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Installation and Maintenance of Raised Pavement Markers at State Transportation Agencies: Synthesis of Current Practices

Hamed Zamenian
Dulcy M. Abraham

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AUTHORS

Dulcy M. Abraham, PhD
Professor of Civil Engineering
Lyles School of Civil Engineering
Purdue University
(765) 494-2239
dulcy@purdue.edu
Corresponding Author

Hamed Zamenian
Graduate Research Assistant
Lyles School of Civil Engineering
Purdue University

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16. Abstract

Although raised pavement markers (RPMs) have been widely applied by the Indiana Department of Transportation (INDOT), there have been multiple cases where snowplowing activities have damaged pavements as well as the raised pavement markers on INDOT's roadway assets. Dislodged raised pavement markers could reduce the design life of pavements because they leave openings for water and debris to infiltrate through pavement section. Interviews with INDOT personnel indicated that the proper installation of the markers and careful attention to the tooling of the center line of the concrete pavements could alleviate this problem. To explore issues related to the proper installation of RPMs, this study (INDOT/JTRP SPR-4318) was launched by the Indiana Department of Transportation (INDOT)/Joint Transportation Program (JTRP) to develop a synthesis of current practices on installation and maintenance of raised pavement markers at State Transportation Agencies (STAs) in the U.S. The study was conducted using a qualitative exploratory approach focusing on the review of current practices in installation and maintenance of raised pavement markers among STAs. Survey analysis and focused interviews with personnel from STAs, along with reviews of documents provided by STAs were the avenues used for data collection in this project.

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EXECUTIVE SUMMARY

Introduction

A raised pavement marker (RPM) is classified as a delineation device that is often used to provide guidance for drivers about lane discipline and curvature day and night and in good and poor weather. Although raised pavement markers have been widely applied by the Indiana Department of Transportation (INDOT), there have been multiple cases where snowplowing activities have damaged both the pavements and the raised pavement markers on INDOT's roadway assets. Dislodged raised pavement markers could reduce the design life of pavements because they leave openings for water and debris to infiltrate through pavement section. Interviews with INDOT personnel indicated that the proper installation of the markers and careful attention to the tooling of the center line of the concrete pavements could alleviate this problem. To explore issues related to the proper installation of RPMs, this study (SPR-4318) was launched by the Indiana Department of Transportation (INDOT) and the Joint Transportation Program (JTRP) to develop a synthesis of current practices at State Transportation Agencies (STAs) in the U.S. on installation and maintenance of raised pavement markers on concrete pavements. This study was conducted using a qualitative exploratory approach focusing on the review of current practices in installation and maintenance of raised pavement markers among STAs. Survey analysis and focused interviews with personnel from STAs, along with reviews of documents provided by STAs were the avenues used for data collection in this project.

Findings

This study focused on the following 10 themes for the assessment of installation and performance of raised pavement makers: (1) STA practices related to application of raised pavement markers, (2) application of beveled and longitudinal joints/tooled longitudinal joints during installation of raised pavement markers, (3) installation and removal of raised pavement markers, (4) quality control parameters regarding preparation for the installation of raised pavement markers, (5) manuals/specifications regarding preparation of pavements for installation of raised pavement markers, (6) assessment of damages to the pavement/joints caused by raised pavement markers, (7) snowplowing activities on roadway assets, (8) inspection and maintenance of raised pavement markers, (9) assessment of damages to raised pavement markers, and (10) criteria for measuring "satisfaction" of using raised pavement markers. Key findings are summarized below.

- Typically, STAs follow the *Manual on Uniform Traffic Control Devices* (MUTCD) regarding the preparation of pavements for the installation of raised pavement markers. The MUTCD focuses on providing guidelines on the spacing requirements of RPMs and the replacement of RPMs based on their retroreflective aspect, but *it does not specifically address installation practices that could enhance the initial and long-term condition of the pavement-RPM assembly*.
- Some STAs including Delaware, New Jersey, Utah, and Louisiana have additional state-specific standards for the installation of raised pavement markers.
- There was *no common installation practice* of RPMs on concrete pavement across STAs. For instance, Delaware DOT has banned the installation of RPMS on PCC pavement joints. While Illinois DOT installs RPMs at least 2 inches away from the longitudinal joint in concrete pavement.
- STAs recognize that factors such as ambient temperature, pavement surface temperature, epoxy hardness, depth of groove, and pavement cleanliness are classified as quality control parameters for the installation of raised pavement markers.
- The majority of the STAs have routine inspection program for raised pavement markers; however, the frequency of inspection varies among agencies. For instance, Utah DOT inspects their raised pavement marker assets once a year; however, Illinois DOT conducts inspections every 4 years.
- Alaska, Idaho, Wyoming, Kentucky, and Kansas DOTs do not use raised pavement markers mainly because raised pavement markers are not resistant to snowplows and result in damages to the pavement, injury, and accidents when they are dislodged.

Based on the literature review and interviews with STAs, the research team suggests that INDOT further explore the following RPM installation practices on PCC pavements:

- *Criteria from Delaware DOT:* (1) If possible, do not install on a PCC pavement joint and (2) If RPMs are needed, install them a minimum of 2 inches away from longitudinal joints.
- *Criterion from Illinois DOT:* The closest edge of the RPM is installed at least 2 inches away from the longitudinal joint.
- *Criterion from North Carolina DOT:* Install markers to avoid placement at or on a longitudinal joint or surface defect.

Implementation

Based on the analysis of survey responses, interviews with STA personnel, and discussions with the Study Advisory Committee (SAC) of this project, the following suggestions are presented for further investigation by INDOT.

- Conduct a follow-up interview with the Iowa Department of Transportation to determine their prior experience with (1) their current standard specification regarding the use of a joint-forming device (Bobsled) with the slipform paver, (2) their RPM installation criteria, and (3) the condition of longitudinal joints in concrete pavements that are installed using the Bobsled.
- Conduct a follow-up interview with the Kentucky Transportation Cabinet and Dynatech Company regarding Inlaid Pavement Marker (IPM) or Banana-Cut Marker to (1) obtain more data about construction and maintenance procedures for installation of these markers, and (2) plan a site-visit to review the performance of installed Inlaid Pavement Markers.
- Conduct a follow-up interview with the Delaware DOT regarding RPM installation practices on PCC pavements. The criteria from Delaware DOT is to (1) if possible, do not install on a PCC pavement joint, and (2) if RPMs are needed, install them a minimum of 2 inches away from longitudinal joints.
- Conduct a follow-up interview with the Illinois DOT regarding RPM installation practices on PCC pavements. The criterion from Illinois DOT is that the closest edge of the RPM be installed at least 2 inches away from the longitudinal joint.

- Conduct a follow-up interview with the North Carolina DOT regarding RPM installation practices on PCC pavements. Criterion from North Carolina DOT is to install markers to avoid placement at or on a longitudinal joint or surface defect.
- Conduct a pilot study to evaluate the effectiveness of slotted pavement markers on concrete pavements and their impact of the installation and maintenance activities of these RPMs on the condition of concrete pavements as well as on the condition and performance of the RPMs.

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1. INTRODUCTION

Pavement markings are intended to convey information to drivers about lane discipline and curvature on roadways in good and severe weather, and during day and night. Although many pavement markers are available for use by State Transportation Agencies (STAs) during dry and night-time conditions (such as waterborne paints, epoxy paints, retroreflective tape, and rumble stripes with thermoplastic), precipitation can greatly affect the visibility of such as markers. A pavement marker that has proven to be effective in wet conditions and at night-time is the Raised Pavement Marker (RPM). Raised Pavement Markers (RPMs) have been widely applied by different STAs as delineation tool to improve driver preview distances and provide guidance on lane discipline and roadway curvature. The *Indiana Department of Transportation—2013 Design Manual* (INDOT, 2013) states that "RPMs provide a supplemental method of delineation and are a positive position guidance device. They should not be used as a replacement for standard pavement markings or conventional roadside delineation." Due to the high visibility of RPMs during the nighttime and inclement weather, they decrease the overall accident rates by 78% (Dwyer & Himes, 2019); reduce the nighttime crashes as traffic volumes increase (Bahar et al., 2004); and improve safety in the work zone areas (Meyer, 2000).

1.1 Background

As shown in Figure 1.1, RPMs are classified into two basic varieties: (1) non-snowplowable RPM (NSRPM) and (2) snowplowable RPM (SRPM). NSRPM have a rounded or square reflector epoxied to the pavement surface. SRPMs consist of a metal casting that is installed in the pavement using adhesive materials. The casting is sloped so that snowplow blades will ride over the casting during plowing operations.

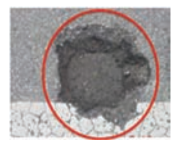
Guidance for installation of RPMs is provided in the *Manual on Uniform Traffic Control Devices* (U.S. Department of Transportation, 2012). The guidance focuses on the installation criteria such as spacing of RPM and lists the types of roads on which RPMs can be used. For example, the typical spacing between RPMs should be 80 feet; however, at the curves, transitions, and lateral shifts the spacing should be limited to 40 feet. The NCHRP Report-518 reviewed the current installation practices of RPMs among State Highway Agencies (SHAs) in the U.S. (Bahar et al., 2004) and indicated that each STA uses RPMs on certain types of roads based on certain characteristics, such as annual average daily traffic (AADT) and speed limit. Table 1.1 shows examples of RPM installation practices among STAs in the Midwestern region of the U.S.

Figure 1.1 Non-snowplowable RPM (NSRPM) and snowplowable RPM (SRPM) (GSHP, n.d.a; n.d.b).

TABLE 1.1
Example of installation practices of RPMs among different SHAs

STA	Guideline
Illinois DOT	Install on: Rural two-lane roads with ADT > 2,500 vpd Multilane roads with ADT > 10,000 vpd Horizontal curves where advisory speed more than 10 mph below posted speed limit Lane reduction transitions, rural left turn lanes, and two-way left-turn lanes (TWLTLs)
Indiana DOT	Install on: Rural two-lane roads with ADT > 2,500 vpd Multilane roads with ADT > 6,000 vpd
Kansas DOT	Install on roads with AADT > 3,000 vpd and truck AADT > 450 vpd
Kentucky DOT	SRPMs not used on bridge decks or local roads
Michigan	Installed on all freeways without illumination
West Virginia	Installed on roads with AADT > 10,000 vpd
Wisconsin	Installed on all roads with speed limit > 65 mph

TABLE 1.2
Common modes and causes of RPM failure in asphalt and PCC pavements

#	Mode of Failure	Cause of Failure	Visualization	
1	Detached SRPM[1]	End of SRPM service life Poor quality installation Caught by a snowplow blade		SRPM dislodged from the pavement surface
2	Casting Failure[1]	End of SRPM service life Poor quality installation		Fracture occurred on the SRPM casting
3	Pavement Failure[1]	Caught by a snowplow blade Installed on construction joints		SRPM dislodged due to snowplowing activities
4	Adhesive Failure[1]	Improper installation Epoxy adhesive is not hardened		SRPM dislodged due to adhesive failure
5	Pavement Failure	Installed near or on a longitudinal joint or crack		Improper installation of SRPM resulted in joint failure

[1]Photos from the Ohio Department of Transportation's Traffic engineering manual.

The type of maintenance activities for RPMs also varies among STAs (Bahar et al., 2004). Some STAs have routine maintenance programs where RPMS' reflectors are replaced on a regular 2-to-3 year cycle, (for instance, at roadways assets maintained by PennDOT and ODOT). In some cases, STAs follow the guidelines provided by manufacturers of RPMs for replacement of reflectors or castings based on the service life of RPMs. Other STAs have regular inspection program linked with ongoing maintenance activities. For instance, New Jersey DOT conducts visual inspection of RPMs when work crews performing other work in the area.

1.2 Problem Statement and Research Objectives

Failed SRPMs could detach from pavement surface and cause crashes through windshield (Smith, 2010) and dislodged RPMs could reduce the design life of pavements because they leave openings for water and debris to infiltrate through pavement section (Brennan et al., 2014). Table 1.2 shows the common modes and cause of failure for RPMs. Meyer (2000) investigated the disadvantages of using RPMs from the perspective of STAs. In this study, the STAs reported that RPMs cause installation and maintenance challenges that are more expensive to address compared to the use of traditional pavement strips. For instance, the cost of installation, removal and replacement of each SRPM in 2006 in Virginia was found to be $23.02, $18.57, and $6.38, respectively (Fontaine & Gillespie, 2009). Due to the costly maintenance associated with RPMs, the transportation agencies in Colorado and Iowa removed all RPMs and decided not to use them anymore (Bahar et al., 2004).

2. METHODOLOGY

This study uses a qualitative exploratory approach to the review the installation and maintenance of RPMs across different STAs. Qualitative research analysis is the preferred research strategy when "how" and "why" questions are being posed and when the focus of the study is on a contemporary problem with some real-life context (Yin, 2009). According to Cresswell (2009), "the idea behind qualitative research is to purposefully select participants or sites that will best help the researcher understand the problem and the research question." Three primary methods: (1) survey of STAs, (2) focused interviews, and (3) review of documents obtained during the literature search and resources provided by STAs were the avenues used for data collection in this study. Figure 2.1 shows the methodological approach for this project.

A literature search was conducted to identify the state-of-art and state-of-practice among STAs for the installation and maintenance of RPMs on PCC pavements. The first round of literature review was performed by using both archival resources as well as on-line sources such as the FHWA, the NCHRP, and the websites of different STAs. Based on the findings from this review, a preliminary list of themes was generated for further exploration of installation and maintenance of RPMs at different STAs. Recognizing that qualitative research heavily relies on subject matter expert as an important source of information (Marshall & Rossman, 2011), the SPR-4318 research team with guidance from the business owner, the project administrator and the study advisory committee (SAC) developed a survey questionnaire (see Appendix A) in order to be deployed among STAs.

The survey questions consisted of two parts with an estimated 15-minute completion time (Appendix A). The first part of the survey questions collected general information from survey participants including contact information and willingness to participate in phone interview. The second part of the survey focused on current RPM installation and maintenance practices and challenges experienced by STAs during the installation and maintenance of RPMs.

The survey question was sent to all fifty STAs within the U.S. with particular attention to STAs located in the Midwest region. Collection efforts were initiated via e-mail originated through the Lyles School of Civil Engineering at Purdue University and Joint Transportation Research Program, explaining this research and requesting that the survey be completed by a person in the agency responsible for RPM installation and/or maintenance. Data was gathered during a period of approximately 6 months. Figure 2.2 shows the geographical representation of respondents to the survey questionnaire.

Synopses of key findings/observations from the survey responses were shared with the SAC team to identify areas which needed further investigation, and more nuanced follow-up questions were developed. Personnel at STAs were asked to participate in phone interviews in order to assist the research team in obtaining greater insight into how STAs conduct installation and maintenance activities of RPMs. Four STAs agreed to participate in phone interview: including the Illinois Department of Transportation, the South Carolina Department of Transportation, the Kentucky Transportation Cabinet, and the Indiana Department of Transportation. Appendix B lists the participants in each of the interviews. A second round of literature review was conducted to clarify issues that were raised during the interviews.

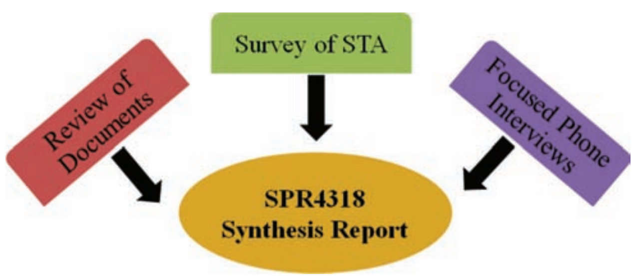


Figure 2.1 Methodological approach.

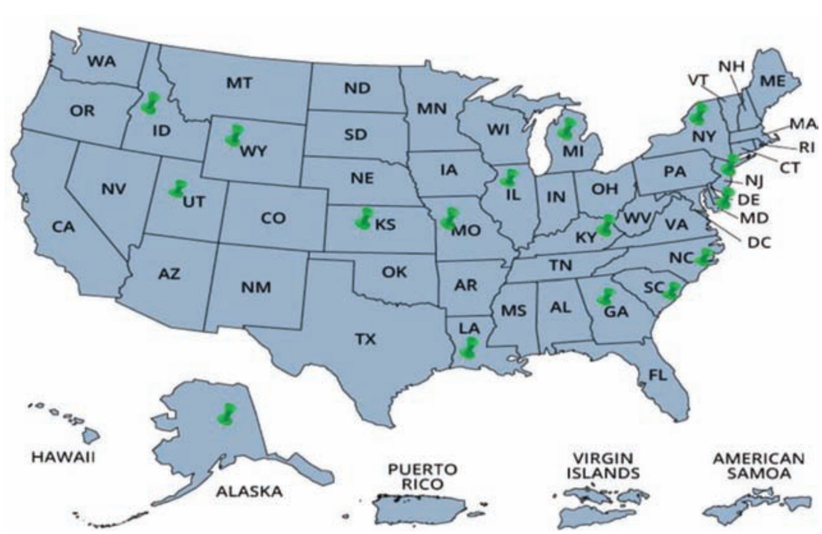


Figure 2.2 Geographical representation of survey respondents.

3. FINDINGS

This study focused on ten themes including: (1) STA practices related to application of raised pavement markers in PCC pavements, (2) application of beveled and longitudinal joints/tooled longitudinal joints during installation of raised pavement markers in PCC pavements, (3) installation and removal of raised pavement markers, (4) quality control parameters regarding preparation for the installation of raised pavement markers, (5) manuals/specifications regarding preparation of pavements for installation of raised pavement markers in PCC pavements, (6) assessment of damages to the pavement/joints caused by raised pavement markers, (7) snowplowing activities on roadway assets, (8) inspection and maintenance of raised pavement markers, (9) assessment of damages to raised pavement markers, and (10) criteria used for measuring "satisfaction" of using raised pavement markers.

Raised pavement markers are widely used as a traffic safety indicator to assist drivers by delineating lanes and intersections over a wide range of environmental conditions, especially in night-time and wet conditions. Non-snowplowable RPMs are used by the southern and western STAs of the United States where snowfall is not a concern; however, snowplowable RPMs, with a metal housing designed to protect the marker from snowplowing activities, are used in Northern and Midwestern SHAs (Bahar et al., 2004). Although there is safety improvement due to the utilization of RPMs, some STAs are not satisfied with the use of RPMs and are seeking alternate technologies, mainly due to durability issues. For instance, the Colorado Department of Transportation has halted all RPMs due to high maintenance costs (Liu et al., 2018).

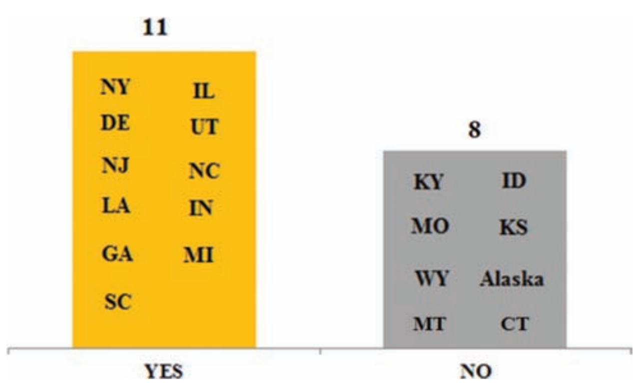


Figure 3.1 Usage of RPMs among SHAs.

The first question of survey was to identify whether STAs use RPM on their roadways or not. As shown in Figure 3.1, out of 19 STAs responding to the survey, 58% indicated that they use RPM and 42% indicated that they do not use RPMs. Snowplowing activities that remove and dislodge RPMs, as well as damage to the pavement when RPMs are dislodged, were the primary reasons cited by respondent STAs that did not use RPMs.

In addition, the STAs were asked to provide the relative cost associated with different types of RPMs such as temporary RPMs, non-snowplowable RPMs, snowplowable RPMs, and recessed RPMs. Table 3.1 presents a summary of RPMs' service life and the associated installation and removal costs.

In response to the benefits that each SHA expected by implementing RPMs, majority of respondents underscore the safety and delineation factors. Responses to this question are summarized in Table 3.2 for each SHA.

3.1 Application of Beveled and Longitudinal Joints/Tooled Longitudinal Joints During Installation of Raised Pavement Markers

Joints in concrete pavements are vital for eliminating early stage cracking and ensuring strong long-term performance of the pavement. There are different types joints used in the construction of concrete pavements including: (1) contraction joints, (2) longitudinal joints,

TABLE 3.1
Summary of RPMs service life and associated installation and removal cost

Type of RPMs	Installation Cost	Removal Cost	Service Life	STA
Temporary RPMs	$6.60/each	—	1 year	NC
	Varies	—	1 season	MI
	$12.50/each	Included with installation	1 year	IN
Non-Snowplowable RPMs	$6.50/each	—	4 years	NC
	$900/mile	$200/mile	—	LA
Snowplowable RPMs (SRPMs)	$34.66	—	—	DE
	$25/unit	$10/unit	10 years	NJ
	$35/each	$15/each	3 years	DE
	$45/each	$15/each	15 years	IL
	$21.91/each	$5.23/each	20 years casting 4 years reflectors	IN
Recessed SRPMs	$10.55/each	—	Still under test	UT
	$35/each	—	Lens 3 years, marker 8 years	NC

TABLE 3.2
Actual benefits of using RPMs

Actual Benefits	STA
Better delineation but the temporary ones walked on freeways	MI
Still evaluating—final report of test project expected this winter	UT
They are very effective at increasing visibility under night time rain/wet conditions	DE
Positive lane guidance for motorists in dark and wet conditions	IL
Traffic safety	DE
RPMs were popular with local residents	IN
RPMs serve as a supplemental method of delineation	
RPMs provide positive guidance during wet weather	
RPMs complement delineators on freeways and expressways	
Safe for drivers—helps with nighttime and wet weather driving	SC

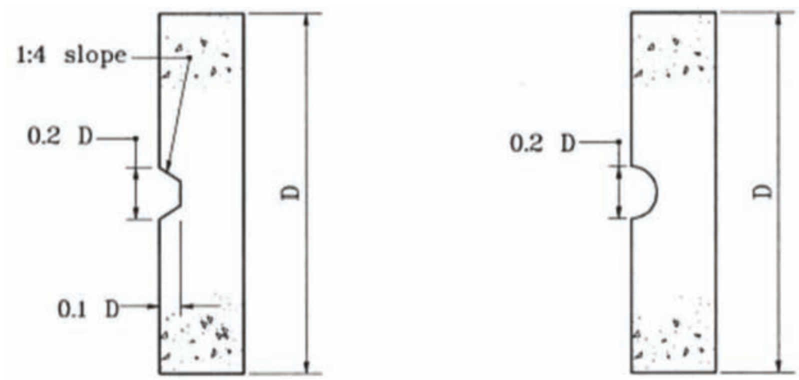


Figure 3.2 Keyway joints (INDOT, 2007a).

Figure 3.3 Saw cut vs. beveled joint (NRMCA, 2006).

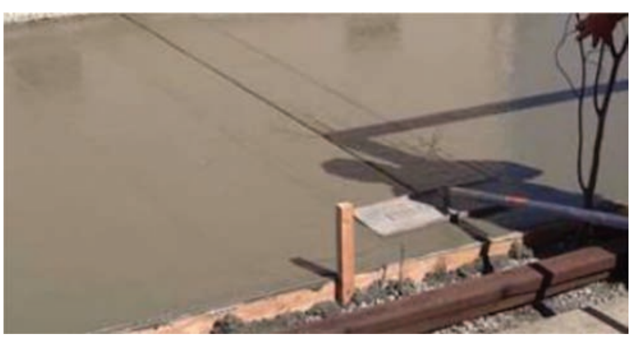


Figure 3.4 Tooled joint installation (T. Nantung, personal communication, August 16, 2019).

(3) transverse construction joints, (4) terminal joints, and (5) expansion joints. A longitudinal joint is one of the construction joints that is required in all pavements wider than 16 feet and is placed parallel to the center line (INDOT, 2007b). "Some longitudinal joints require the use of a keyway with no tie bars" (INDOT, 2007b). Keyways (as shown in Figure 3.2) may be trapezoidal or semi-circular in shape and are referred to as beveled or tooled joint.

A beveled joint is a "V" shaped joint; it is a tooled joint but with a V shape as shown in Figure 3.3. Tooled joints are created by using a special trowel resulting in a rounded edge (Figure 3.4). Beveled joints and tooled joints are typically used in concrete pavement patches.

Since RPMs are placed along the centerline of the pavement, selection of appropriate longitudinal joint is an important factor in order to reduce the damage to the joints and increase the life cycle of concrete pavement. Table 3.3 lists the factors that can reduce damage to longitudinal joints in concrete pavements. STAs indicated that clearance of at least 2 inches from the longitudinal joint could reduce damage to

TABLE 3.3
Factors that can reduce damage to longitudinal joints in concrete pavements

STA	Factors that Can Reduce Damages to the Longitudinal Joints in Concrete Pavements[1]
Delaware	Not installed on a PCC pavement joint RPM's are placed a minimum of 2 inches away from longitudinal joints
Illinois	The closest edge of the RPM is installed at least 2 inches away from the longitudinal joint
North Carolina	Install markers to avoid placement at or on a longitudinal joint or surface defect

[1]These installation criteria have been used by STAs in order to reduce damages to longitudinal joints in concrete pavements. These STAs have not performed any tests or collected data to validate if their installation criteria were indeed the reasons for reduced damages in concrete pavements (only anecdotal information was provided during the interviews).

TABLE 3.4
Installation procedure for non-snowplowable RPMs

Step	Action	Visualization
1	Clean the pavement surface	
2	Apply adhesive to non-snowplowable RPM	
3	Install non-snowplowable RPM on the pavement	

longitudinal joints in concrete pavements. Offsetting of RPMs used in concrete roadways is not currently addressed by INDOT. However, the INDOT *2013 Design Manual*, Chapter 76, (INDOT, 2013, p. 23) mentions that RPMs should not be placed at a location that is scheduled for resurfacing or reconstruction within the next 4 years.

3.2 Installation and Removal of Raised Pavement Markers

The *Manual on Uniform Traffic Control Devices* (U.S. Department of Transportation, 2012) provided guidelines on the installation of RPMs. Installation mechanisms for non-snowplowable RPM and snowplowable RPM are different. Table 3.4 and Table 3.5 demonstrate the installation procedures for non-snowplowable and snowplowable RPM (Ohio Department of Transportation, 2002).

The MUTCD manual specifies spacing requirements for installation of RPMs (see Table 3.6) and states that the spacing should vary based upon the geometry of the road and the manner in which RPMs are used to supplement continuous markings (Liu et al., 2018; U.S. Department of Transportation, 2012).

Bahar et al. (2004) assessed installation practices of RPMs among 29 State Highway Agencies in the U.S. The authors classified the usage of RPMs in two categories: (1) non-selective and (2) selective. The states of Ohio, Texas, and California installed RPMs on all state-maintained roads (non-selective installation). In several other states, RPMs were installed selectively based on certain characteristics, such as AADT, speed limit, or geometric considerations (Liu et al., 2018). Table 3.7 synthesizes the location criteria for installation of RPMs among different STAs.

The survey respondents were asked to specify the location of each class of RPMs. Table 3.8 shows the location criteria for using different classes of RPMs.

The survey respondents were asked to specify the spacing required for each class of RPMs. Table 3.9 shows the spacing criteria for using different classes of RPMs. The survey results indicated that STAs use their own spacing criteria for installation of RPMs, and do not strictly follow the guidelines provided by MUTCD.

TABLE 3.5
Installation procedure for snowplowable RPM

Step	Action	Visualization
1	Saw cut of the pavement	
2	Apply adhesive epoxy around casting	
3	Placement of casting in saw cut using epoxy bond	
4	Installed RPM	

TABLE 3.6
Spacing criteria for installation of RPMs (U.S. Department of Transportation, 2012)

#	Location	Spacing Requirement
1	Typical spacing, skip lines	80 feet
2	Solid lines, curves, transitions, or lateral shifts	40 feet or less
3	Straight, level freeway sections skip lines	Up to 120 feet
4	Left edge lines	20 feet or less

3.3 Quality Control Parameters Regarding Preparation for the Installation of Raised Pavement Markers

One of the important factors that has impact on the durability of RPMs is the preparation and quality of installation (Gartner et al., 2016). The Arkansas Department of Transportation and the Georgia Department of Transportation classified pavement surface temperature, ambient temperature, pavement surface moisture, and pavement cleanliness as the quality control parameters monitored during installation of RPMs. The Maryland Department of Transportation, the New Mexico Department of Transportation, the Ohio Department of Transportation, and the Utah Department of Transportation also considered two additional factors—depth of groove cut and epoxy hardness as quality control parameters—during installation of RPMs (Gartner et al., 2016).

The survey participants were asked to provide their quality control parameters for installation of RPMS. Four STAs responded to this question and identified quality control factors as listed in Table 3.10.

3.4 Manuals/Specifications Regarding Preparation of Pavements for Installation of Raised Pavement Markers

The MUTCD provides guidelines on the spacing requirements of RPMs and replacement of RPMs with primary focus on the retroreflective aspects of RPMs. Many STAs have also developed their own criteria for installation and maintenance of RPMs (Bahar et al., 2004). For instance, in Ohio, Texas, and California, RPMs are installed on all state-maintained highways; however, Maryland, Massachusetts, Wisconsin, Pennsylvania, Illinois, Indiana, and Kansas use RPMs on certain roadway types, such as freeways, and selectively on other roadway types on the basis of one or more of the following parameters: (1) roadway type, (2) traffic volume, (3) illumination, (4) safety record, (5) speed limits, and (6) horizontal curves (Bahar et al., 2004; Jiang, 2006; Meyer, 2000). For example, in Maryland, RPMs are installed on all two-lane highways with speed limits exceeding 45 mph, versus in Indiana, RPMs are installed on rural two-lane roads with ADT higher than 2,500 vpd, and on multilane roads with ADT above 6,000 vpd (Jiang, 2006). Table 1.1 provides a comprehensive overview of installation criteria for each.

The survey asked respondents to list drawings, manuals and/or specifications that are used by their STA to seek guidance regarding *preparation of pavements* for installation of RPMs. Table 3.11 represent the results from eight STAs. The survey results indicated that all of responding agencies rely on specifications from the MUTCD and may use additional state specific guidelines.

TABLE 3.7
Installation practices of RPMs among STAs (Liu et al., 2018)

STA	Guideline
Delaware	Not used on right edge line except in special cases where additional delineation needed
Illinois	Installed on: Rural two-lane roads with ADT > 2,500 vpd Multilane roads with ADT > 10,000 vpd Horizontal curves where advisory speed more than 10 mph below posted speed limit Lane reduction transitions, rural left turn lanes, and two-way left-turn lanes (TWLTLs)
Indiana	Installed on: Rural two-lane roads with ADT > 2,500 vpd Multilane roads with ADT > 6,000 vpd
Kansas	Installed on roads with AADT > 3,000 vpd and truck AADT > 450 vpd
Kentucky	SRPMs not used on bridge decks or local roads
Maryland	Installed on: All two-lane roads with speed limit > 45 mph Horizontal curves where advisory speed more than 10 mph below posted speed limit One-lane bridges, TWLTLs, lane transitions
Massachusetts	Installed on all undivided highways with speed limit > 50 mph
Michigan	Installed on all freeways without illumination
Mississippi	Installed on interstates and other multilane divided highways
Nevada	Installed in areas where it doesn't snow
New Mexico	Used on multi-lane highways, with high speeds, with high accidents
New Jersey	RPMs are installed along all centerlines and skip lines, regardless of traffic volume, roadway geometry, and roadway classification
Ohio	RPMs are installed 100% on all the interstates, U.S. routes, and state routes
Oregon	Installation strategy varies depending on the region
South Carolina	Installed only on interstates and multilane primaries with AADT > 10,000 vpd
Utah	Installed on all unlit exit ramps with AADT > 100 vpd
West Virginia	Installed on roads with AADT > 10,000 vpd
Wisconsin	Installed on all roads with speed limit > 65 mph

TABLE 3.8
Location criteria for using different classes of RPMs

Class of RPMs	Location Criteria	STA
Temporary RPMs	As needed, construction zones	NC
	Crossovers and chip seal projects	MI
	Temporary RPMs are rarely used	IN
	Work zones	SC
Non-snowplowable RPMs	Lane and edge lines, gores	LA
	As needed or requested	NC
	Primary routes, secondary routes, interstate routes	SC
Snowplowable RPMs	Center lines	DE
	Most state jurisdiction roadways other than low AADT	LA
	SR-50 (MP 150-153), I-15 (MP 33-36), US-89 (MP100-103)	UT
	Higher snowfall areas or high volume routes	NC
	Extensive inventory of RPM's (see Indiana Design Manual figure 502-2C or INDOT's functional classification maps)	IN
	Interstate routes	SC

TABLE 3.9
Spacing criteria for using different classes of RPMs

Class of RPMs	Spacing Criteria	STA
Temporary RPMs	25 ft	MI
	Center, edge, lane = 40 ft	IN
	Taper, gore = 20 ft	
Non-snowplowable RPMs	40′ OC	LA
Snowplowable RPMs	40–80 ft	DE
	80 ft (normal broken line pattern is 10′/30′ with RPMs on 2N spacing)	IL
	40 ft	UT
	Generally, 80 ft (more detail see INDOT Standard Drawing Series 808-MKRM)	IN

TABLE 3.10
Quality control parameters for installation of RPMs

STA	Quality Control Parameters
Louisiana	Ambient temperature, pavement surface moisture, pavement cleanness
Utah	Depth of groove, epoxy hardness
Indiana	Pavement surface temperature, ambient temperature, depth of groove, pavement surface moisture, pavement cleanliness
South Carolina	Pavement surface temperature, ambient temperature, pavement surface moisture, pavement cleanliness, epoxy hardness

TABLE 3.11
Manual/specification for installation of RPMs

STA	Drawings, Manuals, and/or Specifications
Delaware	Manual on Uniform Traffic Control Devices (MUTCD)
	State DOT Standard Specifications
Illinois	Manual on Uniform Traffic Control Devices (MUTCD)
Indiana	Manual on Uniform Traffic Control Devices (MUTCD)
Louisiana	Manual on Uniform Traffic Control Devices (MUTCD)
	State DOT Standard Specifications
Michigan	Manual on Uniform Traffic Control Devices (MUTCD)
North Carolina	Manual on Uniform Traffic Control Devices (MUTCD)
New Jersey	Manual on Uniform Traffic Control Devices (MUTCD)
	State DOT Standard Specifications
Utah	Manual on Uniform Traffic Control Devices (MUTCD)
	State DOT Standard Specifications

3.5 Assessment of Damages to the Pavement/Joints Caused by Raised Pavement Markers

Some STAs using concrete pavements have seen premature deterioration of the pavement at joints and have observed that joints that exhibit this type of damage are close to RPMs. Figures 3.5 and Figure 3.6 show examples of premature deterioration on PCC pavement close to the joints where RPMs were installed, particularly where there was detachment of RPMs. However, there was no consistent pattern for the locations of the damages to the RPM and the longitudinal joints.

The survey participants were asked to provide assessment of damages to the pavement/joints caused by raised pavement markers. As listed in Table 3.12, the majority of survey respondents do not have a common program for inspecting the damages in pavements/joints, caused by installation or remove of RPMs. For instance, at New Jersey DOT, operation and maintenance crews report damages related to RPMs, while Delaware STA has a 3-year cycle for inspecting and assessing condition of RPMs. Table 3.13 summarizes the RPM-related factors (based on the perspective of STAs) leading to longitudinal failures in pavement.

3.6 Types of Snowplowing Activities

Some states have a stringent policy for ice and snow removal from their pavements. For example, the Pennsylvania Department of Transportation and the Utah Department of Transportation have polices requiring that the roads be kept clear regardless of the impact on pavement marking materials (Van Schalkwyk, 2010). The Pennsylvania Department of Transportation uses snowplowable RPMs on all interstates and the agency spends $3 to $4 million annually on SRPMs (Van Schalkwyk, 2010). Snowplowing operation may dislodge RPMs from pavement surface and the dislodged RPM's may then become projectiles that are launched into windshields. For this reason, three states, Alaska, Montana, and Colorado, have removed all RPMs and plans for future installations have been halted (Liu et al., 2018).

Typical snowplowing blades are made of steel or carbide. These types of snowplowing blades could easily damage raised pavement markers. Some STAs have started using other types of plowing mechanisms to try to limit this damage such as urethane-rubber blade or blades on wheel rollers (blades supported by small wheels to reduce the force applied on pavement markings) (Gartner et al., 2016).

Figure 3.5 Damage to the longitudinal joints caused by removal of RPMs (Lafayette, IN-US 231).

Figure 3.6 Damage to the longitudinal joints caused by RPMs (West Lafayette, IN-US 52).

TABLE 3.12
Assessment of damages to the pavement/joints caused by RPMs

STA	Assessment of Damages to the Pavement
Delaware	Maintains RPMs on a 3-year cycle at which time the roads are inspected and assessed
Illinois	Visual inspection
New York	RPMs are rarely used and only as supplemental temporary markings in work zones
Michigan	Only uses temporary RPMS
New Jersey	Maintenance and Operations staff report on the damage issues with RPM's
Utah	Currently does not have a formal system inspection for RPMs—only three test locations with recessed pavement markers

TABLE 3.13
RPM-related factors leading to longitudinal failure in pavement

STA	Factors for the Longitudinal Failure in Pavement	Intensity (1=lowest; 5 = highest)
NJ	Pothole—RPM becomes dislodged	2
DE	Too close to the joint—the only time we have witnessed failure in the pavement joint due to RPMs is when they are installed too close to the joints	5
IL	Proximity to transverse and longitudinal joint—RPMs installed too close to transverse and longitudinal joint	1
NC	Delamination—Failures are fairly rare on the pavement surface on which the RPM is installed. It is typically resurfacing when problems arise—improperly removed and patched areas can cause delamination in the new surface course	5

TABLE 3.14
Types of snowplowing activities

STA	Type of Snowplow
Delaware	Both rubber and carbide snowplows
Illinois	High carbon steel blades with no downforce limiters
Indiana	Joma blade, metal plow blades, partial rubber snowplow blades
North Carolina	Metal, plastic and motor grader blades (metal)
South Carolina	Metal blades
Utah	Joma plow blades

TABLE 3.15
Factors related to snowplowing that affected the quality of RPMs

STA	Factors Related to Snowplowing that Affected the Quality of RPMs
Delaware	When RPMs are not properly installed snowplows cause significant damage to the RPM's When properly installed there is usually no significant damage
New Jersey	Some locations, where snowplow activities are more aggressive, have experienced high incidence of RPM damage and dislodging
South Carolina	During snow removal, RPMs are removed due to the blade hitting them

TABLE 3.16
Factors related to snowplowing that affect the quality of the pavement

STA	Factors for Snowplowing Affected the Quality of Pavement
Delaware	If the RPM's are not properly installed, they will definitely be damaged by snowplows and in the process cause damage to the road
New Jersey	If the RPM's are not properly installed, they will definitely be damaged by snowplows and in the process cause damage to the road
North Carolina	Occasionally forceful removal of a RPM can result in a pothole or other damage

Survey respondents were asked about the types of snowplowing activities used by their STA. Tables 3.14, 3.15, and 3.16 show different types of snowplowing used by STAs, as well as the factors affecting the quality of RPMs and the pavement due to snowplowing activities.

3.7 Inspection and Maintenance of Raised Pavement Markers

The Federal Highway Administration released the *Roadway Delineation Practices Handbook* (Migletz et al., 1994) to assist STAs in making determinations about roadway delineation systems, including the appropriate system for a given situation, when a system has reached the end of its useful life, and how to maintain a quality delineation system. This handbook states that the expected service life of RPMs (which is identified by the RPM manufacturer) should be used by STAs to schedule the replacement of all RPMs on a highway. The handbook also recommends that STAs conduct regular inspections of RPMs and replace castings and lenses as needed (Fontaine & Gillespie, 2009; Migletz et al., 1994).

Bahar et al. (2004) stated that inspection and maintenance practices of RPMs vary among STAs. For example, the Ohio Department of Transportation and the Pennsylvania Department of Transportation replace the reflectors on RPMs on a 2-to-3 year cycle. In the State of Indiana, RPM lens are replaced based on the average daily traffic (ADT) of the roadway where the RPM is installed. The Colorado Department of Transportation and the Iowa Department of Transportation have removed all RPMs and plans for future installations have been abandoned due to their high maintenance costs. Liu et al. (2018) provided the maintenance cycles and criteria for RPMs among STAs (see Table 3.17).

In this study, the STAs were asked about their frequency of RPMs' inspection and their criteria for maintenance activities on RPMs. The survey responses indicate that the frequency of RPM's inspection varies between 1 to 4 year cycles (Table 3.18). Also, the primary criteria of maintenance is the identification of damaged and missing RPMs. Table 3.19 represents the summary of criteria of maintenance, frequency, and the cost associated, as reported by the STA.

3.8 Assessment of Damages to Raised Pavement Markers

Shahata et al. (2008) assessed the quality of pavement markers and identified different factors impacting the durability of pavement markings. These factors included markers' material, location of markers, type of traffic, quality of construction, speed of traffic, age of

TABLE 3.17
Maintenance practices for RPMs (Liu et al., 2018)

STA	Replacement Cycles and Criteria
Arkansas	RPMs are replaced typically, 2 years if not plowed off in the winter
California	RPMs are replaced when two successive retroreflective RPMs are missing
Colorado	Due to high maintenance costs, all RPMs have been removed and future installations have been stopped
Delaware	RPMs are replaced every 3 years
Florida	RPMs are replaced when eight or more successive RPMs are missing
Georgia	Typically, 2 years or less on interstate >15,000 ADT on four lanes
Indiana	RPM lens replacement cycles are defined as a function of the average daily traffic (ADT) on a road and the number of lanes present
Iowa	Due to high maintenance costs, all RPMs have been removed and future installations have been stopped
Massachusetts	RPMs are replaced if 30% or more of existing RPMs are missing in an inspected section
New Jersey	Through a visual inspection process, lenses are replaced only if the casting is intact
Ohio	RPM reflectors are replaced on fixed 2 to 3 year cycles
Pennsylvania	RPMs are visually inspected when work crews are performing other work in the area. RPMs are thereafter replaced as needed
Texas	RPMs are replaced when 50% or more of existing RPMs are missing in one mile of highway

TABLE 3.18
Frequency of RPMs inspection

STA	Frequency of Inspection of RPMs
Delaware	During installation and before maintenance
New Jersey	Every 3 years
Illinois	Every 4 years
Utah	Every 1 year
North Carolina	During installation and as needed afterwards (often post winter for high volume routes)
Michigan	During the project length
Indiana	Approximately every 2 years

TABLE 3.19
Maintenance activities for RPMs

RPMs	Criteria of Maintenance	How Often	Unit Cost (per RPM)	State
Replace RPMs lenses	Missing	3 years	$15	NJ
	When missing or damaged	3 years	$16	DE
	As needed through visual inspection	25% replacement every 4 years	$12	IL
	Regular maintenance	—	$6.5	NC
	During the project length	—	$6.5	MI
	Crooked or missing	As needed	$2.50	IN
Replace RPMs casting	Damaged or missing	3 years	$34	NJ
	As needed through visual inspection	25% replacement every 8 years	$45	IL
	If damaged	As needed	$2.25	IN
Replace the entire RPMs casting and lenses	Damaged or missing	3 years	$34	NJ
	When missing or damaged	—	—	LA
	When missing or damaged	3 years	$35	DE
	As needed through visual inspection or with resurfacing	15 year service life	$45	IL
	Three consecutive missing or damaged markers in any group of 7. When 20% of markers missing or damaged	As needed	$35	NC
	If damaged	As needed	$20.25	IN

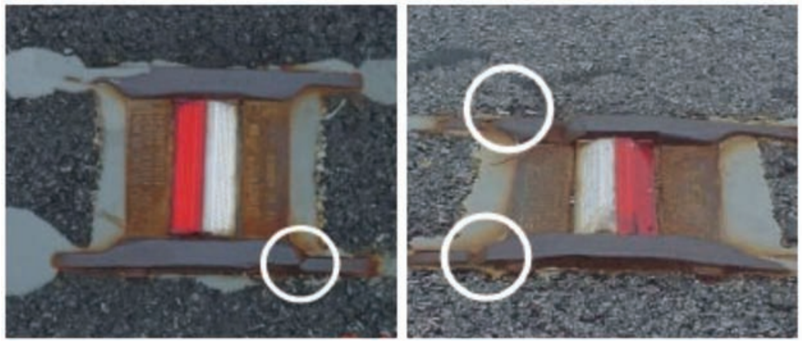


Figure 3.7 Failed RPMs (Ohio Department of Transportation, 2002).

markers, AADT, weather conditions, surface pavement condition, and snow removal operation. In 2005, the Missouri Department of Transportation conducted a survey of the use of RPMs among STAs in the U.S. and Canada. The study defined an RPM casting as having "failed" if it was broken, cracked fully or partially, or if the casting was gouged (see Figure 3.7). Out of 20 respondents participating in the 2005 survey, the most commonly cited factors for damage to RPMs were hits from snowplow blades, pavement failures, or improper installation (AASHTO, 2005, as cited in Fontaine & Diefenderfer, 2011).

In this study, STAs were asked to describe the factors that could damage RPMs, as well as to identify the intensity of each factor based on scale 1 to 5 (1 being the lowest and 5 being the highest). Table 3.20 lists the STA responses to this question.

3.9 Criteria for Measuring "Satisfaction" of Using Raised Pavement Markers

Finally, the survey respondents were requested to rate their satisfaction on the use of RPMs for the following attributes: (1) visibility improvement under wet and inclement weather conditions, (2) improving travel safety for road users, (3) cost of RPM installation, and (4) cost of RPM maintenance. Table 3.21 represents the satisfaction rating (1 being the lowest and 5 being the highest) for the aforementioned attributes.

TABLE 3.20
Factors that could damage RPMs

	Intensity of factors that could damage RPMs (1=lowest; 5 = highest)				
STA	**1**	**2**	**3**	**4**	**5**
NJ	Improper installation (not installed properly by contractor)	Snowplow (aggressive plowing)	Pavement Failure (pavement fails around RPM and requires repair prior to replacing RPM)	—	—
DE	—	—	—	—	Snowplows (snow plows damage or totally remove RPM's that are not properly installed)
NC	—	—	—	Traffic (standard wear during traffic)	Snowplowing
IL		Other types of pavement failure	Traffic directly driving on RPM	Joint failure	Snow removal
UT	—	—	—	Vertical and horizontal curves	—
IN	—	Stones and loose material on road	Snowplows; pavement distresses	—	—

TABLE 3.21
Satisfaction factors of using raised pavement markers among STAs

	Satisfaction Rating (1=lowest; 5=highest)				
STA	**1**	**2**	**3**	**4**	**5**
NJ	—	Cost of RPM installation Cost of RPM maintenance	—	—	Improved visibility under wet and inclement weather conditions Improving travel safety for road users
LA	—	—	Cost of RPM maintenance	Cost of RPM installation	Improved visibility under wet and inclement weather conditions Improving travel safety for road users
IL	—	—	Cost of RPM installation Cost of RPM maintenance	Improved visibility under wet and inclement weather conditions Improving ravel safety for road users	—
MI	—	—	Improved visibility under wet and inclement weather conditions	—	—
IN	—	—	Cost of RPM installation Cost of RPM maintenance	Improved visibility under wet and inclement weather conditions Improving ravel safety for road users	—

4. CONCLUSION

The purpose of this study was to provide a synthesis of current practices for the installation and maintenance of raised pavement markers among STAs in the U.S. A qualitative exploratory research approach using literature review, survey, and structured interviews was used to develop this synthesis on ten main themes of installation and maintenance of raised pavement markers. The survey question was sent to all fifty STAs within the U.S. with particular attention to STAs located in the Midwest region, and 19 completed responses were obtained. In addition, four STAs agreed to participate in phone interviews to provide additional insight on these themes. These themes are (1) STA practices related to application of raised pavement markers, (2) application of beveled and longitudinal joints/tooled longitudinal joints during installation of raised pavement markers, (3) installation and removal of raised pavement markers, (4) quality control parameters regarding preparation for the installation of raised pavement markers, (5) manuals/specifications regarding preparation of pavements for installation of raised pavement markers, (6) assessment of damages to the pavement/joints caused by raised pavement markers, (7) snowplowing activities on roadway assets, (8) inspection and maintenance of raised pavement markers, (9) assessment of damages to raised pavement markers, and (10) criteria for measuring "satisfaction" of using raised pavement markers.

Key conclusions that can be drawn as a result of the analysis of installation and maintenance of raised pavement markers practices are the following:

- Typically, STAs follow the *Manual on Uniform Traffic Control Devices* (MUTCD) regarding preparation of pavements for installation of raised pavement markers. The MUTCD focuses on providing guidelines on the spacing requirements of RPMs and replacement of RPMs based on retroreflective aspect of RPMs and does *not specifically address installation practices that could enhance the initial and long-term condition of the pavement-RPM assembly*.
- Some STAs including Delaware, New Jersey, Utah and Louisiana have additional state specific standards for the installation of raised pavement markers.
- There was *no common installation practice* of RPMs on concrete pavement across STAs. For instance, Delaware DOT has banned the installation of RPMS on PCC pavement joints. While Illinois DOT installs RPMs at least 2 inches away from the longitudinal joint in concrete pavement.
- STAs recognize that factors such as ambient temperature, pavement surface temperature, epoxy hardness, depth of groove, and pavement cleanliness are classified as quality control parameters for the installation of raised pavement markers.
- The majority of the STAs have routine inspection program for raised pavement markers; however, the frequency of inspection varies among agencies. For instance, Utah DOT inspects their raised pavement marker asset once a year; however, Illinois DOT conducts inspection every 4 years.
- Alaska, Idaho, Wyoming, Kentucky, and Kansas DOTs are not currently using raised pavement markers mainly because raised pavement markers are not resistant to snowplows and resulted in damages to the pavement, injury, and accident when they are dislodged.
- STAs believe that close proximity of RPMs to transverse and longitudinal joint is a major factor for the longitudinal failure in pavement caused by RPMs.

Based on the literature review and interviews with STAs, the research team suggests that INDOT further explore the following RPM installation practices on PCC pavements:

- *Criteria from Delaware DOT:* (1) If possible, do not install on a PCC pavement joint and (2) if RPSMs are needed, install them a minimum of 2 inches away from longitudinal joints.
- *Criterion from Illinois DOT:* The closest edge of the RPM is installed at least 2 inches away from the longitudinal joint.
- *Criterion from North Carolina DOT:* Install markers to avoid placement at or on a longitudinal joint or surface defect.

5. SUGGESTIONS FOR FURTHER INVESTIGATION

The key motivation for this study was to analyze the benefits of RPMs (as reported by STAs) and the challenges of maintaining highly functioning RPMs while ensuring the durability of pavements where RPMs are installed. Although the MUTCD and most of the literature that was reviewed discussed the advantages and disadvantages of using RPMs, little or no detail was found on the installation procedure of RPMs that could reduce damages to concrete pavements.

Selecting the most cost-effective installation and maintenance of RPMs is difficult due to the variety of factors such as the retroreflectivity, durability, cost of RPMs, type of road surface, quality control during installation of RPMs, snow removal practices, pavement maintenance activities, etc. Based on the analysis of survey responses and interviews with SHA personnel, the following suggestions are presented for further investigation by INDOT.

5.1 Conduct Follow-Up Interviews with Iowa Department of Transportation to Obtain to Identify Potential Use of Joint-Forming Device (Bobsled) for RPM Installation

Joints are an important part of the pavement and are designed to control cracking and prevent excessive stresses. The current practice to create joints is sawing the pavement surface to induce cracks. However, sawing time and the impact of saw cutting on the joint is influenced by weather conditions, concrete mix design, and set time. Sawing through the concrete compromises the quality of the concrete joint due to the lack of curing and induces weakness area around the joints.

Research at the Iowa Department of Transportation has suggested possible ways of using a joint-forming device (bobsled) with the slip-form paver to induce a plane of weakness in the longitudinal direction of the pavement surface (Steffes & Prasetyo, 2003). The joint-forming device (bobsled) consists of a galvanized fin-like joint tool to form longitudinal joints on the back of the paver in fresh concrete during concrete placement, as shown in Figure 5.1. The bobsled creates this plane of weakness by moving coarse aggregate out of the path, resulting a barely visible crack that involves no sawing or sealing (see Figure 5.2). A follow-up interview could be conducted to identify potential use of this joint-forming device (bobsled) for RPM installation. This type of joint forming will not compromise the concrete curing and it will not induce a weakness area around the joints due to the sawing blade cutting force.

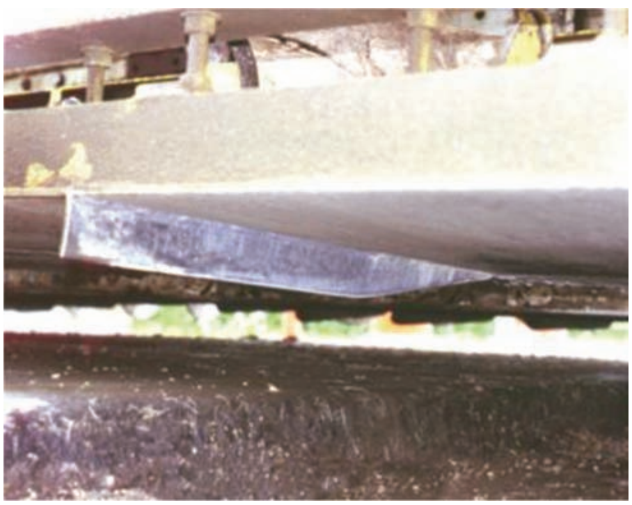


Figure 5.1 An early prototype of the joint-forming knife mounted to the bottom of the paver pan (Bergeron, 2004a).

Figure 5.2 View of the formed joint behind the paver. After hand finishing, the joint becomes much less visible (Bergeron, 2004b).

5.2 Conduct Follow-Up Interviews with Kentucky Transportation Cabinet to Determine Their Experience Using Inlaid Pavement Markers

Since summer 2019, the Kentucky Transportation Cabinet has been using Inlaid Pavement Markers (IPM) or Banana-Cut Markers on roadways. The Inlaid Pavement Marker (IPM) is made from polycarbonate plastic and features a replaceable C40 lens inside the casting bed as shown in Figure 5.3. The marker's casting is placed in a recessed cutout that allows the lens and casting to rest below the road surface for protection against snowplows (see Figure 5.5).

The Dynatech Company, manufacturer of the IPM, recommends installing IPMs in recessed grooves cut into the final course of pavement. The installation procedures is as follow: (1) cut installation grooves using diamond blades on saws that accurately control groove dimensions, (2) remove all dirt, grease, or unsound layers, and any other material from the marker area which would reduce the bond of the adhesive, (3) install IPMs in the recessed groove based on the specification and measurement (provided in Figures 5.2, 5.3, and 5.4), (4) use an approved snowplowable epoxy adhesive to the bottom area of the marker, and (5) remove all excess adhesive from in front of the reflective faces (Kentucky Transportation Cabinet, 2018).

Dynatech also recommends offsetting the recessed groove a minimum of 3 inches from any longitudinal pavement joint or crack and at least one inch from the painted stripe, ensuring that the finished line of markers is straight with minimal lateral deviation (Kentucky Transportation Cabinet, 2018).

5.3 Conduct a Pilot Experiment to Evaluate Experiences with Depressed Pavement Markers on Concrete Pavements

MassDOT has been using the slotted (depressed) pavement markers since 2008, switching from the snowplowable raised pavement markers (RPM) due to concerns of RPMs getting dislodged by snow plowing operations and becoming projectile. The slotted markers are typically installed in new pavements or recently resurfaced roadways. MassDOT *does not install slotted markers on concrete pavements*.

These markers are inserted in a groove, whose minimum depth is 0.75 inches with the top of the markers 1/8″+/- below the pavement surface (see construction detail in Figure 5.6). The grooves must be cleaned prior to application of the epoxy adhesive. The adhesive material is per manufacturer's recommendation. Surface preparation and installation procedure is per manufacturer's instructions. The grooves are approximately 2″ from the longitudinal joint. MassDOT performs visual assessments of damages on the asphalt pavements and the RPMs.

Mr. Bao Lang, Traffic Engineer of MassDOT District 2, stated that MassDOT's experiences with the slotted markers have been mixed. While these

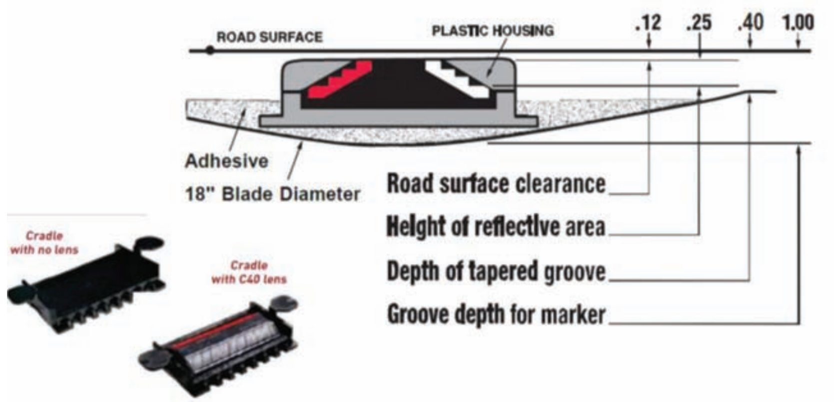


Figure 5.3 Installation of inlaid pavement marker (Kentucky Transportation Cabinet, 2018).

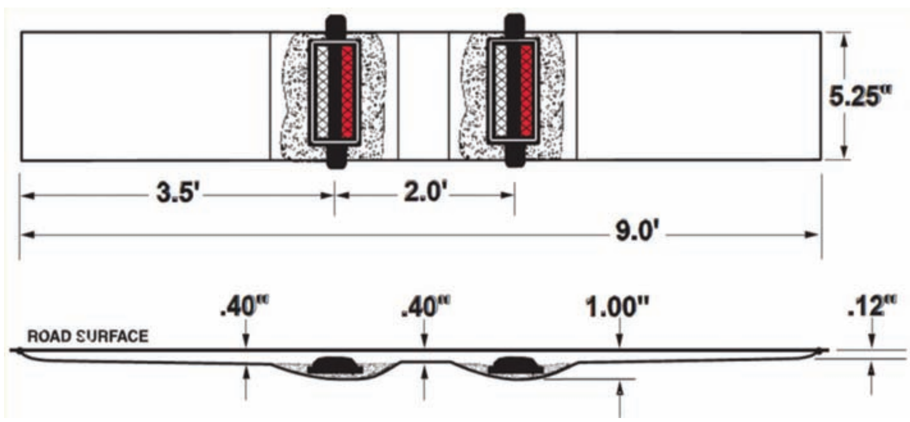


Figure 5.4 Spacing criteria of Banana Cut Marker for installation of RPMs (Kentucky Transportation Cabinet, 2018).

Figure 5.5 Installation of Banana Cut Marker (Dynatech, 2018).

RPMs provide great visual safety enhancements for drivers, the maintenance of the markers has been a concern. There are different factors that can cause the markers to fail; proper installation techniques, quality of epoxy adhesive, traffic classifications/volume, and weather. If the markers are properly installed below the pavement surface and the epoxy adhesive does not fail, then there is little to no damages to the markers from snow removal activities. However, snow and ice buildup in the grooves have been known to reduce the performance of the markers. Snow removal activities can damage the pavement where the slotted markers are already compromised due to the freeze/thaw cycle that pushes the markers above the pavement surface. MassDOT also observed cases where there was deterioration of the pavement around the markers.

The research team suggests that INDOT conduct a pilot study to evaluate the effectiveness of slotted

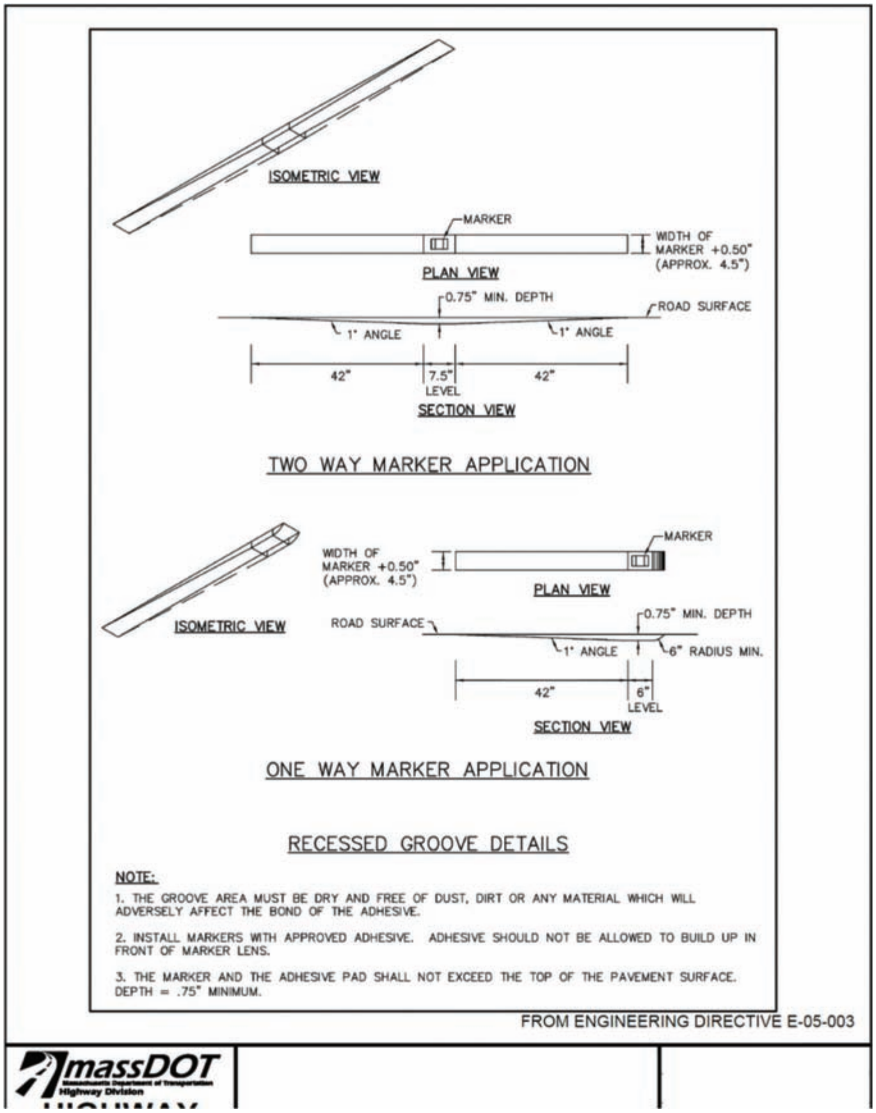


Figure 5.6 Construction detail—groove for slotted pavement marker on asphalt pavement (personal communication, B. Lang, MassDOT, May 29, 2020).

pavement markers *on concrete pavements*, and their impact of the installation and maintenance activities of these RPMs on the condition of concrete pavements as well as on the condition and performance of the RPMs.

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APPENDICES

Appendix A. Survey Deployed to State Transportation Agencies

Appendix B. List of Survey Participants

APPENDIX A. SURVEY DEPLOYED TO STATE TRANSPORTATION AGENCIES

SPR-4318 Installation And Maintenance of Raised Pavement Markers at State Transportation Agencies

The Indiana Department of Transportation/Joint Transportation Research Program (JTRP) and Purdue University are conducting a study (SPR 4318) on the installation and maintenance of raised pavement markers (RPMs) by state transportation agencies. We request you to complete this survey, which includes general questions about your experiences and your agency's criteria to reduce damages to the pavement where RPMs are installed. The questionnaire will take about 12-15 minutes to complete. The information collected will be kept confidential, and it will only be used for academic purposes. You may skip any question you do not wish to answer in the survey. If you have any questions about the survey, please contact Dulcy Abraham, Principal Investigator of this study (dulcy@purdue.edu)

○ Name ____

○ Agency ____

○ Address ____

○ Address 2 ____

○ State ____

○ Postal code ____

○ Country ____

1. Does your State Transportation Agency use Raised Pavement Markers (RPMs)?

○ Yes

○ No

If your answer is Yes, Move to question 2.

If your answer is No, Skip to question 32.

2. What are the types of raised pavement markers used by your agency, and their annual costs and service lives? If your agency uses pavement markers other than those listed below, please add them to the list and enter information about their costs and service life.

	Installation		Removal		Service
	Cost ($)	Unit (i.e., feet, mile)	Cost ($)	Unit (i.e., feet, mile)	Life (years)
1. Temporary RPMs					
2. Non-snowplowable RPMs (NSRPMs)					
3. Snowplowable RPMs (SRPMs)					
4. Recessed SRPMs					
5. Other, please list					

3. Does your State Transportation Agency use beveled longitudinal joints or tooled longitudinal joints during installation of RPMs?

◯ Yes

◯ No

If your answer is Yes, move to question 4.
If your answer is No, skip to question 5.

4. Please describe the installation procedure and describe the characteristics of the tooled longitudinal joints or beveled longitudinal joints used for the installation of the RPMs.

____
____
____

5. Are there any specific RPMs installation criteria used by your agency in order to reduce damages to *the longitudinal joints in concrete pavements*?

   ◯ Yes

   ◯ No

   If your answer is Yes, move to question 6.
   If your answer is No, skip to question 7.

6. Please describe installation criteria to reduce damages to the longitudinal joints in concrete pavements?

   ____
   ____
   ____

7. What are the quality control parameters monitored by your State Transportation Agency regarding preparation for the installation of raised pavement markers?

- ☐ Pavement surface temperature
- ☐ Ambient temperature
- ☐ Depth of groove
- ☐ Pavement surface moisture
- ☐ Pavement cleanliness
- ☐ Epoxy hardness
- ☐ Other, please list ____
- ☐ Other, please list ____

8. What Drawings, Manuals and/or Specifications does your State Transportation Agency employ to seek guidance regarding preparation of pavements for installation of RPMs?

- ☐ Manual on Uniform Traffic Control Devices (MUTCD)
- ☐ State DOT Standard Specifications
- ☐ Other, please list ____
- ☐ Other, please list ____
- ☐ Other, please list ____

9. How does your State Transportation Agency assess damages to the <u>pavement</u> caused by RPMs?

____
____
____
____
____

10. Briefly describe the reasons/factors for the longitudinal failure in pavement caused by RPMs? On a scale from 1 to 5 (1 being the lowest and 5 being the highest), what is the intensity of each reason/factor?

Brief description of reason /factor	Intensity 1	Intensity 2	Intensity 3	Intensity 4	Intensity 5
Reason/Factor	○	○	○	○	○
Reason/Factor	○	○	○	○	○
Reason/Factor	○	○	○	○	○
Reason/Factor	○	○	○	○	○
Reason/Factor	○	○	○	○	○

11. After one year of installation of RPMs, what percentages of pavement failures are caused by improper installation of RPMs?

____

____

____

____

____

12. Describe the type of snowplowing blades adopted by your agency?

____

____

____

____

____

13. Have snow removal activities affected the quality and performance of the pavement where RPMs have been installed? Please explain

____

____

____

____

____

14. Have snow removal activities affected the quality and performance of RPMs? Please explain.

____
____
____
____

15. Please provide brief information on when and where the RPMs are installed.

____
____
____
____

16. What are the novel RPMs used by your agency, and their annual costs and service lives?

	Annual unit		Expected or actual service
	Cost ($)	Unit (i.e., feet, mile)	Life (years)
LED RPMs			
Solar Markers			
other, please list			
Other, please list			

17. If these new technological RPMs are not used by your agency, does your agency intend to use any of them in the future?

○ Yes

○ No

If your answer is Yes, move to question 18.
If your answer is No, skip to question 19.

18. Please provide brief information on when and where they will be installed?

____
____
____
____

19. What were the benefits anticipated to your agency when RPMS were initially proposed for installation at your State Transportation Agency?

	Anticipated benefits when RPMs were proposed for installation
1	
2	
3	
4	
5	

20. What were the actual benefits to your agency after the RPMS were installed?

	Actual benefits after RPMs were installed
1	
2	
3	
4	
5	

21. What are your agency's criteria of using RPMs ?

	Criteria (please list below)
Temporary RPMs	
Non-slowplowable RPMs	
Snowplowable RPMs	
Other, please list	
Other, please list	

22. What are the locations where your agency places RPMs?

	Locations (please list below)
Temporary RPMs	
Non-slowplowable RPMs	
Snowplowable RPMs	
Other, please list	
Other, please list	

23. What are the spacings of your RPMs?

	Spacing (unit) (please list below)
Temporary RPMs	
Non-snowplowable RPMs	
Snowplowable RPMs	
Other, please list	
Other, please list	

24. Does your agency inspect the RPMs?

○ Yes

○ No

If your answer is Yes, move to question 25.
If your answer is No, skip to question 26.

25. How often?

____

26. How does your agency maintain the RPMs?

	Criteria of maintenance	How often	Unit cost
Replace RPMs lenses			
Replace RPMs casting			
Replace the entire RPMs casting and lenses			
Other, please list			

27. Typically, after one year of installation of RPMS, what percentages of RPMSs are <u>damaged</u>?

____

28. Typically, after one year of installation of RPMS, what is the approximate percentage <u>reduction of the retro-reflectivity</u> of the RPMs?

____

29. Briefly describe the reasons/factors for damage to RPMs. On a scale from 1 to 5 (1 being the lowest and 5 being the highest), what is the intensity of each reason/factor?

Brief description of reason /factor	Intensity 1	Intensity 2	Intensity 3	Intensity 4	Intensity 5
Reason/Factor	○	○	○	○	○
Reason/Factor	○	○	○	○	○
Reason/Factor	○	○	○	○	○
Reason/Factor	○	○	○	○	○
Reason/Factor	○	○	○	○	○

30. Please provide a satisfaction rating (1 being the lowest and 5 being the highest) for the following attributes. Please list other factors, if any.

Brief description of reason /factor	Satisfaction rating - 1	Satisfaction rating - 2	Satisfaction rating - 3	Satisfaction rating - 4	Satisfaction rating - 5
Visibility of used RPMs under wet and inclement weather condition	○	○	○	○	○
Improving of travel safety for road user	○	○	○	○	○
Cost of RPMs installation	○	○	○	○	○
Cost of RPMs maintenance	○	○	○	○	○
Please list other factor	○	○	○	○	○

If you fill the table above, please skip to question 33.

31. If your State Transportation Agency does not use RPMs, please list the reasons for not using them.

____

____

32. If your agency does not use RPMs, does your agency intend to use them in the future?

- ○ Yes
- ○ No

33. Are you willing to participate in a 15-minute phone call with the research team associated with this project?

◯ Yes

◯ No

34. Please provide your contact information:

Name	
Email address	
Phone number	

Thank you for participating in the survey. If you would like to receive a copy of the results of the survey, upon completion of the synthesis study, please provide your contact information:

	Please fill below
Name	
Email address	

Thank you on behalf of the SPR-4318 Research Team,

Dulcy M. Abraham
Professor, Lyles School of Civil Engineering, Purdue University

APPENDIX B. LIST OF SURVEY PARTICIPANTS

State Transportation Agencies (STA) who participated in the survey

STA	Uses RPMs	Uses beveled/ tooled joints?	Name	Email Address
Delaware	YES	YES	Nick Mogle	nick.mogle@delaware.gov
Illinois	YES	NO	Kyle Armstrong	kyle.armstrong@illinois.gov
New Jersey	YES	NO	Robert Blight	robert.blight@dot.nj.gov
Idaho	NO	NO RESPONSE	Craig Wielenga	craig.wielenga@itd.idaho.gov
New York	YES	NO	Patrick Galarza	patrick.galarza@dot.ny.gov
Alaska	NO	NO RESPONSE	—	—
Kentucky	NO	NO RESPONSE	Jarrod Stanley	jarrod.stanley@ky.gov
Kansas	NO	NO RESPONSE	—	—
North Carolina	YES	NO	Matt Springer	mspringer@ncdot.gov
Utah	YES	NO	Kendall Draney	kdraney@utah.gov
Michigan	YES	NO RESPONSE	Chuck Bergmann	Bergmannc@michigan.gov
Indiana	YES	YES	Joe Bruno	jbruno@indot.in.gov
Wyoming	NO	NO RESPONSE	Jeff Mellor	jeffery.mellor@wyo.gov
South Carolina	YES	NO RESPONSE	Laura Kline	klinelc@scdot.org
New Hampshire	NO ANSWER	NO RESPONSE	—	—

Missouri	NO	NO RESPONSE	—	—
Louisiana	YES	NO RESPONSE	Todd Humphreys	todd.humphreys@la.gov
Georgia	YES	NO RESPONSE	—	—
Montana	NO	NO	Susan Sillick	ssillick@mt.gov
Connecticut	NO	NO	Mark Makuch	mark.makuch@ct.gov

About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,600 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at http://docs.lib.purdue.edu/jtrp.

Further information about JTRP and its current research program is available at http://www.purdue.edu/jtrp.

About This Report

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