeric results, but all methods indicated the same trend for all crash types. The cross-product analysis indicated a 15-percent increase in nighttime crashes and a nonsignificant 1.4-percent decrease in wet weather crashes. Gart's procedure indicated a 31-percent increase in nighttime crashes and a nonsignificant 1-percent decrease in wet weather crashes. Logistic modeling also indicated a significant increase in nighttime and a nonsignificant decrease in wet weather crashes. These effects were found to be consistent for all crash and severity types with the exception of wet weather sideswipe crashes, which showed a nonsignificant increase. The authors noted that roughly half of the sites showed a reduction in both nighttime and wet weather crashes, but roughly 10 percent of the sites showed very large increases in total crashes, which may have unfairly skewed the overall results.

Mak et al. (*14*) conducted a study using the same Texas locations as Kugle et al. (*11*) to reevaluate the safety effect of PRPMs on nighttime crashes. This study screened the original database of 469 locations and eliminated those that underwent major modifications other than the PRPM installation during the evaluation period, modifications that may have influenced the previous study results. Several other locations were not included in the new analysis because they experienced no crashes in either the 2-year before period or the 2-year after period. After screening for these criteria, only 87 of the original 469 locations remained for further analysis. The new analysis focused on individual locations. The daytime crashes were again used as a comparison group to account for any factors that may have influenced crash frequency between the before and after periods but that were not related to the PRPM installation. However, daytime crashes did not include crashes occurring during dusk or dawn; dusk and dawn crashes that were eliminated from the analysis were reported to be about 1–3 percent of the total crashes. A statistical procedure, based on the cross-product ratio, was used to measure the effect of PRPMs at individual locations, $Z$. This procedure is based on a test statistic:

$$Z = \frac{\ln(T)}{\sqrt{1/x_{11} + 1/x_{12} + 1/x_{21} + 1/x_{22}}} \qquad (2\text{-}3)$$

Where

$$T = \frac{x_{11}x_{22}}{x_{12}x_{21}},$$

$x_{11}$ = Crashes in the after period during nighttime,
$x_{12}$ = Crashes in the before period during nighttime,
$x_{21}$ = Crashes in the after period during daylight, and
$x_{22}$ = Crashes in the before period during daylight.

$Z$ was calculated for each location. If there are no safety effects, $Z$ will be normally distributed with a mean of 0 and a variance of 1. A positive value of $Z$ would indicate an increase in nighttime crashes relative to daytime crashes, a negative value indicates a relative decrease, and a value of zero indicates no change. Of the 87 locations, 56 (64.4 percent) showed a relative increase in nighttime crashes, 30 (34.5 percent) showed a relative decrease, and 1 (1.1 percent) showed no change. Using a confidence level of 10 percent to check for significance, 4 locations (4.6 percent) showed significant reductions in nighttime crashes relative to daytime crashes, 9 (10.3 percent) showed significant increases, and 74 (85.1 percent) showed nonsignificant changes in nighttime crashes relative to daytime crashes.

The effect of PRPMs on crash severity was also studied at 37 locations that had a minimum of 30 crashes in the before or after period or in the two periods combined. Two severity indexes were calculated for each site separately for nighttime and daytime crashes:

- Severe = (percent fatal or incapacitating-injury crashes in after period) – (percent fatal or incapacitating-injury crashes in before period).
- Injury = (percent fatal, incapacitating-injury, or non-incapacitating-injury crashes in after period) – (percent fatal, incapacitating-injury, or non-incapacitating-injury crashes in before period).

A logit model was then used to test for statistically significant differences using the daytime crashes as a comparison group. None of the 37 sites showed a significant change in the percentage of severe crashes, perhaps due to low numbers of these crashes. For injury crashes, 4 locations showed a significant decrease in nighttime crash severity, 1 showed a significant increase, and 32 showed no significant change.

Locations that showed a significant increase (nine total) or decrease (four total) in crash frequency were further examined in an attempt to identify crash characteristics that might be associated with PRPMs. Not enough data were available for statistical tests, but an examination of the relative proportions between the before and after periods indicated that for the sites showing a significant increase in crashes, the proportion of nighttime multivehicle crashes increased and the proportion of nighttime fixed-object crashes decreased. For the locations showing a significant decrease in crashes, this same increase in multivehicle crashes and decrease in fixed-object crashes was found for the daylight hours but not for nighttime hours. For both groups, the proportion of nighttime crashes occurring on horizontal curves greater than 2 degrees increased.

A number of roadway characteristics were also examined for their effect on the influence of PRPMs using the same groups of nine (significant increase) and four sites (significant decrease), but no strong evidence that any of the variables interacted with PRPM installation was found. The examined characteristics included the following:

- Intersection type (none, interchange, T-intersection, four-leg intersection, or multiple intersection),
- Whether the roadway was within the city or outside the city,
- Horizontal curvature (less than 1 degree, 1 to 3 degrees, or more than 3 degrees),
- Grade (less than 3 percent or more than 3 percent),
- Structures (none, culvert, or bridge),
- Number of lanes (less than or equal to four, or more than four), and
- Whether the roadway was divided or undivided.

Griffin (*15*) analyzed the same data as Mak et al. (*14*), which is a subset of the Texas data originally used by Kugle et al. (*11*) using a different statistical approach. Griffin quantified the safety effect of PRPMs on nighttime crashes at 86 locations using daytime crashes as a control group. One of the locations used in the previous analysis was not included in this study because it could not be located. The overall, or average, effect of PRPM installation on nighttime crashes was estimated by calculating a weighted log odds ratio. The log odds ratio, $L$, is calculated by taking the natural logarithm of $T$, defined previously in Equation 2-1.

The weight for the log odds ratio at each site, $w$, is calculated as

$$w = \frac{1}{(1/x_{11} + 1/x_{12} + 1/x_{21} + 1/x_{22})} \quad (2\text{-}4)$$

Where

$x_{11}$ = Crashes in the after period during nighttime,
$x_{12}$ = Crashes in the before period during nighttime,
$x_{21}$ = Crashes in the after period during daylight, and
$x_{22}$ = Crashes in the before period during daylight.

The weighted log odds ratio, $L_{avg}$, is thereafter calculated as

$$L_{avg} = \frac{\sum wL}{\sum w} \quad (2\text{-}5)$$

Where

$L = \ln(T)$

The average effect is equal to the antilogarithm of $L_{avg}$, and the standard error of $L$, $L_{se}$, is equal to

$$L_{se} = \frac{1}{\sum \sqrt{w}} \quad (2\text{-}6)$$

Using this methodology, the expected change in nighttime crashes following the installation of PRPMs was estimated to be a 16.8-percent increase, with the 95-percent confidence limits between a 6.4- and 28.3-percent increase.

Pendleton (*16*) used both "classical" and empirical Bayes before-and-after methods for evaluating the effect of PRPM nighttime crashes on undivided and divided arterials in Michigan. Seventeen locations totaling 56 miles (90 km) served as installation sites, and 42 sites totaling 146 miles (235 km) were used as control sites where PRPMs were not installed. Crash data for 2 years prior to installation and 2 years after installation were used for two categories of analysis. The first category used as a control group daytime crashes at the installation sites, which were assumed to be unaffected by the installation of PRPMs. Daytime crashes did not include crashes that occurred 1 hour before and 1 hour after both sunrise and sunset, a total of 4 hours per day. The second category used nighttime crashes at control sites as a control group. Pendleton made the following conclusions:

- Undivided roadways showed an increase in nighttime crashes and divided roadways showed a decrease in nighttime crashes when analyzed separately. Whether a highway was divided was concluded to be the most significant road characteristic affecting the effectiveness of PRPMs.
- Using daytime crashes at treated sites as a comparison group yielded larger reductions (or smaller increases) in crashes than when nighttime crashes at untreated sites were used as a comparison group. The issue of which comparison group to use stayed unresolved.
- The empirical Bayes methodology generally produced smaller reductions (or larger increases) than the simple or "classical" before-and-after methodology. This conclusion usually is an indication that regression-to-the-mean was at play and accounted for by the empirical Bayes methodology.
- Exposure should be properly accounted for, and the researchers lamented the fact that the estimates of nighttime traffic volume were only approximations. The study also revealed the difficulties of using crash rates (crashes per unit of exposure) to control for exposure differences. These difficulties arise from the nonlinear relationship between crashes and exposure that indicates that these rates can change because of volume changes and not necessarily because of a treatment.

New York State DOT (*17*) undertook a safety assessment of PRPMs in New York to review the DOT's policy on PRPM installation. The DOT used a simple before-and-after study design in which numbers of crashes before and after treatment were compared without controlling for other factors. Two analyses were undertaken using this simple before-and-after design. The first analysis, at 20 sites, targeted PRPMs at sections of unlit suburban and rural roadways with proportionately high numbers of nighttime and nighttime wet weather crashes. Overall, there was a nonsignificant decrease of 7 percent for total crashes, a highly significant decrease of 26 percent for nighttime crashes, and a significant decrease of 33 percent for nighttime wet weather crashes. Furthermore, there was a significant reduction of 23 percent in all guidance-related crashes, which are crashes resulting from a vehicle leaving its assigned travelway (e.g., run-off-road, head-on, encroachment, and sideswipe). There was also a 39-percent reduction in nighttime guidance-related crashes.

The second analysis looked at PRPMs installed non-selectively over 50 long sections of highway. The analysis revealed that nighttime crashes were reduced by a nonsignificant 8.6 percent, that total crashes were reduced by a statistically significant 7.4 percent, and that nighttime wet weather crashes increased by a nonsignificant 7.4 percent. Thus, New York State DOT recommended that PRPMs be installed selectively "when their use is likely to reduce crash frequency cost effectively by improving delineation during nighttime wet weather conditions." It further stated that PRPMs should be installed only at locations having high frequencies of wet weather, nighttime, guidance-related crashes.

Orth-Rodgers and Associates, Inc. (*18*), used the same "odds ratio" methodology as Griffin (*15*) to evaluate the effects of both raised and recessed pavement markers on nighttime crashes at 91 Interstate highway locations in Pennsylvania. PRPMs were installed at these sites between 1992 and 1995, and crash data from 1991 to 1996 were used in the analysis. Daytime crashes at the same sites were used as a comparison group. Sites that had no crashes in any of the daytime or nighttime periods before or after PRPM installation were eliminated since a zero value would render the odds ratio meaningless. This omission creates a subtle bias toward underestimation of effects if the realization of zero crashes at a site in the after period is due to PRPM installation. This underestimation is exaggerated by the fact that the after periods were, on average, much shorter than the before periods and were therefore more likely to contain zero crashes. Sites in urban and lit areas were also eliminated, assumed by the authors as "not good candidates for an analysis of this type."

Several crash types were excluded because they were considered to be unrelated to PRPMs (e.g., crashes that happened during dusk, dawn, or unknown lighting condition; crashes that occurred in weather conditions other than rain or "no adverse conditions"; crashes that occurred when the road surface condition was other than dry or wet; and crashes for which the impact type was "unknown").

Results indicated a 12.3-percent increase in nighttime crashes (95-percent confidence limits of 1.1 and 24.8 percent) for all sites, a nonsignificant 1.2-percent decrease for locations with raised pavement markers, and a significant 20.1-percent increase (95-percent confidence limits of 5.5 and 36.9 percent) for locations with recessed pavement markers. The authors suspected that the small decrease in nighttime crashes due to raised PRPMs might have been because there was a positive effect (i.e., a reduction in crash frequency) on the daytime crashes that was used for the comparison group.

Additional results were obtained for two crash subsets. Nighttime wet condition crashes also showed large increases from 30 to 47 percent (confidence limits not reported), depending on the comparison group of crashes used (daytime wet condition, nighttime other, or all daytime crashes). Nighttime wet road sideswipe and fixed-object crashes were estimated to have increased 56.2 percent (confidence limits not reported) using nighttime dry road sideswipe and fixed-object crashes as a comparison group. Not much emphasis was placed on these additional results since these increases could be exaggerated by a positive effect of PRPMs on the comparison sites.

Table 2-5 summarizes the review of seven relevant evaluations of the safety effects of PRPMs, measured in terms of reductions or increases in crashes (two of the seven studies are re-analyses of subsets of data previously analyzed). All but one of the studies listed in Table 2-5 used daytime crashes

**TABLE 2-5 Summary of literature on the safety effectiveness of PRPMs**

| Study Ref. /Location | Site Type | Installation Location | I – Installation Period B – Before-Period Length A – After-Period Length | Sample Sizes for Treatment and Comparison Groups | Dependent Variable | Independent Variables Analyzed | Comparison Group | Other Notes | Estimated Effects |
|---|---|---|---|---|---|---|---|---|---|
| Wright et al. 1982 (*13*) *Georgia* | Horizontal curves on two-lane highways in excess of 6 degrees of curvature | Centerline | I – 1976-1978 B – 1 to 3 years A – 2 to 4 years | Treatment – 662 locations Comparison – same as treatment group | Total nighttime crashes | ADT, degree of curvature | Total daytime crashes | Both raised and recessed reflective markers were used; at some locations warning signs, chevron markers or other guidance devices were installed | 22% reduction in nighttime crashes; single-vehicle crashes reduced 12% more than other nighttime crashes; reductions independent of ADT or horizontal curvature for curves with degree of curve greater than 6 |
| Kugle et al. 1984 (*11*) *Texas* | Two-, three-, four-, five-, and six-lane roadways | Does not specify | I – 1977-1979 B – 2 years A – 2 years | Treatment – 452 locations Comparison – same as treatment group | Total nighttime crashes, some analysis by crash and severity | ADT, number of lanes, number of wet weather days | Total daytime crashes | None | 15 to 31% increase in nighttime crashes; no significant effect on wet weather crashes |
| Mak et al. 1987 (*14*) *Texas* | Two-, three-, four-, five-, and six-lane roadways | Does not specify | I – 1977-1979 B – 2 years A – 2 years | Treatment – 87 locations Comparison – same as treatment group | Total nighttime crashes, some analysis by crash and severity types | Intersection type, within/outside city, horizontal curvature, grade, structures, number of lanes, divided/ undivided | Total daytime crashes | Used a subset of the data from Kugle et al., 1984 (*11*) | 4.6% of locations wed significant reductions, 10.3% showed significant increases, 85.1% showed nonsignificant effects |
| Griffin, 1990 (*15*) *Texas* | Two-, three-, four-, five-, and six-lane roadways | Does not specify | I – 1977-1979 B – 2 years A – 2 years | Treatment – 86 locations Comparison – same as treatment group | Total nighttime crashes | None | Total daytime crashes | Used a subset of the data from Kugle et al., 1984 (*11*) | 16.8% increase in nighttime crashes, with the 95% confidence interval between a 6.4 and 28.3% increase. |
| Pendleton, 1996 (*16*) *Michigan* | Divided and undivided arterials | Centerline on undivided arterials, lane lines on divided arterials | I – 1989 B – 2 years A – 2 years | Treatment – 17 locations totaling 56.11 mi (90.3 km) Comparison – 42 locations totaling 146.28 mi (235 km) | Total nighttime crashes | Divided/ undivided and VMT (vehicle miles traveled) used in empirical Bayes analysis | Total daytime crashes, total nighttime crashes at comparison sites | None | No significant effect, direction of effect positive or negative dependent on method used and access control |
| New York State DOT, 1989, 1997 (*17, 19*) *New York* | Suburban and rural roadways | Does not specify | I – unknown B – unknown A – unknown | Selective Installation: Treatment – 20 locations totaling 26 mi (41.84 km) Comparison – none used Nonselective Installation: Treatment – 50 locations Comparison – none used | Total crashes, total nighttime crashes | None | None | Regression to the mean is cited as being a factor | 26% decrease in nighttime crashes when placed selectively, no significant effect when installed nonselectively |
| Orth-Rodgers and Associates, Inc., 1998 (*18*) *Pennsylvania* | Interstate highways in rural non-illuminated areas | Does not specify | I – 1992-1995 B – 1-3 years A – 1-3 years | Treatment – 33-76 locations depending on crash type studied Comparison – same as treatment group | Total nighttime crashes, nighttime wet road, nighttime wet road sideswipe fixed-object | None | Total daytime crashes, daytime wet road, daytime wet road sideswipe or fixed-object | Both raised and recessed reflective markers were used | 18.1% overall increase in nighttime crashes, nighttime wet condition crashes increased from 30 to 47%, nighttime wet road sideswipe or fixed-object increased by 56.2% |

as a comparison group for nighttime crashes, based on the assumption that only nighttime crashes would be affected by PRPMs. As discussed in Section 2.3, there is evidence that PRPMs affect driver behavior during daytime as well, manifested by changes in positioning in the lane and significant reductions in lane encroachments, which would be expected to impact both head-on and run-off-road crashes. Consequently, the use of daytime crashes as a comparison group is inappropriate. Table 2-5 shows both significant reductions and increases in crash frequency. Indeed, the two largest studies show opposing effects—one with 662 treatment locations (*13*) showing a 22-percent reduction in nighttime crashes, and the other with 452 treatment locations (*11*) showing a 15- to 31-percent increase in nighttime crashes. Re-analysis (*15, 14*) of the second study, with its troubling result, continued to show a statistically significant increase in nighttime crashes at some locations. As will be seen in Section 2.3, there are mixed findings with respect to speed and an indication that speed effects may be site specific. Changes in speed, along with the effects of PRPMs on daytime encroachments, may be factors in the mixed safety effects.

### 2.2.2 Methodological Problems in Past Research

The relative safety at any location is a function of all roadway, environmental, and driver characteristics. A change in any of these factors from the before to after period affects safety. In order to derive an accurate estimate of the safety effect of PRPM installations, it is important to separate the effect of other changes, including the changes described in the following sections.

#### *2.2.2.1 Changes in Traffic Volumes*

Safety directly relates to traffic volumes. As a result, the difference in traffic volumes between the before and after periods affects the expected difference in the number of crashes between the before and after periods. In most of the previous studies reviewed, traffic volumes were not accounted for explicitly. Daytime crashes have most often been used to control for changes in safety, on the assumption that these are unaffected by the PRPM installation. In the treatment-comparison experimental design used by several researchers, it was assumed that traffic volume changes are controlled for because the percentages of AADT during day and night should not change significantly in the before and after time periods (*18*). This may be a reasonable way of accounting for traffic volume changes if this assumption is met, providing that the changes are small and that the relationship between crashes and traffic volume is approximately linear. In the studies reviewed, it was unclear if these provisions were in fact met. It seems reasonable that one should not rely on such assumptions and that one should seek explicit ways of accounting for traffic volume changes in both the treatment and comparison groups since such volumes may be relatively easy to acquire and influential in the evaluation results.

#### *2.2.2.2 Time Trends*

Areawide safety changes over time because of many factors, such as weather conditions, driver demographics, and vehicle technology. Reporting levels also directly affect crash data. Often either the minimum damage dollar value changes for PDO crashes or the reporting level by police changes. PDO crash data from jurisdictions that have switched from 100-percent police reporting to self-reporting crash data must be used carefully when accounting for the safety effect of PRPMs. Again, most of the previous studies attempted to account for the safety effect of PRPMs by using daytime crashes at the same sites as a comparison group. However, if the installations of PRPMs have a safety effect on daytime crashes and/or the time trends between daytime and nighttime crashes differ, using daytime crashes at the same sites as a comparison group will result in errors in the estimate of safety effectiveness.

#### *2.2.2.3 Regression-to-the-Mean*

If PRPMs were installed at a location experiencing a randomly high number of crashes in the before period, then the number of crashes in the after period would be expected to decrease with or without the installation of PRPMs. This phenomenon (known as regression-to-the-mean, or RTM) is often a factor when study sites are selected based on crash history. Not only could RTM exist for the crash type or locations of interest, but it could also exist in the comparison group, and this existence could exaggerate the positive effects of a measure. For example, Orth-Rogers and Associates (*18*) cite a study by Khan (*20*) in which 184 sites were selected from high-hazard locations having four or more crashes in 1 year before the installation of PRPMs. At a group of control locations where PRPMs were not installed, it was found that the total number of crashes increased. However, at the treated sites, both nighttime and daytime crashes were reduced. It is clear that, given the site selection criterion, RTM will exaggerate the positive effects noted in the Khan study (*20*) and may even explain in entirety the reduction in daytime crashes. However, the increases in the control group may also be due to RTM because these locations may have been untreated because they fell into a group that had fewer than the average number of crashes in 1 year. This RTM would exaggerate the effects of PRPMs even more.

Only one of the previous studies, Pendleton (*16*), directly accounted for RTM effects. The treatment-comparison experimental design can, in principle, use comparison sites to control for RTM, but the treatment and comparison sites need to be matched on the number of crashes. In practice, controlling for RTM using a treatment-comparison experimental design is achievable only if sites are randomly assigned to a treatment and comparison group—a desideratum that is difficult to accomplish in road improvement programming. Alternatively, there will be no RTM concern if the fact that a site had a higher than usual crash history is not used in the selection of the sites for treatment. For example, in the "before and after design with yoked comparison" used by Griffin (*15*) and Orth-Rogers and Associates (*18*), RTM bias is thought to be eliminated by not using the number of crashes as a criterion for selecting sites. It is unclear how RTM bias was eliminated. This strategy, however, is not realistic because it defeats the purpose of safety improvement programs since measures are likely to have the largest safety benefits where a safety concern is manifested in a high crash frequency.

#### *2.2.2.4 Other Measures Simultaneously Applied*

Zador et al. (*21*) acknowledged the difficulty of identifying the effect of one treatment when multiple treatments have been applied. This difficulty presents the following methodological challenge: to discard data where changes in addition to PRPM installation occurred during the study period or to try to isolate the effects due to PRPMs. For the latter option, a promising methodology recently applied by Feber et al. (*22*) could be considered.

#### *2.2.2.5 Selection of the Comparison Group—the Problem of Spillover and Migration Effects*

Treatment-comparison experimental designs are commonly used to control for effects not due to the treatment. The treatment effects would be underestimated if, as some of these studies have found, there were a decrease in target crashes at comparison sites that was due to spillover effects of the treatment. Measures such as red light cameras are believed to have such effects.

The importance of this point is emphasized by Orth-Rogers and Associates (*18*) in their analysis of the Pennsylvania data. As indicated earlier, the authors suspected that PRPMs may have had a positive effect on the daytime crashes used for the comparison group that generated the result that PRPMs caused only a marginal decrease in nighttime crashes. The authors further concluded that if this impact on the comparison group were true, then the fundamental basis of the analysis conducted by Griffin (*15*) as well as on their own study is questionable.

In contrast to the underestimation caused by spillover, treatment effects would be overestimated if there were crash "migration" (i.e., an increase in crashes at the comparison sites due to the compensatory behavior of drivers). The installation of all-way stop control and other speed-control measures are believed to sometimes cause vehicles, and therefore crashes, to "migrate" to other sites; thus, it is conceivable that sites adjacent to PRPM installation sites will experience such migration effects.

## 2.3 LITERATURE REVIEW OF HUMAN FACTORS ISSUES AND PRPMS

The following subsections review the human factors issues related to the use of PRPMs:

- Driver needs with respect to delineation and visibility,
- Visibility of PRPMs, and
- Driver behavior in response to PRPMs.

### 2.3.1 Driver Needs with Respect to Delineation and Visibility

Pavement markings and delineation devices provide an important guidance function for drivers, especially at night. Pavement markings and delineation devices provide drivers with information about the vehicle position within the lane and information about which lanes are available for use. Pavement markings and delineation devices also provide the driver with a preview of upcoming changes in the roadway geometry, including curves, lane drops, narrowing, the start and end of passing zones, crosswalks, and intersections. There is a perception-reaction time delay between seeing a change in the road path and responding to it and between making a steering input and the vehicle responding; therefore, several seconds of preview are required for good lane positioning. Good delineation generally results in better driver performance and greater driver comfort.

Driver requirements for delineation have been established through studies of lane tracking given various driver preview distances and through studies involving the recording of driver eye movements. Driver preview distance may be modified by blocking parts of the forward view through the windshield or by simulating reduced visibility conditions in a driving simulator. In actual vehicles on a tangent section of road, McLean and Hoffman (*23*) found that, at 31 mph (50 km/h), improving sight distance beyond 2 seconds did not further improve lane position control. On a highway, at speeds of 50 to 68 mph (80 to 110 km/h), eye movement recorders showed that drivers looked about 3 seconds ahead of the vehicle (*24*). According to a Commission Internationale de l'Eclairage (International Commission on Illumination, or CIE) report on visual aspects of road markings (*25*), Farber et al. (*26*) found that a minimum of 5 seconds' preview time was necessary to allow for efficient, anticipatory steering behavior.

Based on these and other studies, the CIE report (*25*) recommends a minimum practical preview time of 3 seconds and a desirable preview time of 5 seconds. The sharper the curve, the greater the preview distance required to allow for the time it takes to perceive and react to the curvature by dropping speed.

Surface markings are recognized as sufficient for providing 2 to 3 seconds of preview time, while longer preview times require the use of PRPMs or post-mounted delineators (*2*). At 60 mph (96 km/h), a preview time of 2 to 3 seconds would be equivalent to a driver being able to see 2 to 3 PRPMs ahead at the recommended spacing for tangents (every 80 ft or 24 m), and 4 to 6 PRPMs ahead at the recommended spacing for curves (every 40 ft or 12 m).

### 2.3.2 Visibility of PRPMs

The visibility of PRPMs depends on aspects of the device, its placement, the vehicle head lighting, the highway geometry, and the driver visual capabilities. Drivers detect the presence of a delineator by means of slight differences in brightness between the delineator and the road surface. This difference or contrast, $C$, is defined as

$$C = \frac{L_T - L_B}{L_B} \tag{2-7}$$

Where

$L_T$ = target luminance and
$L_B$ = background luminance.

Once contrast reaches a certain level, known as the threshold contrast, it is just detectable to the viewer. During the day, the visibility of delineators depends only on the contrast between the delineator and the pavement background. At night, visibility depends on the light from headlights as well as on the retroreflectivity of the delineator. Retroreflection means that the light is reflected back at the same angle at which it is projected. If light from the headlights were to be perfectly retroreflected, it would not reach the driver's eyes, which are above the headlights. Since retroreflection is imperfect, some of the light reaches the driver's eyes, increasing the contrast between the delineator and the low-reflectance (pavement) background. The higher the percentage of light that is reflected back to the driver's eye, the greater the contrast and the further away the delineator will be seen.

#### *2.3.2.1 Device Features*

Device design and condition both have strong effects on visibility distance. With respect to device design, Blaauw and Padmos (*27*) compared three types of PRPMs that varied in the arrangement and number of lenses:

- Metallic mounting with three large, biconvex lenses (Category A),
- Plastic mounting with 21 small, biconvex lenses (Category B), and
- Plastic mounting with corner-cube lenses (Category C).

Visibility distances were determined through measurements of the optical characteristics of the PRPMs, combined with data from experiments with subjects. Figure 2-1 shows visibility distances for various types of delineators, including the three types above: under different atmospheric visibility distances, including clear weather ($Z$ = 9.3 miles or 15 km), moderate fog ($Z$ = 0.62 miles or 1 km), and heavy fog ($Z$ = 0.12 miles or 0.2 km); for low-beam headlamps in both new and used condition; and under wet and dry pavement conditions. The line denoted "$V_{85}$ = 100 km/h" (62 mph) indicates the distance necessary to provide 5 seconds of preview time for

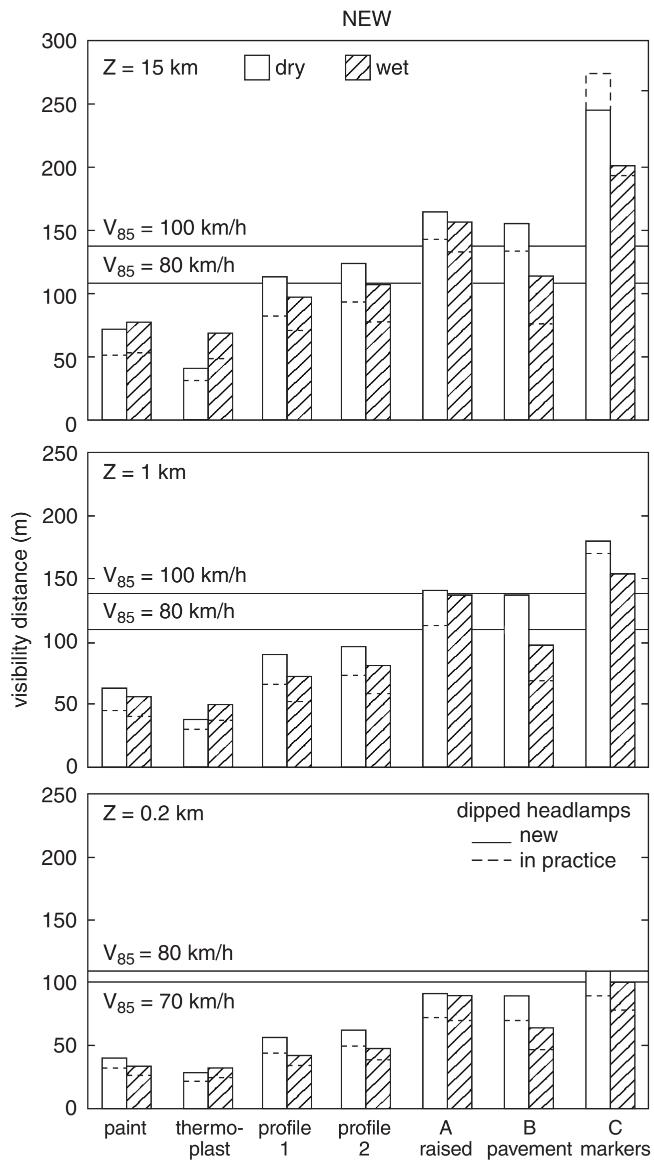


*Figure 2-1. Predicted visibility distances immediately after application for all markings on a dry and wet pavement (Z = atmospheric visibility distance) (27).*

the 85th percentile of the velocity distribution on a rural road with a 62-mph (100-km/h) speed limit. As can be seen in Figure 2-1, the PRPMs with corner-cube reflectors (Category C) had visibility superior to the other two categories (A and B). Headlights deteriorate over time, causing visibility distances to shorten. This phenomenon can be seen in Figure 2-1, where values that are designated "new" have a calculated visibility based on isocandela diagrams provided by the headlamp manufacturer and values that are designated "in practice" were used in the experiment. The distances are based on the measured retroreflection coefficients. Requirements for minimum visibility distances are given for rural roads with $V_{85}$ velocities of 50 and 62 mph (80 and 100 km/h). The requirements for heavy fog ($Z = 0.12$ miles, or 0.2 km) are lower because of the lower effective speeds on roads that experience foggy conditions (*27*).

While PRPMs provide better visibility than painted or tape lane markings, PRPMs deteriorate more rapidly over time. Figure 2-2 shows visibility distances 22 months after application on a highway lane with an AADT of 3,062 veh/day. As can be seen, visibility distances for in-service devices are reduced by as much as half of that of newly installed devices. However, even under dry conditions, the visibility of PRPMs is still better than the visibility of paint.

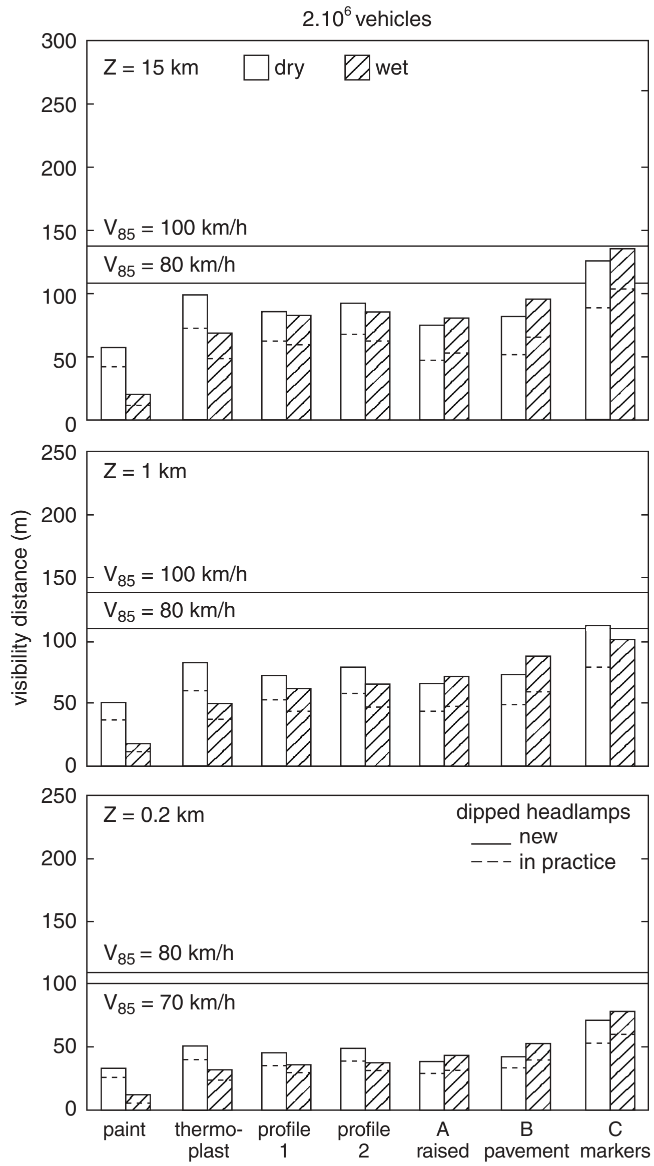


*Figure 2-2. Visibility distance 22 months after application of the markings (27).*

### 2.3.2.2 *Environmental Conditions*

As shown in Figures 2-1 and 2-2, rain and atmosphere transmittance strongly affect delineation visibility. The atmospheric conditions examined include clear weather, moderate fog, and heavy fog. Reductions in visibility of PRPMs due to rain were on the order of 10 to 20 percent depending on the type of marker and the environmental conditions. Reductions due to decreased atmosphere transmittance were larger, ranging from 40 to 60 percent. However, the visibility of the PRPMs was still better than the visibility of paint under all conditions, even after the PRPMs had been in service for 22 months.

### 2.3.2.3 *Headlighting*

Headlight patterns affect delineator visibility. A typical low-beam pattern is shown in Figure 2-3. Headlights are aimed to the right and down a few degrees to avoid glare for oncoming drivers. This means that more light falls on the right side of the road than on the left side, and, with low-beam headlights, delineators on the right will be visible at longer distances than those on the left. Headlights deteriorate over time, causing visibility distances to shorten, as can be seen in Figures 2-1 and 2-2.

### 2.3.2.4 *Road Geometry*

Road geometry affects delineator visibility. The more the face of the delineator is aligned perpendicular to the line of sight of the driver, the more visible the device will be. On curves, maximum visibility will be obtained when the PRPM face is aligned perpendicular to the tangent of the curve. Recommended spacings between PRPMs on tangents and curves are in the "Roadway Delineation Practices Handbook" (*2*).

### 2.3.2.5 *Driver Characteristics*

**Contrast sensitivity.** Driver characteristics, mainly contrast sensitivity, affect delineator visibility. Sensitivity to contrast varies greatly among drivers, even among drivers with "normal" acuity of 20/20. Because of differences in contrast

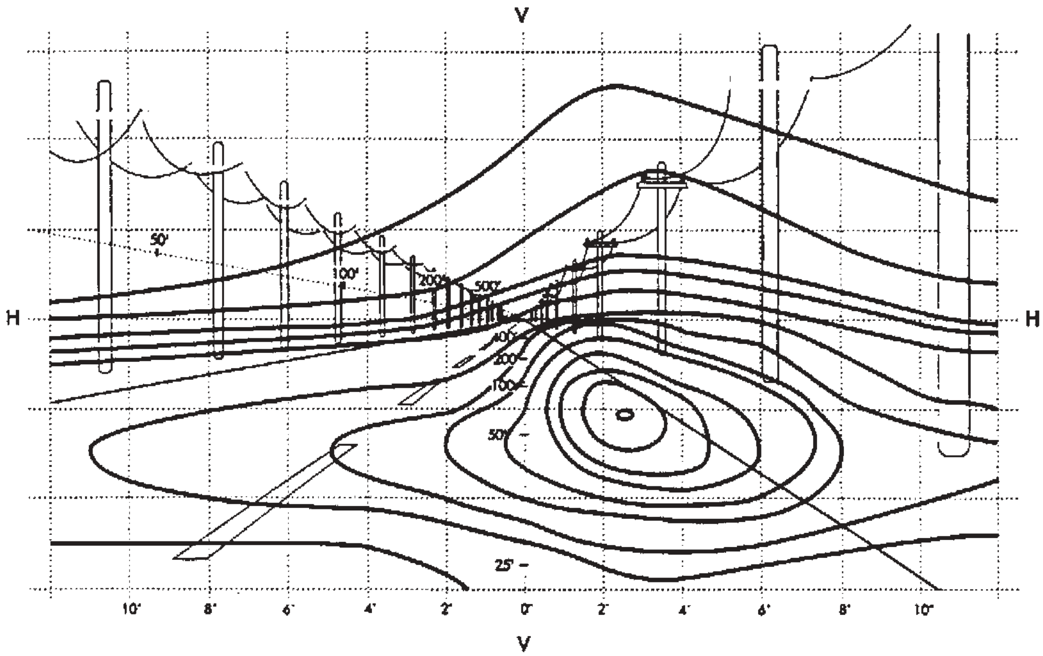


*Figure 2-3. Isocandela diagram of a typical U.S. low-beam pattern superimposed on a road scene (*18*).*

sensitivity, driver detection distances for delineation devices can vary by a factor of 5 to 1. As drivers age, contrast sensitivity declines, reducing preview distances available and leading many older drivers to reduce nighttime driving.

**Age.** In an FHWA study directed at the needs of older drivers with respect to delineation of horizontal curves, Pietrucha et al. (*28*) examined the response of drivers in three age groups (18–45, 65–74, and 75+) to 25 delineation treatment combinations. Table 2-6 describes 12 treatments. The baseline treatment (Treatment 1) was a 4-in. (100-mm) yellow centerline with a measured coefficient of retroreflected luminance ($R_L$) of 100 mcd/m$^2$/lux (referred to as an in-service brightness level). Left and right curves were studied with a radius of

**TABLE 2-6 Details of 12 delineation treatments (*28*)**

| Treatment Number | Centerline Treatment | Edgeline Treatment | Off-Road Edge Treatment |
|---|---|---|---|
| 1 | 4-in. Yellow Line | None | None |
| 2 | 4-in. Yellow Line | 4-in. Structured Line | None |
| 3 | 4-in. Yellow Line + Yellow PRPMs | None | None |
| 4 | 4-in. Yellow Line + Yellow PRPMs | White PRPMs | None |
| 5 | 4-in. Yellow Line | None | Normal Mount Chevrons |
| 6 | 4-in. Yellow Line | 4-in. White | Normal Mount Chevrons |
| 7 | 4-in. Yellow Line | None | Standard Flat Posts (Hi-Intensity) |
| 8 | 4-in. Yellow Line | 4-in. White | Standard Flat Posts (Hi-Intensity) |
| 9 | 4-in. Yellow Line | None | Full Reflection Posts (Hi-Intensity) |
| 10 | 4-in. Yellow Line | None | T-Posts (Hi-Intensity) |
| 11 | 4-in. Yellow Line + Yellow PRPMs | None | T-Posts (Hi-Intensity) |
| 12 | 4-in. Yellow Line | 4-in. White | T-Posts (Engineering) |

500 ft (152 m). Treatments on curves studied included PRPMs on the centerline (Treatments 3 and 11) or on the edgeline and centerline simultaneously (Treatment 4) as well as treatments with and without chevrons and post-mounted delineators. Measures were recognition distance and time spent looking at the roadway. Measurements were taken using a visual occlusion device and using subject assessment.

The first phase of the study involved a laboratory test of simulated nighttime driving. In the second phase of the study, a subset of the best treatments was then field-tested with the youngest and oldest age groups (see Figure 2-4). As is so often the case, the treatment that improved performance for the older drivers also improved performance for younger drivers. The treatment with the highest recognition distance for both groups was Treatment 12, which did not use PRPMs. Treatment 12 had a 4-in. (100-mm) yellow centerline with a measured coefficient of retroreflected luminance ($R_L$) of 100 mcd/m$^2$/lux (in-service level of brightness), a 4-in. (100-mm) white edgeline, and T-posts with engineering-grade reflectivity with standard spacing (65 ft or 19.8 m).

There were significant differences between left- and right-curve recognition distances for some treatments and between older and younger drivers for other treatments. On average, the older drivers had 14 percent less recognition distance than the younger drivers. Furthermore, it has been demonstrated that older drivers who volunteer for testing are likely to have substantially better vision than the average older driver. Consequently, differences amongst the driving public between older and younger drivers are likely to be much more pronounced.

#### *2.3.2.6 Visibility Distance and Benefit-Cost Analysis*

In the Pietrucha et al. study (*28*), a benefit-cost analysis that used visibility distance to determine the benefit, examined the best of 25 initial delineation treatments. The visibility distances for six of the best treatments (Treatments 5, 6, 9, 10, 11, and 12) did not differ with respect to statistical significance. Amongst those treatments, the one recommended on a benefit-cost basis was the treatment with a 4-in. (100-mm) yellow line, no edgeline, and high-intensity post-mounted delineators (Treatment 10). The treatments with PRPMs were more costly for an equal visibility benefit and therefore were not recommended.

### 2.3.3 Driver Behavior in Response to PRPMs

In addition to measures of visibility distance, various measures of driver behavior have been used to evaluate the effectiveness of PRPMs. These measures include visual workload (as determined by number of looks required for comfortable driving), speed, speed variation, lane position, lane position variation, and encroachments into adjoining lanes. Some studies involve measuring the behavior of a group of subjects on test courses, while others involve measuring the behavior of unsuspecting drivers on public roads where test installations have been set up. The greatest number of studies of the impact of delineators on driver behavior were directed to horizontal curves. PRPMs on tangents and on ramps have been examined in one study (*29*). Another study concerned gore areas and deceleration lanes (*30*), and two studies looked at approaches to narrow bridges (*31*, *32)*. These studies are described in the paragraphs below.

#### *2.3.3.1 Driver Lane Position and Speed for PRPMs on Curves*

Table 2-7 summarizes the effects that PRPMs on curves have on driver behaviors. In a before-and-after study comparing delineation with and without centerline snowplowable

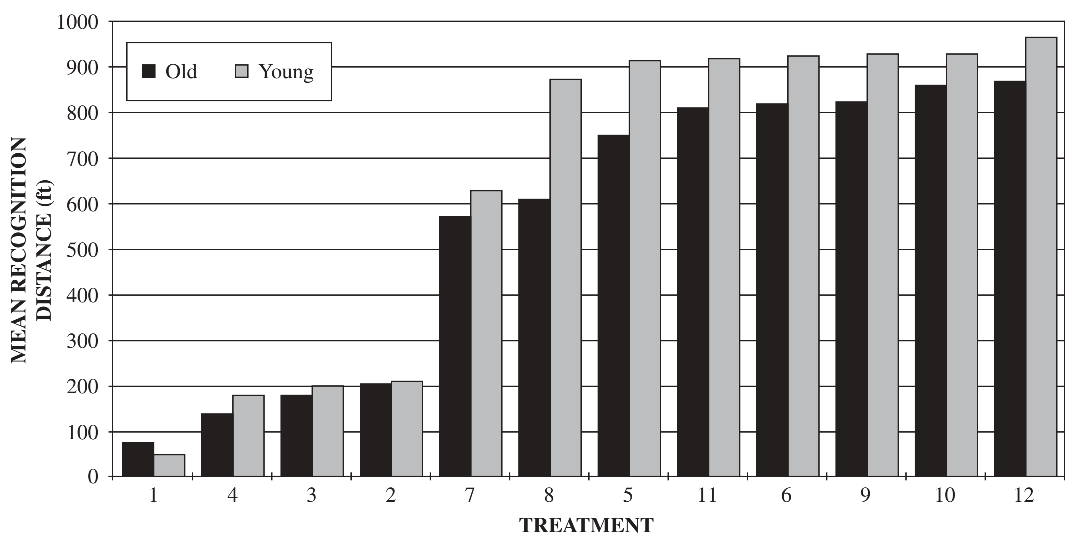


*Figure 2-4. Recognition distance: old versus young groups (combined curves) (*28*).*

**TABLE 2-7 Summary of literature on driver performance and PRPMs (horizontal curves)**

| Study Ref. /Location | Installation Location | PRPM Spacing | Effect on Speed | Effect on Lane Position | Other |
|---|---|---|---|---|---|
| Mullowney (1982) (*30*) *New Jersey* (Night only) | Centerline, edgelines separately | NA | Smoother speed profile through the site | Centerline and edgeline encroachments were reduced by significant amounts (3.7 to 12%) | When combined with illumination, greater reduction of encroachments was measured |
| Niessner (1984) (*31*) *USA* (Day and night) | Centerline, edgeline | Recommended: • 80 ft (24 m) on curves up to 3 degrees • 40 ft (12 m) on curves up to 15 degrees • 20 ft (6 m) on curves with more than 15 degrees of curvature | • No significant difference in mean speeds – nighttime 85th percentile speeds reduced significantly • Speeds increased on one approach and decreased on the other • Smoother speed profile (only night results) | • Centerline encroachments reduced by 50% (daytime and nighttime) • Vehicle placement variability reduced significantly – vehicles shifted significantly toward centerline during daytime and toward edgeline at nighttime • Centerline and edgeline encroachments reduced significantly (only nighttime results) | Mixture of centerline and edgeline markings appear confusing at some sharp curves |
| Agent & Creasey (1986) (*33*) *Kentucky* (Day and night) | Centerline | • 10 ft (3 m) apart • 20 ft (6 m) apart | Daytime and nighttime speeds reduced ($p < 0.01$) | Decreased encroachments for daytime and nighttime (no significance testing) | None |
| Zador et al. (1987) (*21*) 54 sites in *Georgia & New Mexico* (Day and night ) | Both sides of centerline (in conjunction with other measures) | • 80 ft (24 m) apart • 40 ft (12 m) apart for sharper curves | • Overall mean speed increase of 1 km/h at nighttime • Daytime and nighttime mean speed increase 30 m before and 30 m into curve (from graph) | • 6 cm away from centerline: Mean shift 12 cm away from centerline, 30 m before curve • Mean shift 21 cm away from centerline, 30 m into curve (similar effects both daytime and nighttime) | None |
| Krammes & Tyer (1991) (*34*) 5 sites *USA* (Night only) | Centerline | NA | • Speeds were higher with new PRPMs in place • Speeds went down over time | • Vehicles placed further from centerline • Fewer opposite lane encroachments | None |
| Hammond & Wegmann (2001) (*35*) 2 sites in *Tennessee* (Day only) | Both sides of centerline | • 40 ft (12 m) apart • 20 ft (6 m) apart | No significant difference | • Significant reduction in encroachments • No significant difference between 6- and 12-m spacing | None |

PRPMs, Mullowney (*30*) measured impacts on encroachments, on speeds, and on speed variance. Only nighttime data were collected for this study. Speeds were measured using a handheld radar unit. An on-site observer collected encroachment data. Centerline encroachments were measured at three sites, including one control site. Two of the three sites were on the same roadway. Edgeline encroachments were measured at two sites on the same roadway, one of which was a control site, presumably the same delineation but without PRPMs, although this presumption was not stated explicitly.

After the PRPMs were installed at the treatment sites, they were compared with the control sites, and a statistically significant reduction ($p < 0.01$, $p < 0.05$) of 12 percent (site with street illumination) and 3.7 percent (site without illumination) in centerline encroachments was measured. There was also a statistically significant reduction ($p < 0.01$) of 5.7 percent in edgeline encroachments at the sites with PRPMs after installation as compared with before. There was no statistically significant difference at two control sites for this comparison. There is no indication of how long after installation measurements were made, nor is it indicated where installations were centerline only or a combination of edgeline and centerline. The former is assumed.

During Mullowney's study (*30*), speeds were collected at two sites, both on horizontal curves. At the first site, speeds were collected for traffic in both directions at four different locations around the curve. The presence of PRPMs appears to have resulted in a smoother speed profile through this site in both directions, as evidenced by less variation in speed between the data collection points after installation of PRPMs than before installation of PRPMs. Speeds were higher at the apex of the curve than at the curve entrance or at the exit of the curve. At the second site, speeds were collected at three locations around the curve. The speeds at the entrance and exit of the curve after PRPM installation were slower than those speeds before PRPM installation, resulting in a smoother speed profile throughout the site. (Note that the speed data were presented only in graph form—no statistical analysis was performed.)

The effects of PRPMs at three horizontal curve sites were investigated by Niessner (*31*) before and after the installation of PRPMs. At the first site, which was an S-curve, conventional markers were spaced 40 ft (12 m) apart, two on the centerline and one on each edgeline. There was no statistically significant difference in daytime or nighttime speeds, but nighttime 85th percentile speeds were significantly reduced. Centerline encroachments were reduced by 50 percent during both day and night. At the second site, a single row of PRPMs was installed on the centerline as well as on both edgelines. Speed measurements were taken at three points for both directions. Mean speeds decreased for one approach to the curve, but increased for the other approach. During the daytime, the vehicle lane position shifted significantly toward the center of the curve, while at night, the vehicle lane position shifted toward the edgeline. At the third site, which was an S-curve, snowplowable PRPMs were installed along both edgelines and on both sides of the centerline. Speed measurements were taken at four locations along the curve. The snowplowable PRPMs appear to have resulted in a smoother speed profile (i.e., there was less variation in speed through the curve) for both directions. In addition, both centerline and edgeline encroachments were reduced significantly.

Agent and Creasey (*33*) investigated the ability of various traffic control measures to delineate horizontal curves so drivers would perceive the curve, slow to an appropriate speed, and then receive guidance through the curve. A before-and-after analysis was carried out to test the performance of PRPMs, transverse pavement stripes, rumble strips, post delineators, and chevron signs. Speed and encroachment (centerline and edgeline) data were taken at all sites before and after installation, and a before-and-after crash analysis was performed at some of the sites. The after data were taken more than 1 year after installation of the traffic control measures.

PRPMs were applied at two regular curves and two S-configurations, each consisting of two 90-degree curves. The PRPMs were applied in pairs along the centerline at intervals 10 or 20 ft (3 or 6 m) apart, depending on the location. Two sites—one S-curve and one normal curve—had only PRPMs and no other countermeasures installed. The other two sites had PRPMs and other traffic control measures as well.

At the two S-curves with only PRPMs, average speeds were lowered from 23 to 20 mph (37 to 30 km/h) and 25 to 23 mph (40 to 37 km/h), depending on the approach, during the day. At night, average speeds were lowered from 23 to 20 mph (37 to 30 km/h) and from 24 to 22 mph (38 to 35 km/h) after installation of the PRPMs, for the different approaches. These reductions were statistically significant ($p < 0.01$). The percentages of encroachments were reduced from 44 to 22 percent and from 13 to 7 percent during the day and from 52 to 18 percent and from 8 to 7 percent at nighttime. There was no mention of tests of significance for encroachment data.

At the regular curve with only PRPMs installed, average night speeds were reduced from 30 to 27 mph (48 to 43 km/h) on one approach and from 30 to 24 mph (48 to 38 km/h) on the other approach after installation of the PRPMs. These reductions were significant ($p < 0.01$). Encroachments increased on one approach from 22 to 26 percent and decreased on the other approach from 32 to 29 percent. There was no mention of the radii of the curves or of the tests of significance for encroachment data.

The effects of a number of commonly used curve delineation treatments on vehicle speed and placement were examined in a study by Zador et al. (*21*). Treatments were implemented at 51 rural two-lane highway sites. Sites with chevrons, post-mounted delineators, and raised pavement markers were compared with unmodified control sites. Observations were taken at each modified and control site several weeks before and several weeks after the modifications were put in place. Speeds and vehicle placement were taken 100 ft (30 m) before and 100 ft (30 m) into the curve.

Of the 51 sites, 12 used standard 4×4 Stimsonite PRPMs installed on both sides of the double yellow centerline. The markers were usually spaced 80 ft (24 m) apart. Along sharper curves, where three markers could not be seen at one time, the markers were spaced 40 ft (12 m) apart. The results indicated that the PRPMs caused the largest shift from the centerline as compared with the other countermeasures and the control condition. In advance of the curve 100 ft (30 m), the mean displacement was approximately 0.4 ft (12 cm); 100 ft (30 m) into the curve, the mean displacement was approximately 0.7 ft (21 cm).

In comparison, when chevrons were used, the displacement from the centerline was less. With post-mounted delineators, vehicles moved toward the centerline. Nighttime mean vehicle speeds were increased by approximately 0.68 mph (1.1 km/h) with the use of raised pavement markers; daytime mean vehicle speeds increased by a similar amount.

In a nighttime study comparing the impact of PRPMs supplementing the existing centerline with post-mounted delineators, Krammes and Tyer (*34*) determined that drivers placed their vehicles further from new PRPMs than from older post-mounted delineators and made fewer encroachments on the adjacent lane. Two factors are operating here: (1) the new PRPMs would be more conspicuous and (2) the new PRPMs would be placed closer to the traveled lane than the post-mounted delineators would.

With respect to changes over time, speeds were significantly higher with the new PRPMs than with PRPMs that had been in place for 11 months, suggesting that drivers had longer preview distances and therefore were comfortable with higher speeds.

In a recent daytime study, Hammond and Wegmann (*35*) examined the effects on PRPMs at two spacings on curves by measuring changes in speed and encroachment distances into the opposing travel lane. Two minor arterial sites were chosen for this study. Six data points were collected for each vehicle, including speeds at the beginning, middle, and end of the curve, as well as the distance of opposing-lane encroachment. Levels of encroachment were categorized on a scale of zero to eight, with zero being low and eight being high. A shift in one level of encroachment translates into a 4-in. (10-cm) change of the vehicle travel path.

Speeds and encroachment distances were measured before and after the installation of the PRPMs at a 40-ft (12-m) spacing and again after the installation of additional PRPMs, creating a 20-ft (6-m) spacing, for a total of 3 experimental conditions. Stimsonite LifeLite 88A PRPMs were placed in pairs immediately on either side of the painted centerline.

Speed variance was not found to be affected by the presence or spacing of the PRPMs. However, effects on encroachment were statistically significant. At Site 1, the control condition, the 40-ft (12-m) spacing, and the 20-ft (6-m) spacing yielded levels of encroachment of 4.0, 3.0, and 2.8, respectively. At Site 2, the control condition, the 40-ft (12-m) spacing, and the 20-ft (6-m) spacing resulted in levels of encroachment of 2.7, 1.9, and 1.3, respectively.

#### *2.3.3.2 Driver Speed, Visual Workload, and Lane Position Relative to PRPM Spacing on Curves*

As discussed above, Hammond and Wegmann (*35*) compared operating speeds and encroachment distances for PRPMs spaced 40 ft (12 m) and 20 ft (6 m) apart. The authors found no significant difference between the 40-ft (12-m) and 20-ft (6-m) spacings in terms of operating speed or centerline encroachments.

Blaauw (*36*) examined drivers' observation strategy and performance on road sections with various delineation arrangements. Delineation treatments included PRPMs on edgelines and centerlines at spacings of 40, 80, and 118 ft (12, 24, and 36 m) on straight and curved (radius 656 ft [200 m] and radius 3,280 ft [1,000 m]) sections. A visual occlusion technique was used to determine changes in visual strategy as a function of road delineation. Drivers were equipped with glasses with lenses that could be changed from translucent to opaque almost instantaneously. These glasses allowed them half a second to look at the road on the press of a control switch. The researchers found that total observation time increases and driving performance deteriorates when less delineation information is present per unit of road length. This finding was particularly striking on the 656-ft (200-m) radius curve where the 40- and 80-ft (12- and 24-m) spacing distances lead to speed reductions and lane errors. The authors recommend a minimum spacing of 80 ft (24 m) on tangents and 40 ft (12 m) on curves. These results provided a basis for guidelines for the use of PRPMs recommended to FHWA (*5*).

#### *2.3.3.3 Driver Speed, Lane Position, and Encroachments at Hazardous Locations*

In 1982, a study was carried out by 12 state highway agencies to evaluate the effectiveness of raised pavement markers at hazardous locations (*31*). Among the test sites were rural curves on two-lane roadways, narrow bridges, stop approaches, through approaches, two-lane sites with left-turn lanes, interchange gores, four- and six-lane undivided sites, multilane divided highway sites, and four- to two-lane sections. Several locations were tested for each site type.

The report confirmed that PRPMs provide improved nighttime pavement delineation when compared with and used in conjunction with conventional paint stripes. For rural two-lane curves, the report recommended that the double yellow centerline be delineated with one row of PRPMs between the two centerlines, with PRPM spacings of 80 ft (24 m) on curves up to 3 degrees, 40 ft (12 m) on curves between 3 and 15 degrees, and 20 ft (6 m) on curves with more than 15 degrees of curvature. Visual observations indicate that two markers may be needed to provide adequate delineation for locations with curves in excess of 20 degrees. The mixture of centerline and edgeline markings appeared confusing at some sharp curves.

The study determined that PRPMs can significantly reduce instances of erratic maneuvers of vehicles through painted gores at exits and bifurcations. This finding was true whether or not overhead lighting was present. The study recommended that PRPMs be introduced slightly in advance of the highway problem area to prepare motorists for the guidance technique that is to be encountered.

#### *2.3.3.4 Driver Speed and Lane Position in Relation to PRPM Spacing on Tangents and Ramps*

Optimal spacings for PRPMs along tangent sections and on interchange ramps of Interstate highways in Ohio were determined by Zwahlen (*29*) (see Table 2-8). The first step in this process was to predict the illumination reflected back to the driver's eyes on the basis of the following:

- Headlight output;
- Geometry with respect to the PRPM, headlight, and driver eye positions;
- Photometric qualities of the PRPM; and
- Transmissivity of the atmosphere.

**TABLE 2-8 Summary of literature on driver performance and PRPMs (tangent sections)**

| Study Ref. /*Location* | Installation Location | PRPM Spacing | Effect on Speed | Effect on Lane Position | Other |
|---|---|---|---|---|---|
| Zwahlen (1987) (*29*) *Ohio* (night testing only) | Tangent lane line | 59, 121, 240 ft (18, 37, 73 m) | No significant difference | 5-in. (13-cm) shift away from centerline | None |
| Zwahlen (1987) (*29*) *Ohio* (night testing only) | Ramp edgeline | 13, 27, 50 ft (4, 8, 15 m) | No significant difference | No significant difference | Placement of PRPMs on outside edgeline not recommended (no significant difference) |

It was assumed that the headlight output was less than 100-percent efficient (how much less was not stated). Also, to account for wear during the life cycle, the specific intensity value of the PRPM was assumed to be 50 percent of its new value. Once an illumination threshold for human observers of 98-percent probability of detection was reached, the devices were assumed to be visible.

A rain intensity of 1 in. per hour was assumed, since the probability of having a greater rainfall than this within a 30-day period decreases rapidly (e.g., a rainfall of 2.6 in. per hour can be expected once every 25 years). The theoretical calculations indicated that the Stimsonite PRPMs would be visible in rain at 1 in. per hour at a distance of 480 ft (147 m).

A model of driver lane position standard deviation on tangent sections was then used to predict lane position deviation in relation to the number of PRPMs visible. Once there were four or more delineation devices visible, the model predicted little change in standard deviation. Given a visibility of 480 ft (147 m), to have four devices visible requires a spacing of 120 ft (36 m).

On ramp sections in Ohio, the radius of curvature is typically 240 ft (73 m) corresponding to a 24-degree curve. An assumption was made that a solid body of grass or snow 1 to 2 ft (0.3 to 0.6 m) high existed on the inner edge of the ramp curve, limiting the driver's view ahead. Given this geometry, the illumination distance for PRPMs will be best if placed on the outer edgeline of the pavement. Low-beam headlights provide the most light to the right; therefore, the left edge of a left curve has the shortest illumination distance—115 ft (35 m). This is about one-fourth of the visibility available on a tangent section. To have four delineators in view in the 115-ft (35-m) distance, an optimal spacing of 25 ft (7.6 m) was selected.

The theoretical analysis led to field testing with 11 young subjects in wet and dry conditions. To better replicate the illumination levels for PRPMs that have been in service for some time, the new reflectors were cut in half. Vehicle speed and lane position were measured. Conditions tested included spacings both wider and narrower than the predicted optimum:

- Tangent sections included no PRPMs and PRPMs at spacings of 60, 120, or 240 ft (18, 37, or 73 m).
- Ramp sections included no PRPMs and PRPMs at spacings of 12.5, 25, or 50 ft (4, 8, or 15 m).

On tangent sections, there was a slight but consistent shift of about 5 in. (13 cm) toward the right edgeline for PRPM spacing of 60 ft (18 m) compared with 120 ft (36 m). No statistically significant effects on vehicle speed were found. The study concluded that a 120-ft (36-m) spacing should be recommended on tangent sections. The slight improvement in lane positioning for the 60-ft (18-m) spacing was not felt to justify the doubling in cost of installation.

Statistical analysis showed no significant difference in speed or lane positioning related to the presence or spacing of PRPMs on ramp sections; thus, the placement of PRPMs on the outer edgelines of cloverleaf interchange ramps was not recommended.

Zwahlen's study (*29*) suggests that the problem with PRPMs on very sharp curves (i.e., with a radius curve 240 ft [73 m] or less) is the lack of preview distance (i.e., lacking a preview distance of 120 ft [37 m] or shorter). Related work on chevron spacings (*37*) used a paradigm in which subjects viewed curves with up to 12 equally spaced chevrons in laboratory conditions that simulated light levels and a size equivalent to 90-degree curves with typical radii seen at night. The subject task was to determine whether the curve viewed was sharper or gentler than a standard curve. Results showed that performance reached a plateau when four or more equally spaced chevrons were used. Chevrons can be seen considerably further than PRPMs because of their orientation, and there is no reduction in visibility with rain. Consequently, chevrons seem to be preferable to PRPMs on sharp curves.

#### *2.3.3.5 Driver Response to PRPMs in Deceleration Lanes and at Gore Areas*

One study examined the impact of PRPMs at gore areas (see Table 2-9). Mullowney (*30*) found that six out of nine

**TABLE 2-9 Summary of literature on driver performance and PRPMs (freeway exits)**

| Study Ref. /Location | Site Type | Installation Location | PRPM Spacing | Effect on Speed | Effect on Lane Position | Other |
|---|---|---|---|---|---|---|
| Mullowney (1982) (*30*) *New Jersey* (night only) | Deceleration lanes | Gore, lane line, edgeline | 40 ft (12 m) lane line, 40 ft (12 m) edgeline | Two of the three sites exhibited a significant increase ($p < 0.03$, $p < 0.01$) in early entry into deceleration lane | Not determined | None |
| | Painted gore | Gore | 20 ft (6 m) | Six of nine sites experienced statistically significant reductions ($p < 0.02$ or less) in cars that cut through painted gore | Not determined | None |
| Zwahlen (1987) (*29*) *Ohio* (night only) | Interchange ramps 240 ft (73 m) radius | Edgeline | 13, 26, 50 ft (4, 8, 15 m) | No significant difference | No significant difference | Placement of PRPMs on outside edgeline not recommended (no significant difference) |

sites where PRPMs had been implemented had statistically significant reductions in vehicles that cut through the painted gore. When PRPMs were placed on the lane and edgeline of deceleration lanes, two out of three sites showed a significant increase in early entry into the deceleration lane.

### *2.3.3.6 Driver Response to PRPMs at Narrow Bridges*

A before-and-after analysis of vehicle speed and lateral placement at 18 narrow bridge approach sites was conducted by Bowman and Brinkman (*32*) (see Table 2-10). The countermeasures evaluated were combinations of advance warning signs, pavement markings, PRPMs, roadside delineators, object markers, and adhesive delineators. Measurements of vehicle speed and lateral placement were made using FHWA's fully automated Traffic Evaluation System (TES). These countermeasures did not result in statistically significant changes in the mean speeds at the $p < 0.1$ level. However, the countermeasures significantly reduced speed variation when all the vehicle types and time periods were analyzed together.

In the Niessner (*31*) report discussed above, for narrow bridges on rural two-lane roads, a PRPM spacing of 80 ft (24 m) decreasing to 40 ft (12 m) approaching the bridge

**TABLE 2-10 Summary of literature on driver performance and PRPMs (narrow bridges)**

| Study Ref. /*Location* | Installation Location | PRPM Spacing | Effect on Speed | Effect on Lane Position |
|---|---|---|---|---|
| Niessner (1984) (*31*) *USA* | Edgeline, centerline | 80 ft (24 m) decreasing to 40 ft (12 m) | Two sites:<br>1. Significant reduction in nighttime 85th percentile speeds—no significant difference in daytime speeds<br>2. Vehicle speed at night increased (no mention of daytime speeds) | Two sites:<br>1. Moderate and severe encroachments over the centerline were reduced for both daytime and nighttime<br>2. No significant difference for daytime or nighttime |
| Bowman and Brinkman (1988) (*32*) *USA* | Centerline (with other counter-measures) | Unknown | Speeds reduced ($p < 0.1$) | No significant difference |

resulted in a significant reduction in the nighttime 85th percentile speeds. There was no significant difference in daytime speeds. Encroachments over the centerline were also reduced significantly for both the daytime and nighttime. The report recommended that PRPMs be placed on both the edgeline and centerline to delineate the decrease in pavement width.

### 2.3.4 Summary

Five studies found that PRPMs were associated with fewer encroachments into the adjacent lane on horizontal curves (*30, 31, 33, 34, 35*). One of these studies examined sites with and without lighting and found that while encroachments were significantly reduced at both sites, they were reduced more at the site with lighting (*30*). This finding confirms the findings of other studies showing that encroachments were reduced during the day as well as at night after the placement of PRPMs on curves. Two studies found that drivers moved away from the PRPMs (*27, 34*). One study found that, at one site, lane position variability decreased significantly (*31*).

With respect to speed, findings were very mixed, with two studies finding smoother speed profiles through curves (*29, 30* night only at one sight), one study finding one site with no significant difference in speed after PRPM application (*35*), one study finding a significant reduction in 85th percentile speed at one site (*31*), three studies finding significant increases in speed (*27, 31* at one approach only, *34*), and one study finding a reduction in speeds both day and night (*33*). One study that examined the effects 11 months after installation of PRPMs found that speeds were lower, possibly because the lower reflectivity reduces preview distance (*34*). At night, better delineation may induce higher speeds, particularly on tangents and large radius curves, and possibly on smaller radius curves where only centerline (not edgeline) PRPMs are implemented. This possibility has not been adequately studied, but is likely given the results of studies showing that improved delineation (i.e., higher contrast lane striping) was associated with higher speeds.

One study found that applying PRPMs in deceleration lanes resulted in drivers entering the deceleration lane earlier (*30*). This study also found that using PRPMs in gore areas reduced the frequency of encroachments to the gore areas.

CHAPTER 3

# DATA COLLECTION AND PREPARATION

This chapter describes the process followed to identify and select potential states to participate in the PRPM safety evaluation study. Two sections compose this chapter. First, the process to select the states with potential data for this study is described. Second, details of the data collection activities follows the state selection process. The research team devised procedures throughout the study to gather as much data as feasible, to test the quality of the data collected, and to prepare the data sets to undergo the statistical analyses.

## 3.1 STATE SURVEY AND SELECTION OF POTENTIAL STATES FOR PRPM SAFETY EVALUATION

To obtain a comprehensive knowledge of the state of the practice relating to PRPMs and to assist the research team in selecting candidate states for inclusion in the study, iTRANS surveyed 29 states with known PRPM installations (see Table 3-1). Information was obtained from these states through a combination of questionnaires and telephone interviews. The responses received from the states varied in their completeness. Each response was assessed as a potential candidate for inclusion in the proposed comprehensive evaluation plan.

After reviewing the material received by the research team and additional personal contacts, iTRANS selected the following states for the next stage of information assembling: California, Illinois, Indiana, Maryland, Massachusetts, Michigan, Missouri, New Jersey, New York, Ohio, Oregon, Pennsylvania, Texas, Utah, Virginia, and Wisconsin. The states were requested to provide more detailed information on PRPM installation locations, historical crashes, roadway inventory, and traffic volume databases.

The research team made key decisions during the selection process:

- **To confine the study to locations where raised snowplowable pavement markers have been installed.** The majority of current installations reported by the states were of the raised snowplowable marker type. States that implement recessed markers either could identify only very small samples of roadways with this marker type or have discontinued their implementation in recent years. California and Texas were the only two states that implement the conventional marker type on a wide scale; however, no recent PRPM installations took place, and a suitable sample for a before-and-after safety evaluation was not available.
- **To seek PRPM installations that took place during 1995 or more recently.** This decision leads to more recent data files and provides the opportunity to analyze more current installations and markers and to develop guidelines based on the current PRPM practices and technologies.
- **To seek PRPM installations and related data at the following roadway types: two-lane undivided roadways, four-lane divided expressways (at-grade intersection control), and four-lane freeways (controlled access).** The iTRANS survey indicated that PRPMs are used extensively on four-lane divided roadways (expressways and freeways) and two-lane undivided roadways. Although PRPMs are also installed on four-lane undivided roadways and multilane freeways (i.e., with more than four lanes), the research team did not identify a sufficient sample of these roadway types that met the other criteria for this study.
- **To select states where it seems feasible to obtain large samples of sites representing selective and nonselective PRPM implementation policies.** An important issue that requires consideration during analysis is the potential driver expectation and driver response to PRPMs when the PRPMs are implemented either selectively at sites with known safety concerns or nonselectively using a systemwide approach. It is important to ensure that, in particular for two-lane treatment sites, there are representative samples of sites that are based on both PRPM implementation policies.
- **To consider the states that have electronic crash data for at least 2 years before PRPM implementation and 1 year after PRPM implementation, as well as accessible roadway inventory and traffic volume count information, preferably in electronic format.** For the safety evaluation, it is critical that data be available and accessible in a useful format.

In conclusion, the following selection criteria were devised when reviewing the information received from the states:

**TABLE 3-1 States surveyed for establishing availability of data related to PRPM installations**

| | | |
|---|---|---|
| Arkansas | Kentucky | North Dakota |
| California | Maine | Ohio |
| Colorado | Maryland | Oregon |
| Connecticut | Massachusetts | Pennsylvania |
| Florida | Michigan | Texas |
| Georgia | Minnesota | Utah |
| Illinois | Missouri | Virginia |
| Indiana | New Jersey | West Virginia |
| Iowa | New York | Wisconsin |
| Kansas | North Carolina | |

- The type of marker included raised snowplowable (retroreflective) markers.
- Roadway types included two-lane undivided, four-lane divided expressway (at-grade intersection control), and four-lane freeways (controlled access).
- Implementation dates were preferably between 1995 and 1999.
- Crash data included electronic crash data for at least 2 years before implementation and 1 year after implementation.
- Other data included accessible roadway inventory and traffic volume count information, preferably in electronic format.

On the basis of the information received, six states were selected for the safety evaluation of PRPMs: Illinois (District 8), New Jersey, New York, Missouri, Pennsylvania (Districts 1, 3, 5, and 8), and Wisconsin. Table 3-2 summarizes the PRPM use in these six states.

## 3.2 DATA COLLECTION

This section provides an overview of the data collection and data preparation processes applied during the research project. To conduct a statistically defensible safety evaluation of PRPMs in a manner that will provide sufficient information to develop implementation guidelines, the following types of data were required:

- PRPM treatment sites inventory,
- Reference group and comparison group locations,
- Historical crash data for all locations,
- Roadway attribute data for all locations,
- Traffic volume data for all locations, and
- Additional delineation and guidance measures at treatment locations.

The reference and comparison group location data were required for developing safety performance functions to control for changes in safety at treatment locations that are due to factors other than PRPM installation (e.g., changes in traffic volume).

### 3.2.1 PRPM Treatment Sites Inventory

Electronic or hard-copy sources of the following variables relating to the installations of PRPMs were assembled for each state:

- Beginning and ending route numbers and mileposts,
- Date or year of PRPM installation,
- Spacing (e.g., 40 ft or 80 ft), and
- Placement (e.g., centerline, edgeline, or lane lines).

**TABLE 3-2 States selected for the PRPM safety evaluation**

| State | Roadway Types | PRPM Implementation Dates | Policy |
|---|---|---|---|
| Illinois (District 8) | Two-lane | 1994 –1999 | Nonselective |
| New Jersey | Two-lane | 1993 | Nonselective |
| New York | Two-lane | 1998 | Selective |
| | Four-lane freeway | 1998 | Nonselective |
| Missouri | Four-lane freeway | 1992–2000 | Nonselective |
| Pennsylvania (Districts 1, 3, 5, and 8) | Two-lane | 1992–2000 | Selective |
| | Four-lane freeway | 1992–2000 | Nonselective |
| | Four-lane expressway | 1992–2000 | Nonselective |
| Wisconsin | Four-lane freeway | 1999 | Nonselective |
| | Four-lane expressway | 1999 | Nonselective |

It became evident that there are very few differences in the PRPM implementation practices among states. On two-lane roadways, the general practice is to implement two-way yellow PRPMs only on the centerline at a spacing of 80 ft (24 m). On most curves, the spacing of PRPMs is reduced to 40 ft (12 m).

Table 3-3 shows the proportion of the total length of two-lane PRPM treatment sites where PRPMs were implemented at a spacing of either 40 ft (12 m) or 80 ft (24 m). On freeways and expressways, the general practice is to implement one-way, white PRPMs on the lane line only at a spacing of 80 ft.

Table 3-4 provides a summary of the all treatment site data used in the analysis.

**TABLE 3-3 Percentage of two-lane treatment sites with 40-ft and 80-ft PRPM spacings**

| State | % that had 40-ft (12-m) PRPM spacing | % that had 80-ft (24-m) PRPM spacing |
|---|---|---|
| Illinois | 0.5 | 99.5 |
| New Jersey [1] | unknown | unknown |
| New York | 11.1 | 88.9 |
| Pennsylvania | 5.3 | 94.7 |

[1] The spacing of PRPMs at treatment sites in New Jersey could not be confirmed from the videolog recordings received from New Jersey DOT.

### 3.2.2 Reference and Comparison Group Sites

For states in the study group that have selective implementation policies (i.e., Pennsylvania and New York), samples of untreated roadways of the relevant roadway types were identified to compose a reference group from which safety performance functions (SPFs) or crash prediction models were calibrated for each year of the analysis period. Table 3-5 summarizes the reference group data used for this study.

In states where PRPMs were installed nonselectively (e.g., for four-lane freeways in Wisconsin, Missouri, and Pennsylvania and for two-lane roadways in Illinois and New Jersey), the reference group information used for calibrating SPFs made up the before-period data collected for sites with

**TABLE 3-4 Summary of treatment site data used in the analysis**

| State/ Road Type | Miles (Sites) | Before Period | | | | After Period | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Mile-Years | Average AADT (veh/ day) | Crash Count | | Mile-Years | Average AADT (veh/ day) | Crash Count | |
| | | | | Total | Fatal and Injury | | | Total | Fatal and Injury |
| **All two-lane roadways** | **983** | **5153** | **NA** | **8970** | **3011** | **2615** | **NA** | **6006** | **2166** |
| Illinois two-lane roadways | 460 | 2755 | 2850 | 2783 | 706 | 1139 | 2650 | 1133 | 292 |
| New Jersey two-lane roadways | 174 | 348 | 10944 | 1522 | 656 | 696 | 10951 | 2508 | 1219 |
| New York two-lane roadways | 82 | 409 | 9140 | 1431 | 1000 | 164 | 9650 | 1121 | 424 |
| Pennsylvania two-lane roadways | 267 | 1641 | 5486 | 3234 | 649 | 616 | 5887 | 1244 | 231 |
| **All four-lane freeways** | **2713** | **17201** | **NA** | **42472** | **11906** | **6330** | **NA** | **16058** | **4074** |
| Missouri four-lane freeways | 1441 | 10929 | 14007 | 25565 | 8271 | 3488 | 16844 | 9195 | 2720 |
| New York four-lane freeways | 37 | 185 | 15390 | 326 | 180 | 74 | 16370 | 335 | 91 |
| Pennsylvania four-lane freeways | 779 | 3807 | 24995 | 5750 | 741 | 2312 | 29920 | 3640 | 501 |
| Wisconsin four-lane freeways | 456 | 2280 | 20900 | 10831 | 2714 | 456 | 22970 | 2888 | 762 |
| **All four-lane expressways** | **251** | **1228** | **NA** | **2899** | **487** | **471** | **NA** | **1122** | **210** |
| Pennsylvania four-lane expressways | 106 | 503 | 13810 | 725 | 126 | 326 | 16200 | 531 | 86 |
| Wisconsin four-lane expressways | 145 | 725 | 11770 | 2174 | 361 | 145 | 12590 | 591 | 124 |

**TABLE 3-5 Summary and description of reference site data used in the analysis**

| Road type | State | Description | Miles | Mile-years | All crashes | Fatal and injury crashes | Average AADT |
|---|---|---|---|---|---|---|---|
| Two-lane roadways | Pennsylvania | Untreated two-lane roadway sections | 170 | 1690 | 2332 | 455 | 4517 |
| | New York | Untreated two-lane roadway sections | 182 | 1683 | 2400 | 1211 | 4300 |
| | New Jersey | Before-period data of treatment sites | 191 | 1337 | 8737 | 3338 | 12737 |
| | Illinois | Before-period data of treatment sites | 460 | 2755 | 2783 | 706 | 22850 |
| Four-lane freeways | Missouri | Before-period data of treatment sites | 1826 | 14801 | 30274 | 9642 | 13560 |
| | Pennsylvania | Before-period data of treatment sites | 779 | 3807 | 5750 | 741 | 24995 |
| | New York | Untreated two-lane roadway sections | 122 | 1098 | 3387 | 1497 | 12870 |
| | Wisconsin | Before-period data of treatment sites | 456 | 2280 | 10831 | 2714 | 20900 |
| Four-lane divided expressways | Pennsylvania | Before-period data of treatment sites | 106 | 503 | 725 | 126 | 13810 |
| | Wisconsin | Before-period data of treatment sites | 145 | 725 | 2174 | 361 | 11770 |

PRPMs. This meant that data availability for the purpose of calibrating the SPFs would be nonexistent for the period after nonselective installations were implemented and could be scarce toward the completion of the nonselective installations statewide. To calibrate the SPFs for these later years, a comparison group of sites was identified that consisted of as-yet untreated locations or locations on which PRPMs had been installed prior to the beginning of the study period. The comparison group accounted for time trends throughout the SPF calibration period. Special attention was given by the research team when selecting roadways to avoid any roadways near PRPM locations in order to minimize the influence of any spillover or migration effects.

Because of the widespread implementation of PRPMs in Illinois, it was not possible to select a suitable comparison group of sites in this state. Thus, for this state, SPFs were fitted to the data for the later years of the after period to develop time trend factors for these later years.

However, in Wisconsin, the widespread implementation of PRPMs on four-lane freeways and expressways during 1999 resulted in very limited comparison group data for a total of 43 miles of four-lane freeway. To address this constraint and to account for time trends in more recent years (i.e., 1998–2000), the research team collected additional data for urban Interstate highways in Madison County, Wisconsin.

### 3.2.3 Crash Data

The crash databases obtained from each state contained the variables listed in Table 3-6. Table 3-7 shows the period

**TABLE 3-6 Crash data variables obtained from each state**

| Category | Variable |
|---|---|
| Time variables | Crash date<br>Crash time |
| Environmental variables | Road surface condition<br>Weather condition<br>Light condition |
| Crash-related variables | Impact type<br>Crash severity<br>Initial direction<br>Vehicle maneuver<br>Alignment<br>Location type (intersection vs. nonintersection) |
| Roadway variables | Route number<br>Milepost or reference point and offset |

**TABLE 3-7 Crash data period, source, and roadway referencing system**

| State | Period | Source | Referencing System |
|---|---|---|---|
| Illinois | 1991–2000 | Highway Safety Information System (HSIS) | County, route, milepoint |
| Missouri | 1991–2000 | Missouri DOT | Route, milepoint |
| New Jersey | 1991–1998 (excluding 1996) | Internet/New Jersey DOT | Route, milepoint |
| New York | 1991–2000 | New York DOT | Reference marker |
| Pennsylvania | 1991–2001 | Pennsylvania DOT | County, route, segment, offset |
| Wisconsin | 1994–2001 | Wisconsin DOT | Route, reference point, offset |

for which crash data were collected, the data source, and the roadway referencing systems. Table 3-8 defines the crash types used in the safety analysis.

Extensive examination of the data was undertaken. The iterative process enabled the research team to improve and overcome most of the issues found in the databases. Some of these issues are described here. For example, during 1996, the location referencing system in Illinois changed. Before 1996, the reference for a route would restart at mile point zero each time it crossed a county boundary. After 1996, the reference for a route would continue through the county boundary without restarting at mile point zero. This change in the referencing system was reflected in the crash data files. To compute correct and comparable before-and-after crash totals for the different PRPM roadway sections, the mile point data in the post-1996 crash and roadway attribute files for each PRPM route were aligned with the data of the pre-1996 referencing system.

Another example of data preparation is the assessment of crash counts on freeways and expressways in Wisconsin. This data set revealed that there was a disproportionately greater number of crashes recorded involving vehicles traveling north and east than involving vehicles traveling south and west. This observed anomaly is likely the result of crashes being miscoded. Therefore, the safety analyses for freeways and expressways in Wisconsin considered the different travel ways together.

Non-intersection-related crashes were extracted from the databases for the safety analysis of PRPM installations along road segments. The daytime and nighttime crashes were defined on the basis of the sunset and sunrise times received from a national source of such times for different months of the year for each state (*38*).

### 3.2.4 Roadway Attribute Data

Table 3-9 lists the roadway variables at PRPM and reference group sites according to their importance for the evaluation analysis. The variables were classified as critical or desirable for each of the roadway types. Table 3-10 lists the roadway data files and their sources. The research team reviewed the data files to determine any missing data variables in the recorded databases or hard copies. For every missing data variable deemed critical for comprehensive safety evaluation of PRPM installations, means to collect the information were explored, and whenever at all feasible, those variables were collected by the members of the research team. Some examples are described next.

The data received for two-lane treatment and reference group sites in New York and New Jersey contained no information on horizontal alignment (e.g., curve location, curve radius, and curve length). This information for horizontal curves for New York and New Jersey was obtained from individual roadway design drawings, from New York DOT's headquarters in Albany, and from New Jersey DOT's headquarters in Trenton.

Information on terrain type for New Jersey was obtained from video-log recordings. Information on terrain type for Illinois was collected during field visits to District 8.

Tables 3-11, 3-12, and 3-13 provide a summary of the roadway data collected at two-lane treatment sites for lane widths, degree of curvature, and terrain type, respectively. Tables 3-14 through 3-19 provide a summary of the roadway data collected for lane widths, shoulder widths, and environment types at four-lane freeway and four-lane expressway treatment sites.

### 3.2.5 Traffic Volume Data

The variables required at treatment sites, reference group sites, and comparison group sites were

- AADT volumes,
- Percentage of annual average nighttime traffic volumes, and
- Percentage of heavy vehicles.

*(text continued p. 31)*

**TABLE 3-8 Crash type definitions**

| Crash Type | Definition |
|---|---|
| Total | All crashes reported and entered in the database |
| Fatal and injury | Crashes that resulted in fatal or nonfatal injuries |
| Daytime | Crashes that occurred between sunrise and sunset |
| Nighttime | Crashes that occurred between sunset and sunrise |
| Dry | Crashes that occurred on "road surface condition" reported as "dry" |
| Wet | Crashes that occurred on "road surface condition" reported as snow, wet, ice, or any other nondry conditions |
| Wet-nighttime | Crashes that occurred "road surface condition" reported as snow, wet, ice, or any other nondry conditions between sunset and sunrise |
| Guidance-related | Crashes with reported "impact type" as run-off-road, head-on, and sideswipe for fatal, injury, and property-damage-only combined |
| Head-on | Crashes with reported "impact type" as head-on for fatal, injury, and property-damage-only combined |

**TABLE 3-9 Critical and desirable roadway variables**

| Variables | Two-lane | Four-lane expressway | Four-lane freeway |
|---|---|---|---|
| Type of location (e.g., curve or tangent) | ✓ | Δ | Δ |
| Terrain type (flat, rolling, mountainous) | ✓ | ✓ | Δ |
| Type of access control | ✓ | ✓ | ✓ |
| Roadway width | ✓ | ✓ | ✓ |
| Number of lanes | ✓ | ✓ | ✓ |
| Lane width | ✓ | ✓ | ✓ |
| Median type (e.g., raised, painted, and no median) | NR | ✓ | ✓ |
| Left and right shoulder types (e.g., surfaced and gravel) | ✓ | ✓ | ✓ |
| Horizontal alignment (e.g., degree of curve) | ✓ | Δ | Δ |
| Vertical alignment (e.g., grade and vertical curvature) | Δ | Δ | Δ |
| Median width | NR | Δ | Δ |
| Left and right shoulder widths | Δ | Δ | Δ |
| Design speed | Δ | Δ | Δ |
| Speed limit | Δ | Δ | Δ |
| 85th percentile speed | Δ | Δ | Δ |

✓ = Critical variables.
Δ = Desirable variables.
NR = Variables not relevant (two-lane roadways do not have medians).

**TABLE 3-10 Roadway data files and their sources**

| State | Data Files Received | Source |
|---|---|---|
| Illinois | Sufficiency files for 1991, 1992, 1994, and 1997 to 2000 | Highway Safety Information System (HSIS) |
| Missouri | Roadway inventory<br>Rumble strip inventory<br>Median inventory | Missouri DOT |
| New Jersey | Straight line diagrams (1994 to 2001) | New Jersey DOT |
| New York | Sufficiency files for 1991 to 2001 | New York DOT |
| Pennsylvania | Roadway inventory<br>Guiderail inventory<br>Shoulder inventory<br>Alignment data | Pennsylvania DOT |
| Wisconsin | Highway log | Wisconsin DOT |

**TABLE 3-11 Summary information: lane widths at two-lane treatment sites**

| State | % of total roadway length for lane widths ≤ 10 ft | % of total roadway length for lane widths > 10 ft and ≤ 11 ft | % of total roadway length for lane widths > 11 ft and ≤ 12 ft | % of total roadway length for lane widths >12 ft | Minimum lane width (ft) | Maximum lane width (ft) | Average lane width (ft) |
|---|---|---|---|---|---|---|---|
| Illinois | 5.0 | 30.2 | 54.3 | 10.6 | 8.0 | 22.0 | 11.6 |
| New Jersey | 44.0 | 6.5 | 46.6 | 2.8 | 10.0 | 25.0 | 11.2 |
| New York | 2.4 | 22.8 | 72.2 | 2.6 | 10.0 | 25.0 | 11.8 |
| Pennsylvania | 13.7 | 32.3 | 45.6 | 8.4 | 8.0 | 32.0 | 11.8 |

**TABLE 3-12 Summary information: degree of curvature at two-lane treatment sites**

| State | % of total roadway length when DOC = 0 | % of total roadway length when DOC ≤ 3.5 | % of total roadway length when DOC > 3.5 | Minimum DOC | Maximum DOC | Average DOC |
|---|---|---|---|---|---|---|
| Illinois | 97.4 | 0.8 | 1.8 | 0.0 | 114.9 | 0.13 |
| New Jersey | 87.1 | 9.0 | 3.9 | 0.0 | 9.99 | 0.36 |
| New York | 68.5 | 18.7 | 12.8 | 0.0 | 76.4 | 4.04 |
| Pennsylvania | 50.0 | 35.6 | 14.4 | 0.0 | 68.24 | 1.61 |

DOC = degree of curvature.

**TABLE 3-13 Summary information: terrain type at two-lane treatment sites**

| State | % of total roadway length on flat terrain | % of total roadway length on rolling terrain | % of total roadway length on mountainous terrain |
|---|---|---|---|
| Illinois | 81.9 | 9.1 | 0.0 |
| New Jersey | 61.1 | 38.9 | 0.0 |
| New York | 61.5 | 38.5 | 0.0 |
| Pennsylvania | 85.0 | 15.0 | 0.0 |

**TABLE 3-14 Summary information: lane widths at four-lane freeway treatment sites**

| State | % of total roadway length when lane width < 12 ft | % of total roadway length when lane width = 12 ft | % of total roadway length when lane width > 12 ft | Minimum lane width (ft) | Maximum lane width (ft) | Average lane width (ft) |
|---|---|---|---|---|---|---|
| Missouri | 0.1 | 98.7 | 1.2 | 11.0 | 18.0 | 12.0 |
| New York | 0.5 | 98.7 | 0.8 | 9.0 | 17.0 | 12.0 |
| Pennsylvania | 1.9 | 94.2 | 3.5 | 10.0 | 25.5 | 12.2 |
| Wisconsin | 0.0 | 99.7 | 0.3 | 12.0 | 18.0 | 12.0 |

**TABLE 3-15 Summary information: shoulder widths at four-lane freeway treatment sites**

| State | % of total roadway length when shoulder width ≤ 4 ft | % of total roadway length when shoulder width > 4 ft and ≤ 6 ft | % of total roadway length when shoulder width > 6 ft and ≤ 8 ft | % of total roadway length when shoulder width > 8 ft and ≤ 10 ft | % of total roadway length when shoulder width > 10 ft | Minimum shoulder width (ft) | Maximum shoulder width (ft) | Average shoulder width (ft) |
|---|---|---|---|---|---|---|---|---|
| Missouri | 8.2 | 2.9 | 2.2 | 86.7 | 0.0 | 3.0 | 10.0 | 9.3 |
| New York | 0.2 | 0.1 | 2.0 | 56.8 | 40.9 | 0.0 | 12.0 | 10.8 |
| Pennsylvania | 45.7 | 3.0 | 6.3 | 43.1 | 2.0 | 0.0 | 12.0 | 6.3 |
| Wisconsin | 0.3 | 0.4 | 63.1 | 33.7 | 2.5 | 0.0 | 13.0 | 8.5 |

Table 3-20 describes the AADT data received and data sources for each state. For Wisconsin, New Jersey, and Illinois, AADT data could not be obtained for each year of the study period. Estimation procedures, using the existing counts, were applied in the calculation of the missing AADT volumes.

None of the data files received from the study group states contained information on the percentage of annual average nighttime traffic (i.e., annual average traffic between sunset and sunrise). Permanent traffic counting stations (which collect continuous annual traffic counts) and average monthly sunrise and sunset times were used to estimate the percentage of annual average nighttime traffic at the various roadways.

### 3.2.6 Additional Delineation and Guidance Measures

Information was collected on the following additional delineation and guidance measures:

- Illumination,
- Rumble strips, and
- Delineation (e.g., chevrons and post-mounted delineators).

Since none of the data files received from the states contained information on these additional delineation and guidance measures, the research team followed other data collection strategies (see Table 3-21).

Tables 3-22, 3-23, and 3-24 show the percentage of two-lane treatment sites with and without illumination, additional delineation (e.g., chevrons and post-mounted delineators), and shoulder rumble strips, respectively.

The states reported that chevrons are not placed on four-lane freeways and expressways. However, post-mounted delineators are placed along freeways at a spacing of 60 to 100 ft (18 to 30 m). Less than 1 percent of four-lane freeway and expressway sites are illuminated.

Tables 3-25 and 3-26 show the percentage of treatment site length with and without shoulder rumble strips for freeways and expressways, respectively.

**TABLE 3-16 Summary information: environment type at four-lane freeway treatment sites**

| State | % of total roadway length (urban) | % of total roadway length (rural) |
|---|---|---|
| Missouri | 19.1 | 80.9 |
| New York | 32.1 | 67.9 |
| Pennsylvania | 29.7 | 70.3 |
| Wisconsin | 12.6 | 87.4 |

**TABLE 3-17 Summary information: lane widths at four-lane expressway treatment sites**

| State | % of total roadway length when lane width < 12 ft | % of total roadway length when lane width = 12 ft | % of total roadway length when lane width > 12 ft | Minimum lane width (ft) | Maximum lane width (ft) | Average lane width (ft) |
|---|---|---|---|---|---|---|
| Pennsylvania | 11.0 | 78.9 | 10.1 | 8.0 | 25.0 | 12.4 |
| Wisconsin | 0.0 | 97.2 | 2.8 | 12.0 | 18.0 | 12.0 |

**TABLE 3-18 Summary information: shoulder widths at four-lane expressway treatment sites**

| State | % of total roadway length when shoulder width ≤ 4 ft | % of total roadway length when shoulder width > 4 ft and ≤ 6 ft | % of total roadway length when shoulder width > 6 ft and ≤ 8 ft | % of total roadway length when shoulder width > 8 ft and ≤ 10 ft | % of total roadway length when shoulder width > 10 ft | Minimum shoulder width (ft) | Maximum shoulder width (ft) | Average shoulder width (ft) |
|---|---|---|---|---|---|---|---|---|
| Pennsylvania | 54.0 | 6.1 | 21.3 | 8.9 | 9.7 | 0.0 | 12.0 | 4.8 |
| Wisconsin | 0.4 | 1.6 | 73.2 | 19.8 | 5.0 | 2.0 | 13.0 | 8.5 |

**TABLE 3-19 Summary information: environment type at four-lane expressway treatment sites**

| State | % of total roadway length (urban) | % of total roadway length (rural) |
|---|---|---|
| Pennsylvania | 18.6 | 81.4 |
| Wisconsin | 11.6 | 88.4 |

**TABLE 3-20 AADT data and sources**

| State | Information Received | Source |
|---|---|---|
| Illinois | AADTs for 1991, 1992, 1994, and 1997 to 2000 | Highway Safety Information System (HSIS) |
| Missouri | AADTs for 1991 to 2001 | Missouri DOT |
| New Jersey | Short-term counting station data (downloaded from Internet)—various years | New Jersey DOT |
| New York | AADTs for 1991 to 2001 | New York DOT |
| Pennsylvania | AADTs for 1991 to 2001 | Pennsylvania DOT |
| Wisconsin | Traffic count books for 1995, 1997, and 2000 | Wisconsin DOT |

**TABLE 3-21 Additional delineation and guidance measures: data collection strategies**

| State | Data Collection Strategies |
|---|---|
| Illinois | Undertaking field visits |
| Missouri | Contacting DOT staff |
| New Jersey | Reviewing video-logs |
| New York | Reviewing video-logs |
| Pennsylvania | Reviewing video-logs and contacting DOT staff |
| Wisconsin | Contacting DOT staff |

**TABLE 3-22 Percentage of two-lane treatment sites with and without illumination**

| State | % with presence of illumination | % without presence of illumination |
|---|---|---|
| Illinois | 7.1 | 92.9 |
| New Jersey | 42.0 | 58.0 |
| New York | 26.0 | 74.0 |
| Pennsylvania | 0.0 | 100.0 |

**TABLE 3-23 Percentage of two-lane treatment sites with and without additional delineation (chevrons or post-mounted delineators)**

| State | % with additional delineation | % without additional delineation |
|---|---|---|
| Illinois | 1.0 | 99.0 |
| New Jersey | 1.0 | 99.0 |
| New York | 26.0 | 74.0 |
| Pennsylvania | 7.4 | 92.6 |

**TABLE 3-24 Percentage of two-lane treatment sites with and without shoulder rumble strips**

| State | % with rumble strips | % without rumble strips |
|---|---|---|
| Illinois | 0.0 | 100.0 |
| New Jersey | 0.0 | 100.0 |
| New York | 0.0 | 100.0 |
| Pennsylvania | 6.6 | 93.4 |

**TABLE 3-25 Percentage of four-lane freeway treatment sites with and without shoulder rumble strips**

| State | % with rumble strips | % without rumble strips |
|---|---|---|
| Missouri | 53.1 | 46.9 |
| New York | 63.3 | 36.7 |
| Pennsylvania | 37.7 | 62.3 |
| Wisconsin | 100.0 | 0.0 |

**TABLE 3-26 Percentage of four-lane expressway treatment sites with and without shoulder rumble strips**

| State | % with rumble strips | % without rumble strips |
|---|---|---|
| Pennsylvania | 21 | 79 |
| Wisconsin | 100 | 0 |

CHAPTER 4

# SAFETY IMPACT ANALYSIS OF PRPM INSTALLATIONS

Two sets of analyses were undertaken to investigate the safety impact of snowplowable PRPMs on non-intersection-related crashes. First, composite analyses based on the empirical Bayes before-and-after procedure were used to assess the overall impact of PRPMs on different crash types. The same procedure was also applied to a sample of adjacent nontreatment sites to assess whether there were any spillover (i.e., crash migration) effects associated with PRPM implementation for two-lane roadways in Pennsylvania. Second, a disaggregate analysis, applying univariate analysis and multivariate regression techniques, was performed on the results of the nighttime composite analysis for individual sites. The disaggregate analysis aimed to determine the circumstances under which PRPMs were beneficial to safety. The results of these analyses were used to support the development of PRPM implementation guidelines.

This chapter first describes the two methodologies (composite and disaggregate) used to evaluate the safety performance of PRPMs. It then presents the results of these analyses for two-lane roadways, four-lane freeways, and four-lane divided expressways, respectively. A more in-depth discussion of the results is presented in Chapter 5. Appendix A contains tables with the individual safety performance functions and annual factors developed during the analysis.

## 4.1 COMPOSITE ANALYSIS METHODOLOGY

An empirical Bayes before-and-after procedure (*39*) is presented in this section. The procedure was used to account for RTM while normalizing, where possible, for differences between the before periods and after periods. Overcoming these differences, as described in Section 2.2, is key to achieving a statistically defensible analysis. The empirical Bayes procedure accommodates temporal differences between before and after periods, such as traffic volumes, weather, traffic reporting practices, driving demographics, and vehicle technology.

The steps followed by the empirical Bayes approach are as follows:

- *Step 1:* Calibrate SPFs for total nonintersection crashes using data from the reference groups without PRPMs, as described in Chapter 3. The calibration of SPFs applies negative binomial generalized linear modeling. SPFs for disaggregate crash types were obtained by applying a multiplier to the SPF for total crashes. This multiplier is the ratio for the reference group and consists of the number of crashes of a specific type divided by the total number of crashes. To account for the effect of trends in safety not related to traffic volumes, annual factors were estimated using a procedure documented by Harwood et al. (*40*). The resulting SPFs, multipliers ($\alpha_f$), and annual factors are presented in Appendix A.
- *Step 2:* Determine SPF predictions for each year in the before and after period at each PRPM location [i.e., $E(K_1) \ldots E(K_{n-1}), E(K_{n+1}) \ldots E(K_Y)$], where $n$ is the PRPM implementation year.
- *Step 3*: Determine $C_y$, the ratio of the SPF estimate for Year $y$ relative to Year 1

$$C_y = \frac{E(K_y)}{E(K_1)} \tag{4-1}$$

- *Step 4*: Determine $C_b$ and $C_a$, the sum of the ratios during the before period and the after period, respectively:

$$C_b = \sum_{1}^{n-1} C_y \tag{4-2}$$

$$C_a = \sum_{n+1}^{Y} C_y \tag{4-3}$$

- *Step 5*: Calculate $\hat{K}_1$, the expected nonintersection crash frequency for the base year, Year 1:

$$\hat{K}_1 = \frac{X_b + k}{k / E(K_1) + C_b} \tag{4-4}$$

Where

$X_b$ = Number of recorded nonintersection crashes during the before period and

$k$ = Constant for a given model. $k$ is estimated from the SPF calibration process with the use of a maximum likelihood procedure. In the calibration process, a negative binomial distributed error structure is assumed, with $k$ being the dispersion parameter of this distribution.

- *Step 6*: Calculate the total expected number of nonintersection crashes ($B$) and its variance [VAR($B$)] during the after period that would have occurred if PRPMs were not implemented:

$$B = \hat{K}_1 \times C_a \tag{4-5}$$

$$\mathrm{VAR}(B) = \frac{B + C_a}{C_b + k/E(K_1)} \tag{4-6}$$

- *Step 7*: Determine for each site its index of effectiveness ($\theta_{site}$) and it variance VAR($\theta_{site}$):

$$\theta_{site} = \frac{A}{(B)\left(1 + \mathrm{VAR}(B)/B^2\right)} \tag{4-7}$$

$$\mathrm{VAR}(\theta_{site}) = \frac{\theta_{site}^2\left(1/A + \mathrm{VAR}(B)/B^2\right)}{\left(1 + \mathrm{VAR}(B)/B^2\right)^2} \tag{4-8}$$

Where

$A$ = Total crash count during the after period.

- *Step 8*: Determine the composite index of effectiveness ($\theta$) and it variance VAR($\theta$) for all sites combined:

$$\theta = \frac{\sum A}{\left(\sum B\right)\left(1 + \left(\sum \mathrm{VAR}(B)\right)/\sum B^2\right)} \tag{4-9}$$

$$\mathrm{VAR}(\theta) = \frac{\theta^2\left(1/\left(\sum A\right) + \left(\sum \mathrm{VAR}(B)\right)/\left(\sum B\right)^2\right)}{\left(1 + \left(\sum \mathrm{VAR}(B)\right)/\left(\sum B\right)^2\right)^2} \tag{4-10}$$

Where

$\sum A$ = Sum of all crashes over the after period for all PRPM locations,

$\sum B$ = Sum of the expected number of crashes ($B$) for all PRPM locations, and

$\sum \mathrm{VAR}(B)$ = Sum of the variances of the expected number of crashes, VAR($B$).

The standard error (s.e.) of $\theta$ is given by

$$\text{s.e.}(\theta) = \sqrt{\mathrm{VAR}(\theta)} \tag{4-11}$$

The percent change in the number of crashes is equal to $100(1 - \theta)$; thus, $\theta = 0.7$ denotes a 30-percent reduction in crashes. The standard error (s.e.) indicates the accuracy of the index of effectiveness. An approximate 95-percent confidence interval can be determined by adding and subtracting twice the value of the standard error ($2 \times$ s.e.) from the value of $\theta$. Thus, if $\theta$ equals 0.7 and the standard error is 0.12, then the confidence interval ranges from 0.46 to 0.94. This confidence interval indicates a significant positive effect.

To summarize, if the confidence interval contains the value 1, then no significant effect has been observed. If $\theta$ is less than the value 1 and the upper value of the confidence interval is less than the value 1, then the treatment has had a significant positive effect on safety (i.e., a reduction in crashes). Conversely, if $\theta$ is greater than 1 and the lower value of the confidence interval is greater than 1, then the treatment had a significant negative effect on safety (i.e., an increase in crashes).

## 4.2 DISAGGREGATE ANALYSIS METHODOLOGY

Disaggregate analysis performed on nighttime crashes included both univariate exploratory analysis and formal multivariate modeling. The univariate exploratory analysis was used to identify and isolate factors that might be associated with the variation in the safety impact of PRPM installations. The results of the exploratory analysis were used to guide the multivariate modeling in an attempt to relate the safety impact of PRPMs to variables found in the initial univariate analysis. These two analyses are described below.

### 4.2.1 Univariate Exploratory Analysis

Using two-dimensional plots and spreadsheets sorted on variables of interest, the relationship between various factors and the calculated index of effectiveness ($\theta$) for each site was explored by visual inspection for differences in effects that might relate to different levels of a variable in the statistical analysis. For the purpose of this study, a site is a homogeneous segment of road represented by a set of attributes (shoulder width, type, lane width, AADT, terrain, guide rails, horizontal alignment, etc.).

### 4.2.2 Multivariate Modeling of the Index of Effectiveness ($\theta$)

The results of the nighttime crash composite analysis for all states were combined to develop a model to estimate the index of effectiveness (i.e., the safety effect of PRPMs) using traffic volumes, site characteristics (e.g., surface width, shoulder widths, illumination, and other delineators), and PRPM characteristics (e.g., spacing) as explanatory variables. The model form is a linear model with a gamma error distribution for $\theta$ (*39*). The model was of the general form:

$$\theta_{site} = \alpha + b_1 x_1 + b_2 x_2 + b_3 x_3 + \ldots\ b_n x_n \tag{4-12}$$

Where

$$\alpha = \text{Calibrated intercept and}$$
$$b_1, b_2, \ldots b_n = \text{Estimated effects on } \theta \text{ of factors or variables } x_1, x_2, \ldots x_n.$$

With this model form, categorical variables were desirable to ascertain conditions that favor PRPM installation. Thus, for variables such as degree of curvature and AADT, ranges had to be assigned an ordinal value. This assignment of ordinal values was an iterative process considering the number of crashes in a range, the variation in crashes per mile-year within and among ranges, and the observations from the univariate exploratory analysis.

Stepwise linear regression was performed using the SAS™ statistical analysis software package (*41*), estimates of θ, and values of factors for individual sites. Statistically nonsignificant variables at the 90-percent degree of confidence were eliminated. The absence of a variable in the final model does not imply that the variable does not affect the safety impact of PRPM because a statistically nonsignificant effect could result from correlation with other variables, a lack of variation in the data, or a sample that is too small. In addition, the generally small size of the composite safety effects of PRPMs strongly indicates that one is unlikely to detect many factors that affect the safety effect of PRPMs.

## 4.3 RESULTS OF ANALYSES FOR TWO-LANE ROADWAYS

### 4.3.1 Composite Analysis

Table 4-1 shows the results of the composite safety evaluation of snowplowable PRPMs on nonintersection segments of two-lane roadways. Statistically significant results (at the 95-percent confidence level) are shown in bold. Key findings are as follows:

- Illinois shows significant increases in total crashes (9.1 percent), daytime crashes (17.9 percent), wet weather crashes (15.5 percent), and dry weather crashes (8.7 percent) after the nonselective implementation of PRPMs.
- New Jersey shows a significant decrease in head-on crashes (19.6 percent) after the nonselective implementation of PRPMs.
- New York shows a significant decrease in total crashes (9.5 percent), nighttime crashes (13 percent), wet weather crashes (20 percent), and wet weather nighttime crashes (23.9 percent) after the selective implementation of PRPMs (at sites selected on the basis of wet-night crash history).
- Pennsylvania shows significant increases in head-on crashes (37.2 percent) and guidance-related crashes (19.7 percent) after the selective implementation of PRPMs (at sites selected on the basis of overall nighttime crash experience).

### 4.3.2 Univariate Disaggregate Analysis

In the univariate disaggregate analysis, key findings are as follows:

- The safety benefits of PRPMs on nighttime crashes increases as traffic volumes increase, decreases as degree of curvature increases, and decreases as roadway width and shoulder width decrease.
- There is a correlation between traffic volumes and roadway design parameters (e.g., roadway width and shoulder width) that could mask safety effects and that necessitates the more formal multivariate modeling described in the next section.

### 4.3.3 Multivariate Modeling of the Index of Effectiveness ($\theta_{site}$)

Table 4-2 shows the results of the multivariate modeling of $\theta_{site}$. The model includes variables relating to AADT and degree of curvature only. These variables are significant at a 95-percent confidence level. Other variables relating to PRPM design (e.g., spacing), other delineation measures (e.g., chevrons), and roadway geometry (e.g., lane widths and shoulder widths) were also considered, but were found not to improve the model significantly. The sample size for the modeling for two-lane roadways consisted of 925 miles.

It was necessary to group data for modeling because segments tended to be short. This tendency to be short resulted in considerable variations in individual values of θ, models with nonsignificant parameter estimates, and a poor overall fit when ungrouped data were used. The data used for modeling were combined when sites shared a set of characteristics (e.g., all urban, no curvature, AADT < 20,000). The data were further grouped by segment lengths, the count of nighttime collisions in the after period, and the expected after period collisions without PRPM over all sites. Using these groupings, a θ value was obtained. The model was estimated with the characteristics of each group as individual data points, with weights applied for the total length of the segments in a group.

To facilitate the grouping, ranges for variables such as degree of curvature and AADT had to be assigned an ordinal value. This was accomplished with the use of an iterative process to determine the best ranges by considering the number of crashes within a range, the variation in crashes per mile-year within and among ranges, and the observations from the univariate analysis.

The degree of curvature variable is the degree of curve in degrees per 100 ft and is calculated as (18,000/3.14 × radius), where radius is the radius of the curve in feet. Roadways with a degree of curvature less than 3.5 include gentle curves as well as roadway tangent sections (i.e., where the degree of curvature equals 0). Table 4-3 shows the accident modification factors (AMFs) derived from the respective models in Table 4-2. An AMF, like the index of effectiveness, is an index of how much crash experience is expected to change

**TABLE 4-1 Results of safety evaluation of two-lane roadways (nonintersection crashes) with snowplowable PRPMs (selective and nonselective implementation)***

| Crash Type | Illinois | | | New Jersey | | | New York | | | Pennsylvania | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | (Nonselective) | | | (Nonselective) | | | (Selective) | | | (Selective) | | |
| | # Sites = 5347<br># Miles = 460.53 | | | # Sites = 779<br># Miles = 173.98 | | | # Sites = 226<br># Miles = 81.75 | | | # Sites = 5383<br># Miles = 266.94 | | |
| | Obs[1] | θ | % | Obs | θ | % | Obs | θ | % | Obs | θ | % |
| | Exp[2] | s.e. | Ch[3] | Exp | s.e. | Ch | Exp | s.e. | Ch | Exp | s.e. | Ch |
| Total | 1133 | **1.091** | **9.1** | 3508 | 1.032 | 3.2 | 1121 | **0.905** | **-9.5** | 1244 | 0.980 | -2.0 |
| | *1038* | *0.035* | | *3399* | *0.027* | | *1238* | *0.034* | | *1270* | *0.030* | |
| Fatal and injury | 292 | 1.071 | 7.1 | 1219 | 0.955 | -4.5 | 424 | 1.020 | 2.0 | 231 | 1.017 | 1.7 |
| | *272* | *0.065* | | *1275* | *0.038* | | *415* | *0.057* | | *227* | *0.068* | |
| Daytime | 592 | **1.179** | **17.9** | 2338 | 1.047 | 4.7 | 672 | 1.003 | 0.3 | 739 | 0.963 | -3.7 |
| | *502* | *0.051* | | *2232* | *0.034* | | *669* | *0.048* | | *767* | *0.038* | |
| Daytime fatal and injury | 167 | 1.080 | 8.0 | 861 | 0.976 | -2.4 | 293 | 1.074 | 7.4 | 133 | 0.978 | -2.2 |
| | *155* | *0.086* | | *882* | *0.044* | | *272* | *0.072* | | *136* | *0.086* | |
| Nighttime | 541 | 1.001 | 0.1 | 1148 | 0.991 | -0.9 | 449 | **0.873** | **-12.7** | 505 | 1.039 | 3.9 |
| | *540* | *0.045* | | *1158* | *0.040* | | *514* | *0.052* | | *486* | *0.048* | |
| Nighttime fatal and injury | 156 | 1.106 | 10.6 | 350 | 0.899 | -10.1 | 131 | 1.000 | 0.0 | 98 | 1.074 | 7.4 |
| | *141* | *0.091* | | *389* | *0.058* | | *131* | *0.097* | | *91* | *0.110* | |
| Dry | 773 | **1.087** | **8.7** | 2601 | 1.05 | 5.0 | 764 | 1.047 | 4.7 | 798 | 0.978 | -2.2 |
| | *711* | *0.041* | | *2476* | *0.032* | | *729* | *0.048* | | *816* | *0.037* | |
| Wet | 284 | **1.155** | **15.5** | 876 | 0.972 | -2.8 | 333 | **0.798** | **-20.2** | 440 | 1.047 | 4.7 |
| | *246* | *0.072* | | *900* | *0.045* | | *417* | *0.05* | | *420* | *0.053* | |
| Head-on | 28 | 0.859 | -14.1 | 180 | **0.804** | **-19.6** | Sample size too small | | | 120 | **1.372** | **37.2** |
| | *-33* | *0.163* | | *224* | *0.068* | | | | | *87* | *0.127* | |
| Wet-night | Sample size too small | Sample size too small | | Sample size too small | Sample size too small | | 140 | **0.761** | **-23.9** | Sample size too small | Sample size too small | |
| | | | | | | | 183 | 0.075 | | | | |
| Guidance | 397 | 1.018 | 1.8 | Sample size too small | Sample size too small | | Sample size too small | | | 279 | **1.197** | **19.7** |
| | 390 | 0.053 | | | | | | | | 233 | 0.074 | |

*A site is a homogeneous segment of road represented by a set of attributes (shoulder width, type, lane width, AADT, terrain, guide rails, horizontal alignment, etc.). Statistically significant results (at 95% confidence level) are shown in **bold.**

[1] Obs = Observed crash frequency.

[2] Exp = Expected crash frequency.

[3] Ch = change.

following the implementation of a measure such as PRPMs. The AMF is the ratio between the number of crashes per unit of time expected after a measure is implemented and the number of crashes per unit of time estimated if the implementation does not take place. An AMF less than 1 would indicate a positive safety effect (i.e., a reduction in crashes), while an AMF greater than 1 would indicate a negative safety effect (i.e., an increase in crashes). For example, according to Table 4-2, at AADTs ranging between 15,000 and 20,000 on a roadway with a degree of curvature less than 3.5, the AMF is 0.757 (1.1573 − 0.4004), which translates into a 24.3-percent [100(1 − 0.757)] reduction.

The results of the multivariate modeling of the index of effectiveness confirm the observations from the univariate

**TABLE 4-2 Index of effectiveness model for two-lane roadways (nighttime crashes)**

| Model Parameters | Applicable Condition | Estimate | Standard Error | *p*-value |
|---|---|---|---|---|
| Constant | AADT ≤ 5000<br>Degree of curvature ≤ 3.5 | 1.1573 | 0.0260 | < 0.001 |
| AADT 2 | 5000 < AADT ≤ 15000 | -0.1700 | 0.0395 | 0.003 |
| AADT 3 | 15000 < AADT ≤ 20000 | -0.4004 | 0.0607 | < 0.001 |
| Degree of curvature | Degree of curvature > 3.5 | 0.2736 | 0.0824 | 0.011 |

**TABLE 4-3 AMFs (nighttime crashes) derived from Table 4-2**

| AADT (veh/day) | AMF when DOC ≤ 3.5 | AMF when DOC > 3.5 |
|---|---|---|
| 0–5000 | 1.16 | 1.43 |
| 5001–15000 | 0.99 | 1.26 |
| 15001–20000 | 0.76 | 1.03 |

DOC = Degree of curvature.

analysis that, generally, PRPMs are more effective on higher-volume roadways (possibly a reflection of the higher design standards of these highways) and on roadways with more gentle curvature. For example, at AADTs ranging between 15,000 and 20,000 on a roadway with a degree of curvature less than 3.5, a decrease in nighttime crashes of 24.3 percent following PRPM installation can be estimated from the model as noted above. At lower AADTs and sharper curvature, PRPMs can in fact be associated with an increase in crashes. For example, for PRPMs installed on roadways with AADTs between 5,000 and 15,000, an increase in nighttime crashes of 26 percent can be estimated from the model. That PRPMs are more effective on roadways with more gentle curvature (i.e., where the degree of curvature is less than 3.5) is contrary to a belief held by many. One possible explanation is that PRPMs may promote an increase in operating speeds and that the speed increase is a greater safety concern on a sharper curve.

### 4.3.4 Spillover Analysis

The same before-and-after evaluation methodology used for PRPM locations was applied to a sample of road segments found immediately surrounding the treated road segments to examine possible migration and spillover effects. As discussed in Chapter 2, if a significant spillover effect were found, it would have been necessary to consider this effect in assessing the net effect of PRPM installations.

Pennsylvania two-lane roadways were selected for the spillover study because their PRPMs were installed selectively, and the state DOT had the required data to support a spillover analysis study. New York, despite its selective policy for PRPM installation, did not have sufficient data for a spillover analysis. In New Jersey, spillover analysis could not be undertaken for two-lane facilities and for four-lane freeways and expressways because of the nonselective implementation policies. The nonselective policies resulted in too small samples of potential spillover sites.

Using data for Pennsylvania two-lane roadways, several nonoverlapping locations within 2 miles of a given PRPM installation were identified. The results of the spillover analysis are shown in Table 4-4.

According to the results of the statistical analysis for the sample of two-lane roadways in the state of Pennsylvania, there were no significant spillover effects to adjacent roadways to those roadways where snowplowable PRPM were installed.

## 4.4 RESULTS OF ANALYSIS FOR FOUR-LANE FREEWAYS

### 4.4.1 Composite Analysis

Table 4-5 shows the results of the composite safety evaluation of PRPMs on four-lane freeways. Statistically significant results (at 95-percent confidence level) are shown in bold.

As mentioned in Chapter 3, the widespread implementation of PRPMs on four-lane freeways and expressways during 1999 meant that Wisconsin DOT could only provide

**TABLE 4-4 Results of spillover analysis: two-lane roadways in Pennsylvania (total crashes)**

| Crash Type | Pennsylvania Two-Lane Spillover Sites<br># Sites[1] = 5227<br># Miles = 306.55 | | |
|---|---|---|---|
| | Obs[2] / Exp[3] | θ / s.e. | % Ch[4] |
| Total | 1447 | 1.048 | 4.8 |
| | 1381 | 0.030 | |

[1] A site is a homogeneous segment of road represented by a set of attributes (shoulder width, type, lane width, AADT, terrain, guide rails, horizontal alignment, etc.).

[2] Obs = Observed crash frequency.

[3] Exp = Expected crash frequency.

[4] Ch = change.

**TABLE 4-5 Results of safety evaluation of four-lane freeways (nonselective implementation) with snowplowable PRPMs**

| Crash Type | Missouri Freeway # Sites[1] = 1327 # Miles = 1441.80 | | | New York Freeway # Sites = 64 # Miles = 36.49 | | | Pennsylvania Freeway # Sites = 1629 # Miles = 778.93 | | |
|---|---|---|---|---|---|---|---|---|---|
| | Obs[2] Exp[3] | θ s.e.[4] | % Ch[5] | Obs Exp | θ s.e. | % Ch | Obs Exp | θ s.e. | % Ch |
| Total | 9195 *9394* | 0.979 *0.012* | -2.1 | 335 *324* | 1.031 *0.074* | 3.1 | 3640 *3860* | **0.943** *0.019* | **-5.7** |
| Fatal and Injury | 2720 *2876* | **0.946** *0.021* | **-5.4** | 91 *77* | 1.179 *0.141* | 17.9 | 501 *501* | 1.000 *0.047* | 0.0 |
| Daytime | 5955 *6080* | 0.979 *0.015* | -2.1 | 177 *169* | 1.046 *0.100* | 4.6 | 2155 *2305* | **0.935** *0.024* | **-6.5** |
| Daytime Fatal and Injury | 1801 *1919* | **0.938** *0.026* | **-6.2** | 55 *46* | 1.195 *0.183* | 19.5 | 293 *286* | 1.023 *0.062* | 2.3 |
| Nighttime | 3240 *3269* | 0.991 *0.020* | -0.9 | 158 *175* | 0.900 *0.090* | -10.0 | 1485 *1547* | 0.960 *0.028* | -4.0 |
| Nighttime Fatal and Injury | 919 *942* | 0.975 *0.035* | -2.5 | 36 *38* | 0.951 *0.171* | -4.9 | 208 *211* | 0.988 *0.070* | -1.2 |
| Dry | 6343 *6066* | 1.046 *0.016* | 4.6 | 167 *167* | 0.997 *0.100* | -0.3 | 2228 *2329* | 0.956 *0.024* | -4.4 |
| Wet | 2852 *3270* | **0.872** *0.019* | **-12.8** | 161 *165* | 0.974 *0.096* | -2.6 | 1404 *1484* | **0.946** *0.027* | **-5.4** |
| Guidance-related | 3870 *4315* | **0.897** *0.017* | **-10.3** | Sample too small | | | 834 *845* | 0.986 *0.038* | -1.4 |

[1] A site is a homogeneous segment of road represented by a set of attributes (shoulder width, type, lane width, AADT, terrain, guide rails, horizontal alignment, etc.).

[2] Obs = Observed crash frequency.

[3] Exp = Expected crash frequency.

[4] Statistically significant results (at 95% confidence level) are shown in **bold.**

[5] Ch = change.

comparison group data (i.e., roadways without PRPMs) for a total of 43 miles of four-lane freeway. Additional crash data (total and fatal and injury) were collected for urban Interstate highways without PRPMs in Milwaukee County as an alternative comparison group. Both comparison groups were used for composite analyses, and the results were compared. The methodology that was applied to estimate the annual factors for the two comparison groups is as follows:

- **Comparison Group 1: 43 miles of four-lane freeways.** The crash data for the 43 miles of freeway were used to derive a ratio between the crash counts for 2000 and the average annual crash counts for 1994 to 1998 (before period). This ratio was used as a multiplier to determine an annual calibration factor for the year 2000 (after period) crashes. This data preparation was undertaken for all crash types (see Appendix A, Table A-10).
- **Comparison Group 2: Milwaukee County.** The urban Interstate highways without PRPMs in Milwaukee County were all illuminated and had a lower posted speed limit (45 mph or 72 km/h) when compared with four-lane freeways (55 mph or 86 km/h) on which PRPMs were installed. The crash data showed an increase in 2000 (after period) of 27 percent for total crashes and 16 percent for fatal and injury crashes when compared with the same crash types for 1994 to 1998 (before period). Thus, for the composite analysis, these percentages were applied for crash types accordingly (see Appendix A, Table A-10).

The composite analyses for the two comparison groups for Wisconsin showed conflicting results with respect to safety impact of PRPMs for all crash types. Therefore, the research team concluded that these data did not provide the required integrity to continue into further disaggregate analyses.

Key findings from the analysis included the following:

- Missouri shows significant reductions in fatal and injury crashes (5.4 percent), daytime fatal and injury crashes (6.2 percent), wet weather crashes (12.8 percent), and guidance-related crashes (10.3 percent) after the nonselective implementation of PRPMs.
- Pennsylvania shows significant reductions in total crashes (5.7 percent), daytime crashes (6.5 percent), and wet weather crashes (5.4 percent) after the nonselective implementation of PRPMs.

### 4.4.2 Univariate Disaggregate Analysis

As described previously, the univariate disaggregate analysis assists in the selection of variables to be considered in the subsequent multivariate analysis. Results from this analysis show that the safety benefit of PRPMs on nighttime crashes increases as traffic volumes increase and is greater on urban than on rural freeways.

### 4.4.3 Multivariate Modeling of the Index of Effectiveness ($\theta_{site}$)

The results of the modeling for freeways are shown in Table 4-6. The AMFs derived from this model are shown in Table 4-7. The AADT variable is the only significant variable. This variable was grouped for reasons explained earlier using the method outlined.

The model confirms the findings of the univariate analysis that the safety benefits of PRPMs on freeways increase with increasing traffic volumes. According to this model, PRPMs may only be effective in reducing nighttime crashes where the AADT exceeds 20,000 veh/day. Since higher volumes are more likely to be found in urban areas, the underlying reason for the increasing effect with increasing AADT may relate to factors other than or in addition to AADT that may be peculiar to urban areas. Data were not available to isolate the effects of such factors.

The research team studied the different design elements for potential relationships with the safety effect of PRPMs. Apparently because of little variation in the design attributes (e.g., lane widths and shoulder widths) of the freeway segments, as shown in Tables 3-13 and 3-14, it was not statistically feasible to include these attributes as variables in the multivariate models. The same applied to PRPM installation details, such as spacing.

## 4.5 RESULTS OF THE COMPOSITE ANALYSIS FOR FOUR-LANE DIVIDED EXPRESSWAYS

The research team concluded that, because of the data constraints and intrinsic difficulties encountered in Wisconsin and Pennsylvania for the data collected for the four-lane divided expressways, any further analysis would not result in any reliable findings. Thus, four-lane divided expressways could not be analyzed under this research project.

**TABLE 4-6 Index of effectiveness model for four-lane freeways (snowplowable PRPMs)**

| Model Parameters | Applicable Condition | Estimate | Standard Error | *p*-value |
|---|---|---|---|---|
| Constant | AADT ≤ 20000 | 1.131 | 0.136 | < 0.001 |
| AADT 2 | 20,000 < AADT ≤ 60,000 | -0.193 | 0.160 | 0.249 |
| AADT 3 | AADT > 60,000 | -0.458 | 0.192 | 0.033 |

**TABLE 4-7 AMFs (nighttime crashes) derived from Table 4-6**

| AADT (veh/day) | AMF |
|---|---|
| ≤ 20000 | 1.13 |
| 20001–60000 | 0.94 |
| > 60000 | 0.67 |

CHAPTER 5

# DISCUSSION OF STUDY RESULTS

This chapter discusses the results presented in Chapter 4 in conjunction with related human factors issues. The purpose of the discussion presented here is to link the statistical results of this research study with other findings of past research studies that have analyzed PRPM installations and observed effects in driver behavior. The discussions are presented for two-lane roadways and four-lane freeways separately.

## 5.1 TWO-LANE ROADWAYS

### 5.1.1 Overview of Human Factors Issues

The purpose of PRPMs is to provide improved delineation at night. Studies have shown that drivers on approaches to curves need 3 to 5 seconds of preview distance in order to feel comfortable with the changes in the road path (*25*). At night, such long preview distances cannot be provided by paint, but are possible using PRPMs, post-mounted delineators, and chevrons. It is expected that the improved visibility produced by PRPMs will affect crash rates by affecting two types of driver behavior:

- Lane control and positioning and
- Speed control.

#### *5.1.1.1 Lane Control and Positioning*

Previous studies of *conventional* PRPMs have found that PRPMs on curves cause drivers to shift away from the centerline at night (*21, 34, 42*). However, the impact on lane position during the day is not conclusive: one study (*35*) shows a shift toward the centerline and another study (*21*) shows a shift away from the centerline.

The conventional PRPMs analyzed in the above studies protrude much higher above the road surface than do the snowplowable PRPMs analyzed in this study. Because of this protrusion, conventional PRPMs provide an auditory warning of lane crossing that is not found with snowplowable PRPMs. Therefore, any change in lane position at night with snowplowable PRPMs is expected to result from improved delineation. Kallberg (*42*) found that drivers move away from conspicuous post-mounted delineators. Kallberg's finding may support this report's hypothesis of snowplowable PRPMs' effect on lane control and positioning.

#### *5.1.1.2 Speed Control*

When the preview of the road ahead is reduced, as it is during nighttime with low-beam headlights, lane control becomes more difficult and driver workload increases, causing drivers to compensate by reducing their speed. Conversely, when the preview of the road is improved through delineation, driver workload decreases and drivers may compensate by increasing speeds. Harms (*43*) investigated speed choice in fog and found that drivers tend to undercompensate (i.e., not reduce speeds enough) in poor visibility conditions. Because of this and other studies of driver speed choice, Rumar and Marsh (*44*) predict that drivers overcompensate (i.e., increase speeds too much) in improved visibility conditions.

Studies have found that speed increases at night after the implementation of PRPMs (*21, 34*). Improved delineation, in the form of post-mounted delineators, was associated with nighttime speed increases and increased crash frequency on roads with low design standards, but not on roads with high design standards (*42*).

A driver who increases speed, especially at night, is responding inappropriately. While PRPMs improve the visibility of changes in the road path, they do not improve the visibility of other hazards, such as pedestrians, bicyclists, animals, and debris. Higher speeds lead to longer stopping distances and greater crash potential. Higher speeds in curves will result in an increase in lateral acceleration and a greater potential for run-off-road crashes.

The issue of speed is likely to be more of a problem on curves with small radii. On high-speed roads, such curves force drivers to make large speed reductions. However, studies of driver lateral acceleration in curves show that drivers drive closer to the safety margin on tight curves than on gentle curves (*45*). This suggests that drivers are reluctant to drop speed too much and trade off comfort for time savings. Any small increase in speeds associated with PRPMs will have a greater negative safety effect when drivers are closer to the safety margin. This greater negative safety effect may be the reason underlying the Kallberg study's finding (*42*), which is an increase in crash frequency on roads with low design standards.

Wet weather is another situation in which drivers are likely operating closer to the safety margin by not slowing sufficiently to compensate for increased braking distance. Thus, the negative impacts of any speed increases on tight curves may be exacerbated in wet weather.

### 5.1.2 Expected PRPM Impacts on Two-Lane Roadways

To summarize, the substantial improvements in nighttime centerline visibility and the associated increase in driver comfort after the implementation of PRPMs are expected to have the following impacts on driver behavior:

- Reduced oncoming and left-lane encroachments at night,
- Increases in shoulder encroachments at night, and
- Small increases in speeds at night.

These changes in driver behavior are expected to have the following impacts in turn:

- Decreases in nighttime head-on crashes, with increasing benefits as traffic volumes increase;
- Decreases in safety benefits as the degree of curvature increases;
- Decreases in safety benefits as the vehicle moves closer to the edgeline;
- Decreases in wet weather nighttime crashes;
- Slight decreases in daytime wet weather crashes; and
- Less positive effects of PRPMs on gentle curves and less negative effects on sharp curves on roads with illumination when compared with roads without illumination.

#### *5.1.2.1 Decreases in Nighttime Head-On Crashes, with Increasing Benefits as Traffic Volumes Increase*

The majority of head-on crashes are due to inadvertent excursions into the oncoming lane (only 4 percent of head-on fatalities are associated with overtaking) (*46*). The probability that inadvertent excursions result in head-on crashes increases as traffic volumes increase. Given driver behavior, it is expected that (1) improved delineation of the centerline by PRPMs at night and the consequent movement away from the centerline will reduce head-on crashes at night and (2) the benefit of PRPMs will increase as traffic volumes increase.

The safety impacts expected, as described above, are supported by the results of the composite analyses (see Chapter 4) undertaken in this research study. These results are as follows:

- There were statistically significant decreases in head-on crashes on two-lane roadways in New Jersey (nonselective implementation).
- There were statistically nonsignificant decreases in head-on crashes and a statistically significant increase in total crashes in two-lane roadway Illinois data (nonselective implementation).
- Although available sample sizes did not permit a composite or disaggregate analysis of nighttime head-on crashes, the results in Table 4-3 (AMFs for two-lane roadways) show statistically significant improvements in the safety performance of PRPMs at night as traffic volumes increase.

#### *5.1.2.2 Decreases in Safety Benefits as the Degree of Curvature Increases*

On sharper curves (i.e., with a higher degree of curvature), it is possible that the negative safety impact of speed increases is not offset by the positive safety impact of improved visibility; failure to offset the negative safety impact would result in an increase of nighttime crashes. This proposition is supported by the univariate analysis of two-lane roadways and by the results of the disaggregate analysis in Table 4-3, which show that PRPMs will have negative safety effects on roadways with a degree of curvature exceeding 3.5. The negative safety effect holds true for all ranges of traffic volumes available in this research study.

#### *5.1.2.3 Decreases in Safety Benefits as the Vehicle Moves Closer to the Edgeline*

The risk of run-off-road crashes on two-lane roadways is hypothesized (as described in Section 5.1.1) to be higher on roadways with lower design standards (e.g., with higher degrees of curvature and narrower pavements widths) because vehicles move away from the centerline to the edgeline to avoid the PRPMs. For example, narrower shoulder widths reduce the recovery area for vehicles that leave the travel lane. The univariate analysis indicated a positive correlation between traffic volumes and pavement widths, meaning that higher-traffic-volume roadways are normally associated with higher roadway design standards. This may in part explain why the AMFs in Table 4-3 show decreases in safety benefits with decreased traffic volumes, which are in turn associated with roads with narrower pavement widths.

#### *5.1.2.4 Decreases in Wet Weather Nighttime Crashes*

The significant improvement in visibility in wet weather at night would be expected to reduce run-off-road crashes and head-on crashes on gentle curves where small increases in speed would not significantly increase crash risk. The results of the safety composite analysis shown in Table 4-1 indicated a statistically significant decrease in wet weather nighttime crashes (by 20 percent) in two-lane roadways in New York where locations were selected for PRPM installation on the basis of their nighttime wet weather crash history.

#### *5.1.2.5 Slight Decreases in Daytime Wet Weather Crashes*

Snowplowable PRPMs may improve daytime visibility under wet weather conditions because of the profile of the PRPM housing above the film of water covering the painted markings. This improvement in visibility might contribute to a decrease in daytime wet weather crashes.

The safety composite analysis of the two-lane roadways in New York indicated a 20-percent reduction in all wet weather crashes after selective implementation of snowplowable PRPMs. The composite analysis did not separately evaluate daytime wet weather crashes.

#### *5.1.2.6 Less Positive Effects of PRPMs for Gentle Curves and Less Negative Effects for Sharp Curves on Roads with Illumination when Compared with Roads without Illumination*

The improvement in delineation visibility is expected to be more noticeable on roads without illumination. Illumination is expected to reduce both the positive effects of PRPMs on visibility and the negative effects on speed, since illumination assists drivers in determining lane position and control. The presence of illumination on sharp curves is hypothesized to reduce the potential negative effect of PRPMs due to increased speeds. Because of limited sample sizes of two-lane curves with illumination, it was not possible to determine the net effect of illumination and PRPMs.

The presence of illumination on *gentle curves and tangents* could reduce the positive effects of PRPMs on forward visibility and could cause the results in Table 4-3 to be an overestimation of the effectiveness of PRPMs on illuminated roadways with gentle curvature. On these roadways, as on roadways with sharp curves, it was not possible to determine the net effect of illumination and PRPMs because of limited sample sizes of two-lane curves with illumination.

## 5.2 FOUR-LANE FREEWAYS

### 5.2.1 Overview of Human Factors Issues

The common practice on four-lane freeways is to implement PRPMs nonselectively with the aim of providing a comfortable driving environment and improving safety in conditions of decreased visibility (i.e., nighttime and wet weather conditions).

As with two-lane roadways, the implementation of PRPMs on the lane line of freeways is expected to impact two types of driver behavior:

- Lane control and positioning and
- Speed control.

#### *5.2.1.1 Lane Control and Positioning*

Increased delineation of the lane line is likely to cause drivers to stay better centered in lanes delineated on both sides. Where the lane line but not the edgeline is delineated, drivers are likely to position themselves farther from the delineated line toward the edgelines demarcating the median and the shoulder. The number of lane line encroachments, and therefore the potential for sideswipe crashes, will decrease. Since the possibility that a lane encroachment resulting in a crash is higher at higher traffic volumes, a measure that reduces lane line encroachments will have a proportionally greater effect at higher traffic volumes. The safety benefits of reduced-lane-line encroachments are expected to be greater than the potential negative safety impact of increased shoulder encroachments, where there are wide shoulders and shoulder rumble strips.

#### *5.2.1.2 Speed Control*

Improved visibility is likely to increase driver confidence and comfort to the extent that travel speeds will increase. Freeways have high design standards (e.g., high standards for degree of curvature, lane widths, and shoulder widths); therefore, it is unlikely that small speed increases will cause drivers to operate at or close to the margin of safety with respect to these parameters. Speed increases, however, may result in increased crash occurrence due to increased stopping, deceleration, and weaving distances required, especially during conditions of reduced visibility.

### 5.2.2 Expected PRPM Impacts on Four-Lane Freeways

To summarize, the substantial improvements in visibility of delineation at night and during poor weather conditions, and the associated increase in driver comfort after the implementation of PRPMs, could have the following impacts on driver behavior at night and poor daytime weather conditions:

- Reduced encroachments over the lane line,
- Increased shoulder encroachments, and
- Small increases in speed at night.

These changes in driver behavior are hypothesized to have the following impacts on crashes in turn:

- Decreases in nighttime crashes, with increasing benefits at higher traffic volumes;
- Decreases in guidance-related crashes (e.g., sideswipes); and
- Decreases in wet weather crashes.

#### *5.2.2.1 Decreases in Nighttime Crashes, with Increasing Benefits at Higher Traffic Volumes*

The results of the composite analysis in Table 4-5 show that PRPMs had no overall effect on nighttime crashes. However, the results of the disaggregate analysis, presented in Table 4-7, show that snowplowable PRPMs may only be effective in reducing nighttime crashes on four-lane freeways with AADTs exceeding 20,000 veh/day.

#### *5.2.2.2 Decreases in Guidance-Related Crashes*

The results for four-lane freeways in Missouri (Table 4-5) show a statistically significant 10.3-percent reduction in guidance-related crashes after the implementation of snowplowable PRPMs. A similar statistically significant result was not observed for Pennsylvania four-lane freeways. This difference between the two states may be explained by two design attributes: rumble strips and shoulder width. On average, Missouri freeways have wider shoulders and a higher proportion of freeways with shoulder rumble strips than Pennsylvania freeways have. Table 3-15 shows that the average shoulder width on Pennsylvania freeways is 6.3 ft (1.9 m) compared with the 9.3 ft (2.8 m) in Missouri. Table 3-25 shows that 53 percent of four-lane freeways in Missouri have shoulder rumble strips compared with 38 percent of Pennsylvania freeways.

#### *5.2.2.3 Decreases in Wet Weather Crashes*

The results of the composite analysis indicated that snowplowable PRPMs were effective in reducing wet weather crashes in four-lane freeways in Missouri (12.8 percent) and Pennsylvania (5.4 percent).

CHAPTER 6

# GUIDELINES FOR THE USE OF SNOWPLOWABLE PRPMS

This chapter describes some of the current warrants and guidelines for pavement markings and markers as background for the development of guidelines for the use of PRPMs. It then proposes guidelines for the use of snowplowable PRPMs based on the research study findings documented in Chapter 5. The analytical engineering procedures included in the proposed guidelines are illustrated for two-lane roadways.

## 6.1 BACKGROUND

The "Manual on Uniform Traffic Control Devices" (Section 1A.13) (*3*) defines a warrant for a traffic control device as follows:

> A warrant describes threshold conditions to the engineer in evaluating the potential safety and operational benefits of traffic control devices and is based upon average or normal conditions. Warrants are not a substitute for engineering judgment. The fact that a warrant for a particular traffic control devices is met is not conclusive justification for the installation of the device.

The MUTCD contains a limited number of warrants. There are warrants for

- Traffic signal installation (Section 4C.01),
- Centerline markings and left edgeline pavement markings (Section 3B.01),
- No-passing zone pavement markings (Section 3B.02),
- White lane line and right edgeline pavement markings (Section 3B.04), and
- Edgelines (Section 3B.07).

For traffic signalization, there are eight specific warrants, each of which provides conditions to be met to justify a traffic signal. The MUTCD emphasizes, however, that the satisfaction of a traffic signal warrant or warrants shall not in itself require the installation of a traffic signal. In comparison, the warrants for the pavement markings noted above are less clear and are embedded or inferred within statements under the Standard, Guidance, and Option sections. For example, there are conditions where a centerline marking is required (Standard), where they are recommended (Guidance), and where they are permitted (Option). It could be argued whether or not there are warrants for pavement markings when considering the definition above.

For PRPMs, there are no statements in the MUTCD as to the conditions that would warrant their use. A PRPM is recognized as a "device that is intended to be used as a positioning guide or to supplement or substitute for pavement markings." Standard, Guidance, and Option statements relate how to use PRPMs once it is decided to use them. (It could be argued that since PRPMs may be used as a "substitute for pavement markings" [Section 3B.14], then if an agency prefers to use PRPMs over painted pavement markings, there is a requirement [Standard] for when PRPMs are to be used for centerline markings [Section 3B.01].)

The 2001 edition of the *Traffic Control Devices Handbook* (*47*) recognizes PRPMs as providing excellent visibility at night and in the rain. PRPMs are discussed from a materials standpoint, and no guidance is provided as to when PRPMs should be used.

The "Roadway Delineation Practices Handbook" (*2*) devotes an entire chapter to PRPMs. The advantages of PRPMs are noted. Principal disadvantages are a high initial cost and the need for more expensive snowplowable markers in snowfall areas. Because of the high cost of PRPMs, the "Handbook" notes that their use is limited to important roadways where additional delineation is needed and to roadways having a surface that will not soon be subjected to major repair, replacement, or excavation. Little information is provided on how to determine what is an important roadway or where additional delineation is needed. Narrow bridges on two-lane rural roads are mentioned as a special type of location where PRPMs were found to be effective in reducing nighttime speeds and centerline encroachments.

A project performed by the University of Iowa for the FHWA resulted in "Guidelines for the Use of Raised Pavement Markers" (*5*). These guidelines suggest that PRPMs should be installed

- To supplement double yellow centerlines on two-lane curves;
- To delineate centerlines and edgelines where there are pavement width reductions at a narrow bridge;
- At painted gores, exits, and bifurcations;
- On all freeways and Interstate highways (snowplowable PRPMs); and

- On state highways at locations determined by the Bureau of Traffic Engineering on the basis of accident data (snowplowable PRPMs).

The guidelines suggest that snowplowable PRPMs should not be installed on interchange ramps (*5*). The suggestions above should be considered cautiously because the authors likely did not intend that freeways and Interstate highways in regions with no snowfall should have snowplowable markers.

## 6.2 PROPOSED GUIDELINES FOR PRPMS ON TWO-LANE ROADWAYS

The following guidelines are proposed:

- AMFs shown in Table 6-1 should be used to guide decisions on where not to install PRPMs (i.e., when an AMF is greater than 1). An AMF is the ratio between the number of crashes per unit of time expected after a measure is implemented and the number of crashes per unit of time estimated if the implementation does not take place. An AMF less than 1 would indicate a positive safety effect (i.e., a reduction in crashes), while an AMF greater than 1 would indicate a negative safety effect (i.e., an increase in crashes).
- Given the negative safety impacts that are demonstrated to be associated with curves with more than 3.5 degrees of curvature, and given the findings of speed increases in association with PRPMs, it would seem prudent to avoid placing PRPMs well in advance of roadway sections with substandard geometry or where the feature is unexpected because of the character of the road previously encountered by the driver.
- An analytical engineering procedure should be undertaken at locations where an AMF is less than 1 to assess the cost-effectiveness of the PRPM installation.
- The results of the analytical engineering procedure should form part of the decision-making process for whether to install PRPMs at a given location. Other issues to be considered with this information are
  - Other measures for improving nighttime crashes that may result in higher benefit-cost effectiveness and
  - Other locations that may result in a higher-than-expected cost-effectiveness from the installation of PRPMs (thus, the results of the engineering study should be entered into the safety resource allocation process).

**TABLE 6-1 AMFs (nighttime crashes) derived from Table 4-3**

| AADT (veh/day) | AMF | |
|---|---|---|
| | When DOC ≤ 3.5 | When DOC > 3.5 |
| 0–5000 | 1.16 | 1.43 |
| 5001–15000 | 0.99 | 1.26 |
| 15001–20000 | 0.76 | 1.03 |

DOC = degree of curvature.

## 6.3 PROPOSED GUIDELINES FOR PRPMS ON FOUR-LANE FREEWAYS

The following guidelines are proposed:

- AMFs shown in Table 6-2 should be used to guide decisions on where to install PRPMs (i.e., when an AMF is less than 1). An AMF is the ratio between the number of crashes per unit of time expected after a measure is implemented and the number of crashes per unit of time estimated if the implementation does not take place. An AMF less than 1 would indicate a positive safety effect (i.e., a reduction in crashes), while an AMF greater than 1 would indicate a negative safety effect (i.e., an increase in crashes).
- If a cost-effectiveness study is required, the analytical engineering procedure illustrated for two-lane roadways can be used in a similar manner.

## 6.4 PROPOSED REVISIONS TO THE MUTCD

In light of the findings of the composite and disaggregate analyses of PRPMs on two-lane roadways and four-lane divided freeways, the following changes to the MUTCD are proposed:

1. Add the following paragraph after the initial paragraph under Support for Section 3B.11 on top of page 3B-29:

> Retroreflective raised pavement markers enhance guidance for drivers by providing longer delineation of the travel path during nighttime and wet pavement conditions. They also provide auditory feedback when the motorist approaches the edge of the travel lane, although snowplowable raised markers do so to a much lesser extent. These positive effects can be offset sometimes by inducing higher speeds, which under certain conditions, such as on sharp curves, can result in an overall negative safety benefit.

The purpose of the above paragraph is to recognize the positive and potential negative effects of snow-

**TABLE 6-2 AMFs (nighttime crashes) derived from Table 4-7**

| AADT (veh/day) | AMF |
|---|---|
| ≤ 20000 | 1.13 |
| 20001–60000 | 0.94 |
| > 60000 | 0.67 |

plowable PRPMs on two-lane roadways and four-lane freeways. The MUTCD should refer the reader to this report for additional details.

2. Add the following paragraph under Guidance on page 3B-29:

> The use of any raised pavement markers as a supplement or replacement to standard pavement markings should be based on an analytical engineering study of the potential safety impacts and costs.

The purpose of the above paragraph is to recommend that an analytical engineering procedure be performed to establish the cost-effectiveness of using raised pavement markers. Although this research study has determined the procedure for snowplowable PRPMs on two-lane roadways, there is a need to research analytical engineering procedures for conventional and other PRPMs on other types of road.

## 6.5 OVERVIEW OF THE ANALYTICAL ENGINEERING PROCEDURE

The analytical engineering procedure estimates the likely safety effect of installing PRPMs. The procedure contains a series of steps to be undertaken by an analyst in carrying out the engineering procedure:

- **Step 1: Assemble data to use SPFs.** Include the following:
  a) For the past 3 to 5 years, determine the number of nighttime nonintersection crashes per year for the roadway section under analysis.
  b) For the past 3 to 5 years, obtain or estimate the AADT for each year. Estimate the AADT for the year after PRPM installation.
  c) Use SPFs, as base models, for roadway sections "with PRPMs" and "without PRPMs" (see Tables 6-3 and 6-4 for two- and four-lane roadways, respectively).
  d) Perform local and annual recalibration of the base models using the procedure presented by Harwood et al. (*40*).
- **Step 2: Estimate expected nighttime nonintersection crashes without PRPMs.** Use the empirical Bayes procedure with the data from Step 1 and the "without PRPMs" local SPFs to estimate the expected annual number of nighttime nonintersection crashes that would occur without PRPMs for the last full year for which data are available (i.e., the base year).
- **Step 3: Estimate expected nighttime nonintersection crashes with PRPMs.** Use the "with PRPMs" local SPFs and the AADTs from Step 1 to estimate the expected annual number of nighttime nonintersection crashes that would occur with PRPMs had they been installed in the last full year for which data are available (i.e., the base year).
- **Step 4: Compare expected crashes with and without PRPMs.** Calculate the difference between the expected annual number of nighttime nonintersection crashes estimates from Steps 2 and 3.

**TABLE 6-3 Two-lane roadways: SPFs (base models) for the analytical engineering procedure**

| SPF | Without PRPMs | With PRPMs |
|---|---|---|
| Nighttime nonintersection crashes per mile-yr | $\alpha(AADT)^{\beta 1}\exp(\beta_2 DOC1+\beta_3 DOC2)$ | $\alpha(AADT)^{\beta 1}\exp(\beta_2 DOC1+\beta_3 DOC2)$ |
| $\ln(\alpha)$ (s.e.) | -6.5400 (0.3880) | -5.6940 (0.5370) |
| $\beta_1$ (s.e.) | 0.7345 (0.0415) | 0.6392 (0.0574) |
| $\beta_2$ (s.e.) | 0.0811 (0.0908) | -0.2570 (0.1210) |
| $\beta_3$ (s.e.) | 0.4570 (0.1100) | 0.6750 (0.1430) |
| *K* | 2.1 | 2.2 |

DOC1 = 0 and DOC2 = 1 for degree of curve > 3.5.
DOC1 = 1 and DOC2 = 0 for 0 < degree of curve ≤ 3.5.

**TABLE 6-4 Four-lane freeways: SPFs (base models) for the analytical engineering procedure**

| SPF | Without PRPMs | With PRPMs |
|---|---|---|
| Nighttime nonintersection crashes per mile-yr | $\alpha(AADT)^{\beta 1}$ | $\alpha(AADT)^{\beta 1}$ |
| $\ln(\alpha)$ (s.e.) | -11.5230 (0.7480) | -12.0360 (0.9060) |
| $\beta_1$ (s.e.) | 1.1013 (0.0947) | 1.1530 (0.1190) |
| *K* | 3.9 | 2.4 |

- **Step 5: Conduct a benefit-cost analysis.** Where a decrease in nighttime nonintersection crashes is expected, apply a unit crash cost to the expected change. Compare this benefit with the cost of PRPM installation and maintenance, using conventional life cycle economic analysis tools.

## 6.6 ILLUSTRATION OF THE ANALYTICAL ENGINEERING PROCEDURE FOR TWO-LANE ROADWAYS

This section illustrates the engineering procedure for a two-lane roadway section that is 1 mile long. This roadway section is mostly curved, with all curves having a degree of curvature less than 3.5. For this roadway section, crash data are available for 5 years (1998 to 2002). The base year is 2002, which is the last full year for which data are available.

### 6.6.1 Step 1: Assemble Data to Use SPFs

a) Determine the number of nighttime nonintersection crashes per year. The counts of all nonintersection nighttime crashes in each year of the analysis period are shown in Row 2 of Table 6-5. There were 10 crashes over 5 years, or an average of 2 crashes per year.

b) Obtain or estimate the AADT per year. AADTs are estimated for each year, including the first year after PRPM implementation, using methods suitable to the jurisdiction's practices. For this illustration, AADTs are listed in Row 3 of Table 6-5.

   If actual AADTs are not available for each year, most jurisdictions have trend factors that can be applied to estimate AADTs for each year. More formal and accurate methods for estimating missing AADTs (*48*) are available and can be applied by the more sophisticated analyst.

c) Use SPFs as base models for two-lane roadways (from Table 6-3). When the overdispersion parameter is 2.1,

$$E\left(\hat{K}\right) = 0.001444\left(\text{AADT}^{0.7345}\right)e^{(0.0811\text{DOC1}+0.457\text{DOC2})} \quad (6\text{-}1)$$

When the overdispersion parameter is 2.2,

$$E\left(\hat{K}\right) = 0.003366\left(\text{AADT}^{0.6392}\right)e^{(-0.25\text{DOC1}+0.675\text{DOC2})} \quad (6\text{-}2)$$

Where

$E\left(\hat{K}\right)$ = Nighttime nonintersection crashes per mile-year,

DOC1 = 0 and DOC2 = 1 for degree of curve > 3.5, and

DOC1 = 1 and DOC2 = 0 for 0 < degree of curve < 3.5.

d) Perform local and annual recalibration of base SPFs for roadway sections "with PRPMs" and "without PRPMs." The SPFs provided in this report must be recalibrated for each jurisdiction and for each year of the analysis period. The recalibration procedure is taken from Harwood et al. (*40*) and has recently been tested by Persaud et al. (*49*).

   Recalibration requires annual crash counts and AADTs for a sample of roadway segments in the jurisdiction that are typical of roadways that tend to be considered for PRPM installations. First, the SPF (see Equation 6-1) is used to estimate the number of crashes for each year for each roadway segment in the sample. For each year, the sum of the observed crash counts for each year collected is divided by the sum of the SPF estimates (for the same year of data) to give an annual calibration factor ($\alpha_f$). The calibration factor is applied as a multiplier ($\alpha_f$) to Equation 6-1 to recalibrate the base model to local SPF. The annual values of $\alpha_f$ are shown in Row 4 of Table 6-5 for the example illustrated here.

### 6.6.2 Step 2: Estimate Expected Nighttime Nonintersection Crashes without PRPMs

Using Equation 6-1 and 1998 data, calculate the expected number of nighttime crashes:

$$E(K_y) = \alpha_y * 0.001444(\text{AADT}_y^{0.7345})\,e^{(0.0811\text{DOC1} + 0.457\text{DOC2})}$$

**TABLE 6-5 Summary of Step 1 of the illustration of analytical engineering procedure for two-lane roadways**

| Row | Data and Estimation Parameters | | | | | | |
|---|---|---|---|---|---|---|---|
| 1 | Year ($y$) | 1998 | 1999 | 2000 | 2001 | 2002 | 2002 (With PRPM) |
| 2 | Crashes in year ($X$) | 2 | 0 | 4 | 1 | 3 | To be estimated |
| | | Sum = $X_b$ = 10 | | | | | |
| 3 | AADT | 10900 | 12000 | 11500 | 9800 | 10400 | 10400 |
| 4 | Calibration factor $\alpha_f$ | 1.1 | 1.04 | 1.01 | 0.95 | 1.04 | 1.04 |
| 5 | Overdispersion parameter $k$ | 2.10 | 2.10 | 2.10 | 2.10 | 2.10 | 2.20 |

$$E(K_{1998}) = 1.10 * 0.001444 * (10900^{0.7345}) * e^{(0.0811*1+0.457*0)}$$
$$= 1.591 \text{ nighttime nonintersection crashes per mile-year}$$

The estimates of nighttime nonintersection crashes per mile for each year are shown in Row 6 of Table 6-6.

Calculate the annual correction factors ($C_y$) between the annual estimated number of crashes for each year and the annual estimated number of crashes for 2002 (the base year). The annual correction factors for this example are shown in Row 7 of Table 6-6 and are summed in Row 8.

Using the values in Rows 2 through 8 (Table 6-6) and the empirical Bayes formula, estimate a value of the expected annual number of crashes without PRPMs (and its variance) for the base year (2002):

$$\hat{K}_{2002} = (k + X_b)/[(k/E(K_{2002}) + C_b)]$$
$$= 1.000\,(2.10 + 10)/[(2.10/1.453) + 5.126]$$
$$= 1.841 \text{ crashes per mile-year for roads "without PRPMs"} \quad (6\text{-}3)$$

$$\mathrm{VAR}(\hat{K}_{2002}) = (k + X_b)/[\{k/E(K_{2002}) + C_b\}^2]$$
$$= 1.000(2.10 + 10)/[\{(2.10/1.453) + 5.126\}^2]$$
$$= 0.280$$

Where

$y$ = Subscript to represent the year,
$\alpha_f$ = Recalibrated annual factor,
$k$ = Overdispersion parameter,
$E(K_y)$ = Predicted number of crashes on this roadway section for Year $y$ using SPF,
$C_y$ = Annual correction factor for Year $y$ relative to the base year,
$E(\hat{K})$ = Expected number of crashes during 2002 (the base year) if PRPMs were not installed, and
$E(K_{2002})_{PRPM}$ = Expected number of crashes during 2002 (the base year) were PRPMs to be installed in that year.

These values are summarized in Row 9 of Table 6-6.

### 6.6.3 Step 3: Estimate Expected Nighttime Nonintersection Crashes with PRPMs

The number of crashes (in the base year, 2002) if the PRPMs were to be installed is estimated using the "with PRPMs" SPF model (Equation 6-2).

$$E(K_y)_{PRPM} = \alpha_i * 0.003366(\mathrm{AADT}_i^{0.6392})e^{(-0.257\mathrm{DOC1}+0.675\mathrm{DOC2})}$$

$$E(K_{2002})_{PRPM} = 1.04 * 0.003366 * (10400)^{0.6392} e^{(-0.257*1+0.675*0)}$$
$$= 1.005 \text{ crashes per mile-year for roads "with PRPMs"} \quad (6\text{-}4)$$

$$\mathrm{VAR}(K_{2002})_{PRPM} = E(K_{2002})^2/k$$
$$= 1.0005^2/2.2$$
$$= 0.455$$

These values are shown in Row 10 of Table 6-6.

**TABLE 6-6 Summary of engineering study procedure illustration for two-lane roadways**

| Row | Data and Estimation Results | | | | | | |
|---|---|---|---|---|---|---|---|
| 1 | Year ($y$) | 1998 | 1999 | 2000 | 2001 | 2002 | 2002 (With PRPM) |
| 2 | Crashes in year ($X$) | 2 | 0 | 4 | 1 | 3 | To be estimated |
| | | Sum = $X_b$ = 10 | | | | | |
| 3 | AADT | 10900 | 12000 | 11500 | 9800 | 10400 | 10400 |
| 4 | Calibration factor $\alpha_f$ | 1.10 | 1.04 | 1.01 | 0.95 | 1.04 | 1.04 |
| 5 | Overdispersion parameter $k$ | 2.10 | 2.10 | 2.10 | 2.10 | 2.10 | 2.20 |
| 6 | Model Prediction $E(K_y)$ | 1.5910 | 1.6140 | 1.5190 | 1.2710 | 1.4530 | 1.0005 |
| 7 | $C_y = E(K_y)/E(K_{2002})$ | 1.095 | 1.111 | 1.046 | 0.874 | 1.000 | 1.000 |
| 8 | Comparison ratio for period | Sum = $C_b$ = 5.126 | | | | | $C_a$ = 1.000 |
| 9 | $\hat{K}_{2002}$ [VAR($\hat{K}_{2002}$)] | | | | | | 1.842 [0.280] |
| 10 | $E(K_{2002})_{PRPM}$ [VAR($(K_{2002})_{PRPM}$)] | | | | | | 1.0005 [0.455] |

### 6.6.4 Step 4: Compare Expected Crashes with and without PRPMs

The difference between the expected number of nighttime nonintersection crashes estimates from Steps 2 and 3 is calculated as

$$\Delta = \hat{K}_{2002} - E(K_{2002})_{\text{PRPM}}$$
$$= 1.841 - 1.0005 \quad (6.5)$$
$$= 0.841 \text{ crashes per mile-year}$$

### 6.6.5 Step 5: Conduct a Benefit-Cost Analysis

A sample benefit-cost analytical procedure is presented here:

a) Estimate the relative injury cost (RIC) for all two-lane roadways (or a large sample) in the jurisdiction:

$$\text{RIC} = \frac{w_{\text{fat}}(\text{Fat}) + w_{\text{inj}}(\text{Inj}) + (\text{PDO})}{(\text{Fat}) + (\text{Inj}) + (\text{PDO})} \quad (6\text{-}6)$$

Where

Fat = Number of fatal injury crashes,
Inj = Number of nonfatal injury crashes,
PDO = Number of property-damage-only crashes,
$w_{\text{fat}}$ = Weighting factor for fatal injury crashes, and
$w_{\text{inj}}$ = Weighting factor for nonfatal injury crashes.

The weighting factor for fatal injury crashes ($w_{\text{fat}}$) is the ratio of the cost of a fatal injury crash to the cost of a PDO crash. The weighting factor for nonfatal injury crashes is the ratio of the cost of a nonfatal injury crash to the cost of a PDO crash. The two most commonly used accident cost figures are those contained in the AASHTO *Roadside Design Guide* (*50*) and the FHWA comprehensive cost figures based on the willingness-to-pay concept. Users should choose the set of accident cost figures that best suits their particular study. Table 6-7 shows the crash costs used by the FHWA (*51*) updated to 2002 dollars and the RIC values estimated from these crash cost values.

Assume that on all two-lane roadways within this jurisdiction, the average number of crashes per year is 10 fatal, 1,200 injury, and 4,200 PDO. Therefore, the RIC can be calculated as follows:

**TABLE 6-7 Crash costs and relative injury cost values**

| Crash severity | Cost (2002) | RIC |
|---|---|---|
| Fatal | $3,000,000 | 1304.3 |
| Injury | $63,000 | 27.4 |
| PDO | $2,300 | 1.0 |

$$\text{RIC} = \frac{(1,304.3 * 10 + 27.4 * 1,200 + 4,200)}{(10 + 1,200 + 4,200)} \quad (6\text{-}7)$$
$$= 9.25$$

b) Estimate the potential reduction in crash costs. The average cost of a crash is the product of the RIC and the cost of a PDO crash:

$$\text{Cost per crash} = 9.25 * \$2,300 \quad (6\text{-}8)$$
$$= \$21,275 \text{ per crash}$$

The total savings per year is the product of the average cost of a crash and the expected crash reduction per year:

$$\text{Crash savings benefit per year} = \$21,275 * 0.841 \quad (6\text{-}9)$$
$$= \$17,892 \text{ per mile-year}$$

c) Determine an annual cost of installing and maintaining PRPMs. Each jurisdiction should obtain its own annual cost estimate for the installation and maintenance of PRPMs at the study locations.

The annual cost estimate will consist of three components:

1. **Indirect installation cost.** This includes the cost of providing work zone signs, attenuation vehicles, special law enforcement, and so forth to implement PRPMs. This cost is incurred at each site where PRPM lenses are replaced or PRPMs are installed. The indirect cost per PRPM can be determined by dividing the total indirect cost by the total number of PRPMs to be installed during the contract. The following equation can be used to determine the annual indirect cost, $A$:

$$A = \frac{\text{COST} * i(1+i)^n}{(1+i)^n - 1} \quad (6\text{-}10)$$

Where

COST = Indirect cost of installation per PRPM,
$i$ = Annual discount rate, and
$n$ = Number of years in lens replacement cycle.

If the indirect cost of implementing 500 PRPMs is $5,000, then the indirect cost per PRPM = $5,000/500 = $10. Assuming a discount rate of 5 percent, the annual cost = 10 × 0.05 ×

$(1.05)^3/[(1.05)^3 - 1] = \$3.67$ per PRPM for a 3-year lens replacement cycle.

2. **Direct installation cost.** This refers to the actual cost of installing or replacing the PRPM and includes the cost of material, equipment, and labor. Equation 6-10 can be used to calculate the annual direct installation cost, in which case *n* is equal to the number of years in the PRPM replacement cycle. For example, in Missouri (*52*), the cost of installing one PRPM is about \$42.50, and PRPMs are replaced every 10 years. Assuming a discount rate of 5 percent, the annual cost equals $42.50 \times 0.05 \times (1.05)^{10}/[(1.05)^{10} - 1] = \$5.50$ per PRPM for a 10-year PRPM replacement cycle.
3. **Maintenance cost.** This refers to the average annual cost of replacing the lens according to the replacement cycle and includes the cost of materials, equipment, and labor. Equation 6-10 can be used to calculate the annual maintenance cost, in which case *n* is equal to the number of years in the lens replacement cycle. For example, Missouri DOT replaces the lens every 3 years at a cost of approximately \$6.20 per lens (*52*). Assuming a discount rate of 5 percent, the annual cost equals $6.20 \times 0.05 \times (1.05)^3/[(1.05)^3 - 1] = \$2.28$ per PRPM is estimated for a 3-year lens replacement cycle. If justified by jurisdictional procedures, any annual costs incurred by lens replacement outside the typical cycle should be included in the overall maintenance costs. The total annual cost per PRPM is the sum of these three cost components: \$3.67 + \$5.50 + \$2.28 = \$11.45. Based on this assumed cost, the cost per mile (1 mile = 5,280 ft) for 40 ft and 80 ft PRPM spacings are \$1,511 and \$756, respectively. For the example illustrated here, if PRPMs are implemented at a 40-ft (12-m) spacing (at curves) for 80 percent of the length of the 1-mile-long section and at 80-ft (24-m) spacing for the remainder of the length, the annual PRPM implementation and maintenance cost will be 0.8(\$1,511) + 0.2(\$756) = \$1,360 for a 1-mile-long, two-lane roadway section.

d) Determine benefit-cost ratio. The benefit-cost ratio equals the present value of crash savings divided by the implementation cost (\$17,892/\$1,360 = 13.16).

CHAPTER 7

# CONCLUSIONS

This research study investigated the safety performance of snowplowable PRPMs on a representative sample of two-lane roadways and four-lane freeways in six states: Pennsylvania, Illinois, Missouri, Wisconsin, New Jersey, and New York. Although data were also collected for four-lane divided expressways, intrinsic data issues did not permit performing a sound safety evaluation of PRPM installations for this roadway type. The study assessed the impact of PRPMs on nonintersection-related crashes only.

The PRPMs on four-lane freeways and two-lane roadways in New Jersey and Illinois were installed nonselectively (i.e., crash history was not a criterion in deciding where to implement PRPMs). The PRPMs on two-lane roadways in New York and Pennsylvania were installed selectively (i.e., crash history was the basis for deciding where to implement PRPMs).

Two sets of analyses were undertaken to investigate the safety impact of snowplowable PRPMs on nonintersection crashes. First, composite analyses based on the empirical Bayes before-and-after procedure were used to assess the overall impact of PRPMs on different crash types. Second, the results of the nighttime composite analysis for individual sites were used to conduct a disaggregate univariate analysis, and multivariate regression techniques were used to determine the circumstances under which PRPMs are beneficial to safety. The results of these analyses were used to support the development of guidelines for the use of PRPMs.

The findings that are based on the composite analysis indicate that the nonselective implementation of PRPMs on two-lane roadways does not significantly reduce total or nighttime crashes, nor do PRPMs significantly increase these crash types. Selective implementation policies, however, produced mixed results. Positive effects were found in New York for total, nighttime, and wet weather crashes where PRPMs were installed at locations selected on the basis of the wet weather nighttime crash history. Similar safety effects were not found in Pennsylvania, where PRPMs were implemented at locations selected on the basis of total nighttime crash history.

Improved delineation resulting from the implementation of PRPMs impacts two types of driver behavior that will affect safety at night and in poor visibility conditions: lane control and speed control. The human factors review found that drivers tend to move away from delineation measures, such as PRPMs. Thus, on two-lane roadways with centerline PRPMs, drivers will move away from the centerline toward the shoulder. While this behavior may reduce the incidence of opposing direction (e.g., head-on) crashes, it may increase run-off-road crashes, especially on roads with lower design standards (i.e., with narrow and/or gravel shoulders). The disaggregate analysis found that PRPMs are less effective on roadways with lower traffic volumes. This is likely due to the lower design standards (e.g., narrower lanes, narrower shoulders, etc.) associated with low-volume roads. The human factors review also found some evidence that PRPMs may cause drivers to increase their speeds. Speed increases at locations where drivers already operate close to the margin of safety (e.g., sharp curves) may result in an increased number of crashes. The disaggregate safety analysis in this study concluded that PRPMs on sharp curves with a degree of curvature exceeding 3.5 may cause an increase in nighttime nonintersection crash frequency on two-lane roadways.

The composite analysis of four-lane freeways concluded that PRPMs resulted in small, nonsignificant changes in total crashes in Missouri and New York and a small significant decrease in these crashes in Pennsylvania. Some statistically significant reductions were recorded for a few crash types. For example, significant decreases in wet weather crashes were found for the Missouri and Pennsylvania installations. The disaggregate analysis concluded that PRPMs are only effective in reducing nighttime crashes where the AADT exceeds 20,000 veh/day.

Guidelines for the use of PRPMs have been developed using the results from the disaggregate analysis. An analytical engineering procedure using SPFs for roadways with and without PRPMs has been developed to determine the expected cost-effectiveness of installing PRPMs at a specific location. This procedure is presented as a benefit-cost tool for the agency to apply when considering PRPM installations. This would allow PRPM installation projects to be compared with other potential safety initiatives.

Certain modifications to the MUTCD (*3*) have been proposed on the basis of the expected safety impact of PRPMs. An analytical engineering procedure has also been provided to establish the benefit-cost ratio of using PRPMs.

The research team recommends future research studies to acquire knowledge about the safety impact of conventional PRPM installations on all roadway types, snowplowable PRPM installations on other roadway types (e.g., undivided four-lane roadways, divided expressways, multilane facilities), and intersections and interchanges.

It is also highly recommended that a prospective study be conducted to investigate how the presence of snowplowable PRPMs, under different roadway and PRPM design conditions, influence a driver's choice of an appropriate travel speed and lane position. This type of research would provide information that would explain the seemingly counterintuitive findings that PRPMs are less effective on roadways with a higher degree of curvature and lower roadway design standards. Some questions to be contemplated in the future are the following:

- Does speed increase relatively more with PRPMs on small compared with larger radii curves?
- Does speed increase relatively more in wet as compared with dry conditions with PRPMs?
- Does speed increase at night but not during the day with PRPMs?
- Is centerline milling more effective than PRPMs in reducing lane encroachments without increasing speeds at night?
- Are speed increases at night less pronounced on roadways with illumination?
- Do snowplowable PRPMs contribute to improved visibility of delineation and changes in lane placement or speed during the day in dry and wet conditions?
- Do snowplowable PRPMs provide auditory feedback of centerline and lane line crossing that is noticeable to the average driver?

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# APPENDIX A

## DETAILS OF CALIBRATED SAFETY PERFORMANCE FUNCTIONS

The tables in this appendix summarize the safety performance functions and annual factors developed as part of this study. The information is organized by roadway type:

- Two-lane roadways (Pennsylvania, New Jersey, New York, and Illinois),
- Four-lane freeways (Pennsylvania, New York, Missouri, and Wisconsin), and
- Four-lane divided expressways (Pennsylvania and Wisconsin).

The symbols and short forms in the following tables are defined here:

- $k$ = calibrated parameter relating the mean and variance of the prediction.
- $\alpha_f$ = factor applied to the calibrated model to predict for a crash type other than that used for the model calibration.
- AADT = annual average daily traffic.
- SW = shoulder width in feet.
- TER = 0 if flat terrain, 1 if rolling terrain.
- DOC = degree of curvature.
- ENV = environmental type (either urban or rural).
- s.e. = standard error.
- $\beta_1$, $\beta_2$, $\beta_3$, and $\beta_4$ = model coefficients.

To account for the effect of trends in safety not related to traffic volumes, annual factors were estimated using a procedure documented by Harwood et al. ("Prediction of the Expected Safety Performance of Rural Two-Lane Highways," FHWA-RD-99-207, Federal Highway Administration, 2000).

The methodology used this report compared data before PRPMs were installed with data after PRPMs were installed. The actual year that the PRPMs were installed cannot be used for data analysis because for part of the year there were no PRPMs and for part of the year PRPMs were installed. The data from the same year as the installation of the PRPMs was not used in the analysis, which is why certain years of data are missing.

**TABLE A-1 Safety performance functions for two-lane roadways**

| Model Form Crashes per Mile-yr | Pennsylvania $\alpha(AADT)^{\beta 1}\exp(\beta_2 DOC)$ | | New Jersey $\alpha(AADT)^{\beta 1}\exp(\beta_3 SW)$ | | New York I $\alpha(AADT)^{\beta 1}\exp(\beta_3 SW)$ | | llinois $\alpha(AADT)^{\beta 1}\exp(\beta_3 SW + \beta_4 TER)$ | |
|---|---|---|---|---|---|---|---|---|
| $\ln(\alpha)$(s.e.) | -6.1060 (0.3340) | | -10.4380 (0.8970) | | -7.8980 (0.6050) | | -7.1120 (0.4630) | |
| $\beta_1$ (s.e.) | 0.7640 (0.0398) | | 1.3292 (0.0954) | | 1.0218 (0.0690) | | 0.8988 (0.0576) | |
| $\beta_2$ (s.e.) | 0.0400 (0.0126) | | NA | | NA | | NA | |
| $\beta_3$ (s.e.) | NA | | -0.0504 (0.0148) | | -0.0669 (0.0167) | | -0.0613 (0.0282) | |
| $\beta_4$ (s.e.) | NA | | NA | | NA | | 0.1720 (0.0956) | |
| $k$ | 3.2 | | 2.2 | | 3.5 | | 3.1 | |
| Model parameters | $\alpha_f$ | $k$ | $\alpha_f$ | $k$ | $\alpha_f$ | $k$ | $\alpha_f$ | $k$ |
| Total | 1.000 | 3.2 | 1.000 | 2.2 | 1.000 | 3.5 | 1.000 | 3.1 |
| Fatal and injury | 0.195 | 4.3 | 0.430 | 2.2 | 0.738 | 3.4 | 0.262 | 1.9 |
| Daytime | 0.578 | 2.6 | 0.656 | 1.6 | 0.600 | 3.7 | 0.479 | 3.4 |
| Daytime fatal and injury | 0.101 | 3.8 | 0.298 | 2.1 | 0.468 | 3.2 | 0.148 | 2.2 |
| Nighttime | 0.422 | 3.1 | 0.344 | 2.8 | 0.400 | 2.2 | 0.521 | 2.5 |
| Nighttime fatal and injury | 0.094 | 2.6 | 0.131 | 2.0 | 0.270 | 2.9 | 0.135 | 1.6 |
| Dry | 0.657 | 2.7 | 0.729 | 1.9 | 0.590 | 3.1 | 0.690 | 2.9 |
| Wet | 0.337 | 2.0 | 0.270 | 1.8 | 0.390 | 7.4 | 0.247 | 1.7 |
| Head-on | 0.067 | 3.0 | 0.064 | 2.2 | Sample size too small | | 0.031 | 3.1 |
| Guidance-related | 0.209 | 3.6 | | | 0.045 | 0.7 | 0.368 | 2.5 |

**TABLE A-2 Pennsylvania two-lane roadways: annual factors**

| Annual Factors | Total | Fatal and Injury | Daytime | Daytime Fatal and Injury | Nighttime | Nighttime Fatal and Injury | Dry | Wet | Head-On | Guidance-Related |
|---|---|---|---|---|---|---|---|---|---|---|
| 1991 | 0.94 | 1.00 | 0.84 | 0.81 | 1.09 | 1.21 | 1.01 | 0.84 | 0.75 | 1.05 |
| 1992 | 1.00 | 1.17 | 0.88 | 1.04 | 1.17 | 1.30 | 0.92 | 1.19 | 0.72 | 0.96 |
| 1993 | 1.00 | 1.01 | 0.99 | 0.84 | 1.02 | 1.18 | 1.00 | 1.00 | 0.89 | 0.93 |
| 1994 | 0.84 | 0.84 | 0.80 | 0.80 | 0.89 | 0.99 | 0.83 | 0.83 | 1.01 | 0.98 |
| 1995 | 0.98 | 1.03 | 1.05 | 1.05 | 0.88 | 1.00 | 1.02 | 0.91 | 1.08 | 1.14 |
| 1996 | 0.97 | 0.87 | 0.95 | 0.79 | 0.99 | 0.94 | 0.95 | 0.99 | 0.69 | 1.06 |
| 1997 | 0.97 | 0.85 | 1.02 | 0.78 | 0.90 | 0.93 | 0.87 | 1.18 | 1.30 | 1.12 |
| 1998 | 0.97 | 0.85 | 1.02 | 1.01 | 0.90 | 0.68 | 1.05 | 0.81 | 1.14 | 0.82 |
| 1999 | 1.07 | 0.94 | 1.16 | 1.37 | 0.96 | 0.49 | 1.15 | 0.92 | 1.12 | 1.10 |
| 2000 | 1.19 | 1.35 | 1.21 | 1.41 | 1.16 | 1.29 | 1.13 | 1.25 | 1.19 | 0.76 |

**TABLE A-3 New Jersey two-lane roadways: annual factors**

| Annual Factors | Total | Fatal and Injury | Daytime | Daytime Fatal and Injury | Nighttime | Nighttime Fatal and Injury | Dry | Wet | Head-On |
|---|---|---|---|---|---|---|---|---|---|
| 1991 | 0.89 | 0.91 | 0.92 | 0.94 | 0.84 | 0.84 | 0.91 | 0.84 | 0.89 |
| 1992 | 0.93 | 0.91 | 0.90 | 0.88 | 0.98 | 0.99 | 0.91 | 0.98 | 0.94 |
| 1993 | PRPM Implementation Year | | | | | | | | |
| 1994 | 1.11 | 1.05 | 1.11 | 1.05 | 1.11 | 1.05 | 1.11 | 1.11 | 1.12 |
| 1995 | 1.05 | 0.95 | 1.05 | 0.95 | 1.05 | 0.95 | 1.05 | 1.05 | 1.05 |
| 1996 | PRPM Implementation Year | | | | | | | | |
| 1997 | 1.14 | 0.89 | 1.14 | 0.89 | 1.14 | 0.90 | 1.14 | 1.14 | 1.14 |
| 1998 | 1.00 | 0.85 | 1.00 | 0.85 | 1.00 | 0.85 | 1.00 | 1.00 | 1.01 |

NOTE: It was not possible to extract guidance-related crashes from the New Jersey database.

**TABLE A-4 New York two-lane roadways: annual factors**

| Annual Factors | Total | Fatal and Injury | Daytime | Daytime Fatal and Injury | Nighttime | Nighttime Fatal and Injury | Dry | Wet | Guidance-Related |
|---|---|---|---|---|---|---|---|---|---|
| 1993 | 1.00 | 1.04 | 1.01 | 1.06 | 0.98 | 1.00 | 1.05 | 0.90 | 1.16 |
| 1994 | 1.01 | 0.99 | 1.02 | 0.95 | 0.99 | 1.04 | 0.97 | 1.06 | 1.04 |
| 1995 | 0.98 | 1.05 | 1.00 | 1.09 | 0.94 | 0.96 | 0.97 | 0.97 | 0.87 |
| 1996 | 0.90 | 0.81 | 0.85 | 0.77 | 0.97 | 0.87 | 0.89 | 0.95 | 0.79 |
| 1997 | 1.16 | 0.84 | 1.12 | 0.96 | 1.22 | 0.64 | 1.19 | 1.05 | 0.52 |
| 1998 | PRPM Implementation Year | | | | | | | | |
| 1999 | 1.69 | 0.83 | 1.45 | 0.80 | 2.05 | 0.88 | 1.91 | 1.35 | 0.68 |
| 2000 | 2.04 | 0.87 | 1.77 | 0.92 | 2.43 | 0.79 | 2.04 | 1.99 | 0.87 |
| 2001 | 2.20 | 1.14 | 2.15 | 1.27 | 2.27 | 0.93 | 1.25 | 3.61 | 0.88 |

NOTE: Head-on crashes were not included because of sample size limitations.

**TABLE A-5 Illinois two-lane roadways: annual factors**

| Annual Factors | Total | Fatal and Injury | Daytime | Daytime Fatal and Injury | Nighttime | Nighttime Fatal and Injury | Dry | Wet | Head-On | Guidance-Related |
|---|---|---|---|---|---|---|---|---|---|---|
| 1991 | 1.20 | 0.93 | 1.20 | 1.20 | 1.40 | 0.93 | 1.24 | 1.28 | 1.20 | 1.20 |
| 1992 | 1.10 | 1.07 | 1.10 | 1.10 | 1.16 | 1.07 | 1.17 | 1.10 | 1.10 | 1.10 |
| 1993 | 1.20 | 1.16 | 1.20 | 1.20 | 1.15 | 1.16 | 1.12 | 1.45 | 1.20 | 1.20 |
| 1994 | 1.04 | 1.11 | 1.04 | 1.04 | 1.00 | 1.11 | 1.00 | 0.89 | 1.04 | 1.04 |
| 1995 | 1.13 | 1.41 | 1.13 | 1.13 | 0.94 | 1.41 | 1.13 | 0.96 | 1.13 | 1.13 |
| 1996 | 0.91 | 1.01 | 0.91 | 0.91 | 0.86 | 1.01 | 0.90 | 0.94 | 0.91 | 0.91 |
| 1997 | 0.95 | 1.10 | 0.95 | 0.95 | 0.84 | 1.10 | 0.94 | 0.88 | 0.95 | 0.95 |
| 1998 | 0.89 | 0.81 | 0.89 | 0.89 | 0.78 | 0.81 | 0.88 | 0.83 | 0.89 | 0.89 |
| 1999 | 1.03 | 1.00 | 1.03 | 1.03 | 0.91 | 1.00 | 1.03 | 0.96 | 1.03 | 1.03 |
| 2000 | 1.02 | 0.96 | 1.02 | 1.02 | 0.90 | 0.96 | 1.02 | 0.95 | 1.02 | 1.02 |

**TABLE A-6 Safety performance functions for four-lane freeways**

| Model Form Crashes per Mile-yr | Pennsylvania[1] | | New York | | Missouri[1] | | Wisconsin | |
|---|---|---|---|---|---|---|---|---|
| | $\alpha(AADT/2)^{\beta 1}$ | | $\alpha(AADT)^{\beta 1}$ | | $\alpha(AADT)^{\beta 1}$ | | $\alpha(AADT)^{\beta 1}\exp(\beta_2 ENV)$ | |
| ln($\alpha$) (s.e.) | -7.7170 (0.3850) | | -1.7320 (0.9490) | | -11.1500 (0.3370) | | -9.0480 (0.5980) | |
| $\beta_1$ (s.e.) | 0.8657 (0.0408) | | 0.3450 (0.1010) | | 1.2765 (0.0357) | | 1.0666 (0.0602) | |
| $\beta_2$ (s.e.) | NA | | NA | | NA | | 0.3194 (0.0774) | |
| $k$ | 2.3 | | 2.9 | | 3.2 | | 2.3 | |
| Model parameters | $\alpha_f$ | $k$ | $\alpha_f$ | $k$ | $\alpha_f$ | $k$ | $\alpha_f$ | $k$ |
| Total | 1.000 | 2.3 | 1.000 | 2.9 | 1.000 | 3.2 | 1.000 | 2.3 |
| Fatal and injury | 0.131 | 2.9 | 0.444 | 2.6 | 0.318 | 3.5 | 0.250 | 2.3 |
| Daytime | 0.598 | 1.9 | 0.570 | 2.6 | 0.618 | 2.7 | 0.652 | 2.4 |
| Daytime fatal and injury | 0.075 | 2.6 | 0.263 | 2.0 | 0.199 | 3.1 | 0.151 | 2.3 |
| Nighttime | 0.402 | 2.3 | 0.430 | 3.3 | 0.382 | 4.0 | 0.348 | 2.0 |
| Nighttime fatal and injury | 0.055 | 4.0 | 0.181 | 3.6 | 0.120 | 4.3 | 0.099 | 2.4 |
| Dry | 0.581 | 2.2 | 0.503 | 2.2 | 0.666 | 4.2 | 0.604 | 2.4 |
| Wet | 0.414 | 1.3 | 0.480 | 2.9 | 0.334 | 1.6 | 0.396 | 1.7 |
| Guidance-related | 0.221 | 1.6 | 0.017 | 0.9 | 0.476 | 3.0 | 0.606 | 2.0 |

[1]Data for Pennsylvania and Missouri are for one direction of travel only. AADT variable: for Pennsylvania both directions, for Missouri one-way volume only.

**TABLE A-7 Pennsylvania four-lane freeways: annual factors**

| Annual Factors | Total | Fatal and Injury | Daytime | Daytime Fatal and Injury | Nighttime | Nighttime Fatal and Injury | Dry | Wet | Guidance-Related |
|---|---|---|---|---|---|---|---|---|---|
| 1991 | 0.92 | 0.92 | 0.92 | 0.92 | 0.92 | 0.92 | 0.98 | 0.83 | 0.92 |
| 1992 | 0.92 | 0.92 | 0.92 | 0.92 | 0.92 | 0.92 | 0.98 | 0.83 | 0.92 |
| 1993 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 0.96 | 1.11 | 1.02 |
| 1994 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 0.96 | 1.11 | 1.02 |
| 1995 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 0.96 | 1.11 | 1.02 |
| 1996 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 1.02 | 0.96 | 1.11 | 1.02 |
| 1997 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 1.01 | 0.85 | 0.95 |
| 1998 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 1.01 | 0.85 | 0.95 |
| 1999 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 1.01 | 0.85 | 0.95 |
| 2000 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 1.01 | 0.85 | 0.95 |

**TABLE A-8 New York four-lane freeways: annual factors**

| Annual Factors | Total | Fatal and Injury | Daytime | Daytime Fatal and Injury | Nighttime | Nighttime Fatal and Injury | Dry | Wet | Guidance-Related |
|---|---|---|---|---|---|---|---|---|---|
| 1993 | 0.42 | 0.66 | 0.46 | 0.72 | 0.37 | 0.56 | 0.41 | 0.43 | 0.51 |
| 1994 | 0.46 | 0.71 | 0.46 | 0.66 | 0.46 | 0.79 | 0.44 | 0.47 | 0.31 |
| 1995 | 0.60 | 0.86 | 0.66 | 0.92 | 0.52 | 0.77 | 0.62 | 0.56 | 0.41 |
| 1996 | 0.66 | 0.95 | 0.65 | 0.87 | 0.67 | 1.06 | 0.58 | 0.73 | 0.91 |
| 1997 | 0.82 | 1.08 | 0.87 | 1.09 | 0.76 | 1.05 | 0.72 | 0.95 | 1.11 |
| 1998 | PRPM Implementation Year | | | | | | | | |
| 1999 | 1.04 | 0.66 | 0.99 | 0.66 | 1.11 | 0.67 | 1.15 | 0.94 | 0.50 |
| 2000 | 1.21 | 0.63 | 1.19 | 0.65 | 1.24 | 0.61 | 1.23 | 1.17 | 1.30 |
| 2001 | 1.42 | 0.76 | 1.37 | 0.86 | 1.48 | 0.63 | 0.78 | 2.09 | 1.21 |

**TABLE A-9 Missouri four-lane freeway: annual factors**

| Annual Factors | Total | Fatal and Injury | Daytime | Daytime Fatal and Injury | Nighttime | Nighttime Fatal and Injury | Dry | Wet | Guidance-Related |
|---|---|---|---|---|---|---|---|---|---|
| 1991 | 0.86 | 0.94 | 0.81 | 0.90 | 0.94 | 0.99 | 0.87 | 0.84 | 0.91 |
| 1992 | 0.74 | 0.77 | 0.73 | 0.76 | 0.76 | 0.77 | 0.83 | 0.57 | 0.71 |
| 1993 | 0.97 | 0.95 | 0.93 | 0.90 | 1.04 | 1.03 | 0.90 | 1.11 | 1.01 |
| 1994 | 0.96 | 0.96 | 0.93 | 0.90 | 1.02 | 1.06 | 1.04 | 0.80 | 0.94 |
| 1995 | 0.93 | 0.89 | 0.89 | 0.85 | 0.99 | 0.94 | 0.97 | 0.86 | 0.90 |
| 1996 | 1.05 | 1.03 | 1.07 | 1.04 | 1.02 | 1.01 | 1.00 | 1.15 | 1.03 |
| 1997 | 1.01 | 1.07 | 1.05 | 1.12 | 0.95 | 0.97 | 0.98 | 1.08 | 1.08 |
| 1998 | 1.05 | 1.02 | 1.11 | 1.04 | 0.95 | 0.97 | 1.01 | 1.11 | 1.03 |
| 1999 | 1.11 | 1.07 | 1.27 | 1.25 | 0.86 | 0.76 | 1.07 | 1.20 | 1.02 |
| 2000 | 1.01 | 0.98 | 1.00 | 1.01 | 1.02 | 0.91 | 0.97 | 1.08 | 0.99 |
| 2001 | 0.95 | 0.87 | 1.01 | 0.93 | 0.86 | 0.76 | 0.92 | 1.02 | 0.94 |

**TABLE A-10 Wisconsin four-lane freeway: annual factors**

| Annual Factors | Total | Fatal and Injury | Daytime | Daytime Fatal and Injury | Nighttime | Nighttime Fatal and Injury | Dry | Wet | Guidance-Related |
|---|---|---|---|---|---|---|---|---|---|
| 1994 | 0.73 | 0.69 | 0.69 | 0.70 | 0.82 | 0.68 | 0.72 | 0.75 | 0.95 |
| 1995 | 0.73 | 0.69 | 0.71 | 0.71 | 0.77 | 0.67 | 0.78 | 0.69 | 0.96 |
| 1996 | 0.95 | 1.02 | 0.95 | 0.97 | 0.95 | 1.12 | 0.85 | 1.09 | 1.04 |
| 1997 | 0.93 | 0.98 | 0.94 | 1.00 | 0.92 | 0.96 | 0.88 | 0.99 | 1.03 |
| 1998 | 0.90 | 0.86 | 0.97 | 0.89 | 0.80 | 0.83 | 1.00 | 0.75 | 0.89 |
| 2000 (Comparison Group 1) | 1.24 | 1.48 | 1.30 | 1.41 | 1.12 | 1.58 | 1.04 | 1.54 | 1.42 |
| 2000 (Comparison Group 2) | 1.08 | 0.98 | 1.08 | 0.99 | 1.08 | 0.99 | 1.07 | 1.08 | 1.24 |

Comparison Group 1: based on 43 miles of comparison sites of four-lane freeways; Comparison Group 2: based on a sample of urban Interstate highway in Milwaukee County.

**TABLE A-11 Safety performance functions for four-lane divided expressways**

| Model Form<br>Crashes per Mile-yr | Pennsylvania[1]<br>$\alpha(AADT/2)^{\beta 1}$ | | Wisconsin<br>$\alpha(AADT)^{\beta 1}$ | |
|---|---|---|---|---|
| $\ln(\alpha)$ (s.e.) | -11.40 (1.17) | | -3.47 (1.88) | |
| $\beta_1$ (s.e.) | 1.241 (0.122) | | 0.494 (0.199) | |
| $\beta_2$ (s.e.) | N/A | | N/A | |
| $k$ | 2.3 | | 2.2 | |
| Model parameters | $\alpha_f$ | $k$ | $\alpha_f$ | $k$ |
| Total | 1.000 | 2.3 | 1.000 | 2.2 |
| Fatal and injury | 0.154 | 1.8 | 0.165 | 3.7 |
| Daytime | 0.625 | 2.3 | 0.691 | 1.6 |
| Daytime fatal and injury | 0.098 | 1.8 | 0.090 | 3.4 |
| Nighttime | 0.375 | 2.5 | 0.309 | 4.6 |
| Nighttime fatal and injury | 0.056 | 2.5 | 0.075 | 2.7 |
| Dry | 0.666 | 2.5 | 0.761 | 1.8 |
| Wet | 0.331 | 1.7 | 0.239 | 2.3 |
| Guidance-related | 0.094 | 0.8 | 0.634 | 3.1 |

[1]Data for Pennsylvania is for one direction of travel only. AADT is for both directions.

**TABLE A-12 Pennsylvania four-lane divided expressways: annual factors**

| Annual Factors | Total | Fatal and Injury | Daytime | Daytime Fatal and Injury | Nighttime | Nighttime Fatal and Injury | Dry | Wet | Guidance-Related |
|---|---|---|---|---|---|---|---|---|---|
| 1991 | 0.76 | 0.86 | 0.78 | 0.82 | 0.72 | 0.93 | 0.75 | 0.77 | 0.88 |
| 1992 | 0.76 | 0.86 | 0.78 | 0.82 | 0.72 | 0.93 | 0.75 | 0.77 | 0.88 |
| 1993 | 0.61 | 0.60 | 0.61 | 0.65 | 0.60 | 0.50 | 0.58 | 0.68 | 0.63 |
| 1994 | 0.61 | 0.60 | 0.61 | 0.65 | 0.60 | 0.50 | 0.58 | 0.68 | 0.63 |
| 1995 | 0.61 | 0.60 | 0.61 | 0.65 | 0.60 | 0.50 | 0.58 | 0.68 | 0.63 |
| 1996 | 0.61 | 0.60 | 0.61 | 0.65 | 0.60 | 0.50 | 0.58 | 0.68 | 0.63 |
| 1997 | 0.72 | 0.62 | 0.68 | 0.54 | 0.78 | 0.76 | 0.81 | 0.54 | 0.49 |
| 1998 | 0.72 | 0.62 | 0.68 | 0.54 | 0.78 | 0.76 | 0.81 | 0.54 | 0.49 |
| 1999 | 0.72 | 0.62 | 0.68 | 0.54 | 0.78 | 0.76 | 0.81 | 0.54 | 0.49 |
| 2000 | 0.72 | 0.62 | 0.68 | 0.54 | 0.78 | 0.76 | 0.81 | 0.54 | 0.49 |

**TABLE A-13 Wisconsin four-lane divided expressways: annual factors**

| Annual Factors | Total | Fatal and Injury | Daytime | Daytime Fatal and Injury | Nighttime | Nighttime Fatal and Injury | Dry | Wet | Guidance-Related |
|---|---|---|---|---|---|---|---|---|---|
| 1994 | 0.77 | 0.65 | 0.69 | 0.64 | 0.95 | 0.67 | 0.81 | 0.65 | 1.05 |
| 1995 | 0.69 | 0.60 | 0.69 | 0.66 | 0.69 | 0.52 | 0.76 | 0.48 | 0.99 |
| 1996 | 1.00 | 1.10 | 1.00 | 0.94 | 1.00 | 1.29 | 0.98 | 1.08 | 0.89 |
| 1997 | 1.14 | 1.18 | 1.20 | 1.28 | 1.03 | 1.07 | 1.06 | 1.41 | 0.91 |
| 1998 | 1.28 | 1.35 | 1.31 | 1.35 | 1.23 | 1.35 | 1.29 | 1.27 | 1.05 |
| 1999 | PRPM Implementation Year | | | | | | | | |
| 2000 | 1.42 | 1.71 | 1.43 | 1.70 | 1.43 | 1.72 | 1.43 | 1.43 | 1.42 |

Abbreviations used without definitions in TRB publications:

| | |
|---|---|
| AASHO | American Association of State Highway Officials |
| AASHTO | American Association of State Highway and Transportation Officials |
| APTA | American Public Transportation Association |
| ASCE | American Society of Civil Engineers |
| ASME | American Society of Mechanical Engineers |
| ASTM | American Society for Testing and Materials |
| ATA | American Trucking Associations |
| CTAA | Community Transportation Association of America |
| CTBSSP | Commercial Truck and Bus Safety Synthesis Program |
| FAA | Federal Aviation Administration |
| FHWA | Federal Highway Administration |
| FMCSA | Federal Motor Carrier Safety Administration |
| FRA | Federal Railroad Administration |
| FTA | Federal Transit Administration |
| IEEE | Institute of Electrical and Electronics Engineers |
| ITE | Institute of Transportation Engineers |
| NCHRP | National Cooperative Highway Research Program |
| NCTRP | National Cooperative Transit Research and Development Program |
| NHTSA | National Highway Traffic Safety Administration |
| NTSB | National Transportation Safety Board |
| SAE | Society of Automotive Engineers |
| TCRP | Transit Cooperative Research Program |
| TRB | Transportation Research Board |
| U.S.DOT | United States Department of Transportation |