

NCHRP

SYNTHESIS 380

NATIONAL
COOPERATIVE
HIGHWAY
RESEARCH
PROGRAM

Applications of Illuminated, Active, In-Pavement Marker Systems



A Synthesis of Highway Practice

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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Cover: Lighted pavement markers delineating no entry into a left-turn lane, southbound Fannin Street at Dryden Street, Houston, Texas. Implementing agency: The Metropolitan Transit Authority of Harris County (METRO).

FOREWORD

*By Staff
Transportation
Research Board*

Highway administrators, engineers, and researchers often face problems for which information already exists, either in documented form or as undocumented experience and practice. This information may be fragmented, scattered, and unevaluated. As a consequence, full knowledge of what has been learned about a problem may not be brought to bear on its solution. Costly research findings may go unused, valuable experience may be overlooked, and due consideration may not be given to recommended practices for solving or alleviating the problem.

There is information on nearly every subject of concern to highway administrators and engineers. Much of it derives from research or from the work of practitioners faced with problems in their day-to-day work. To provide a systematic means for assembling and evaluating such useful information and to make it available to the entire highway community, the American Association of State Highway and Transportation Officials—through the mechanism of the National Cooperative Highway Research Program—authorized the Transportation Research Board to undertake a continuing study. This study, NCHRP Project 20-5, “Synthesis of Information Related to Highway Problems,” searches out and synthesizes useful knowledge from all available sources and prepares concise, documented reports on specific topics. Reports from this endeavor constitute an NCHRP report series, *Synthesis of Highway Practice*.

This synthesis series reports on current knowledge and practice, in a compact format, without the detailed directions usually found in handbooks or design manuals. Each report in the series provides a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems.

PREFACE

*By Jon M. Williams
Program Director
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Illuminated, active, in-pavement marker systems (IPMs) can provide a greater level of information to road users than conventional pavement marker systems. Traditionally, IPMs have been used for airport runways and taxiways, and pedestrian crosswalks. More recently, IPMs have been applied in numerous traffic guidance applications. This report documents (1) the state of IPM technology, (2) notable experiences with historical IPM applications, (3) detailed experiences with more recent IPM applications, and (4) IPM research needs. The report will be of particular interest to the traffic and safety engineering community.

Information for this report was obtained through a review of published literature, a formal survey of transportation practitioners, an informal survey of IPM vendors and users, and follow-up interviews.

The consultants, Anthony Voigt, Jodi Carson, Jonathan Tydlacka, and Lori Stevens Gray of the Texas Transportation Institute, collected and synthesized the information and wrote the report. The members of the topic panel are acknowledged on the preceding page. This synthesis is an immediately useful document that records the practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As progress in research and practice continues, new knowledge will be added to that now at hand.

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APPLICATIONS OF ILLUMINATED, ACTIVE, IN-PAVEMENT MARKER SYSTEMS

SUMMARY Various types of illuminated, active, in-pavement marker (IPM) systems are emerging that offer a range of designs and functional features intended to warn, guide, regulate, or provide illumination for road users. Although the number and breadth of IPM system applications has increased in recent years, little documentation has been created about the effectiveness of these systems in enhancing roadway safety, operations, or aesthetics. Further, little guidance is available to support proper planning, installation, operation, and maintenance of the systems.

Based on information obtained through a review of published literature, a formal survey of transportation practitioners, and an informal survey of IPM system vendors and users, this synthesis report documents the current state of knowledge related to IPM system use and effectiveness. More specifically, this report documents: (1) the state of IPM technology, including technology characteristics and standards and guidelines for use; (2) notable experiences from historical IPM system applications; and (3) detailed experiences from more recent IPM system applications, including system and facility characteristics, operation modes, installation and construction methods, maintenance requirements, system costs, and perceived and measured effectiveness. Assimilated in this synthesis report, this information will help to accelerate successful applications and focus future research of IPM systems.

The survey questionnaire was distributed to state traffic engineers from all 50 states, the District of Columbia, and Puerto Rico; traffic or public works engineers from the top 200 metropolitan statistical areas of the United States, and to the ITE Traffic Engineering Council Listserve, a total of 865 contacts. Sixty-two of the 865 completed the survey (a 7.2% response rate).

Key findings related to IPM system applications, technology characteristics, installation and construction methods, operation modes, maintenance requirements, costs, and perceived and measured effectiveness are summarized here.

Given the relative novelty of IPM system use on public roadways, little direction in the form of standards or guidelines is available for practitioners to support proper installation, operation, and maintenance of the systems. At the national level, the 2004 *Manual on Uniform Traffic Control Devices (MUTCD)* provides significant general guidance related to traffic control devices (e.g., signs, markings, and highway traffic signals), but contains few explicit standards, guidance, or options for IPM system use, and focuses exclusively on pedestrian crosswalk applications.

Historically, IPM system use has been limited to airport runway/taxiway or pedestrian crosswalk applications. More recently, IPM systems have been used to enhance: (1) warning through school and construction zones, at highway/rail crossings, at horizontal curves, and during adverse weather; (2) guidance through multiple-turn lanes, at merge locations, and through tunnels; (3) regulation at intersection stop bars and where left turns are prohibited; and (4) illumination at vehicle/truck inspection points and environmentally sensitive areas.

IPM systems generally comprise an illumination source surrounded by a protective housing and lens, a power source, and a system controller in a protective enclosure. None of the IPM systems observed provided automatic notification of system failure; instead, failures were detected through remote surveillance, on-site inspection, or public reports. Should this capability be added to IPM systems, the design and use of this feature could be guided by related Intelligent Transportation Systems standards.

Both incandescent/halogen lamps and light-emitting diodes (LED) have been commonly used as light sources in IPM systems. Laser and electroluminescence technology has also been considered for use; however, each has respective limitations preventing widespread applications. Flexibility in color and luminous intensity, low power consumption, and extended useful life, have caused LED to emerge as the favored light source for IPM systems.

For the IPM systems observed, several issues related to the luminous intensity of the light source were identified. Compromised luminous intensity was reported during daylight operation as compared with nighttime operation at several sites. In addition, luminous intensity was reportedly lower for IPM systems relying on solar technology, as opposed to hardwired or inductive systems. Although not confirmed through measurement, a decrease in luminous intensity was also reported over time. Last, an increased capability in color features (i.e., utilizing more than one color per marker) reduces the number of LEDs illuminated simultaneously and, hence, reduces the luminous intensity of the marker.

Housing materials commonly have been made of plastic, although newer markers are more frequently made of aluminum or stainless steel for improved durability. Lens materials commonly include polycarbonate or boron and glass. Some vendors include a passive retro-reflective lens (i.e., a prismatic surface that reflects external light sources) in addition to active illumination to provide fail-safe operation should the IPM system become disabled.

IPM systems can derive power to operate through hardwired electrical connections, inductive wireless connections, or through solar technology. To date, hardwired electrical connections and inductive wireless connections have outperformed (e.g., through higher luminous intensity and more consistent operation) individual IPM units relying on solar technology. Benefits to solar-powered IPM systems, however, include the ease and flexibility of installation, particularly for remote areas. Continued advancements in solar technology may make this a more viable IPM system power source in the future.

The IPM system controllers are typically housed in a protective cabinet or enclosure. For lightning protection, a ground box with a copper ground rod is typically located near the cabinet or enclosure. In electrical-storm-prone areas, lightning protection for IPM systems is especially important.

Each IPM system vendor provides more detailed installation instructions tailored to their specific product.

For placement of the electrical cable and/or conduit, a common method requires saw-cutting a 3/8 in. to 1/2 in. groove in the pavement for cable-only installations (a larger cut is required to accommodate a larger diameter conduit). The electrical conduit is placed in the groove and typically covered with epoxy. For inductive IPM systems, both the conduit and node assembly are placed in the groove and sealed with epoxy. It is important to provide enough depth to the saw cut to adequately recess and protect the electrical cable and/or conduit. Individually solar-powered IPM units do not require this installation step.

Several of the observed IPM systems noted power supply issues following installation. A few of these instances were attributable to a manufacturer defect. Power supply issues were

more commonly attributed, however, to a lack of familiarity with installation procedures by the contractor or poor quality control during installation (e.g., water penetration).

Markers can be recessed in the pavement through coring or milling methods or affixed directly to the pavement surface. Recessed markers are less prone to “pop-offs” but require additional effort during the installation process. In cold regions, where snowplowing is frequent during the winter months, use of recessed markers is necessary. Also, the performance of marker adhesives, particularly in unusually cold or hot temperatures, can have a significant effect on pop-off frequency. In most instances, manufacturers have been able to significantly reduce the occurrence of pop-offs through the use of alternate adhesive; however, this action generally only follows a period of poor IPM system performance.

As observed in this synthesis effort, markers can also be placed on other roadway features, most commonly including concrete barriers and sign posts. IPM systems that utilized barrier- or post-mounted markers experienced significantly fewer pop-offs.

Based on pedestrian crosswalk experience, a high frequency of system failures in a single jurisdiction was attributable to marker settlement and subsequent power supply issues in asphalt concrete pavements. This issue was purportedly avoidable if the IPM systems were installed in portland cement concrete pavement. Although the IPM systems observed for this synthesis included a range of pavement materials, no additional information was uncovered that described the comparative performance of IPM systems that were installed in either portland cement concrete or asphalt concrete pavements.

Additionally, no consistent standard for IPM system marker spacing was observed within similar applications. Between applications, marker spacing was generally observed to increase as traffic speeds increased.

Activation of IPM systems relies on either manual methods, where the system is activated directly by the road user (e.g., a push-button system), or passive methods, where the system is activated automatically through some type of sensor input. Passive activation can be provided through in-ground sensors, motion sensors, visual image video detection systems, in-pavement loop detectors, integration with traffic control devices, and road-weather information systems. Manual activation methods are typically lowest cost, but require action from the road user to be effective. Passive activation methods are more discrete, but may suffer a high frequency of false positives and misses, particularly when using microwave technology.

Additional IPM system activation methods observed included timer-based activation (in the case of a school zone) and ambient light-sensitive activation through the use of photo-electric cells to detect dusk (for activation) and dawn (for deactivation).

The nature of IPM system activation depends somewhat on the intended function of the system and the characteristics of the environment in which it is placed. Systems that are intended to guide road users are often operated continuously, particularly those in high-traffic environments. Conversely, IPM systems that are intended to warn, regulate, or provide illumination are more commonly operated intermittently, in response to a detected hazard or regulatory action, or to minimize environmental effects and energy consumption.

Depending on the manufacturer, IPM systems offer a range of features that have the potential to enhance roadway operations. Marker color changes can be used to indicate regulatory action required by the road user (e.g., markers show red illumination when vehicles are required to stop). Varying flash rates (including steady burn) can indicate the level of hazard. In addition, “chase” sequences can direct the road user to reduce or increase speeds, or provide directional guidance through an intersection turning movement.

Common IPM system marker colors include white, amber, red, green, and blue. Using LED illumination technology, IPM system markers can illuminate the same color in all directions, can alternate colors consistently (i.e., all markers show red illumination when vehicles are required to stop but return to green or white when vehicles are permitted to travel), or can illuminate two different colors by direction (e.g., to indicate wrong way travel). Use of multiple colors in the IPM system marker reduces the luminous intensity for any single illumination (i.e., a marker that contains 10 total LEDs would illuminate 5 LEDs of one color followed by 5 LEDs of another color).

In the IPM systems observed, use of white, amber, and red markers were noted, most commonly as single-color configurations, although some of the markers provided dual-color illumination to coincide with the red and amber traffic signal indications.

IPM systems can be operated in a steady-burn state or in a flashing mode, consistently or intermittently. The flashing mode may be triggered by a detected hazard (e.g., when upstream speed sensors detect a vehicle traveling too fast for a curve or when road-weather information systems detects fog conditions) and may, depending on the manufacturer, provide an adjustable increasing flash rate consistent with increasing danger (as long as the flash rate remains within an acceptable range). At all other times, the IPM system may show steady or no illumination.

More sophisticated IPM systems offer forward or reverse “chase” sequencing (i.e., adjacent markers are sequentially illuminated giving the effect of moving light along the path). This feature is intended to improve speed-related roadway operations by pacing traffic at consistent and appropriate speeds for conditions. Chase sequencing has been used to maintain or reduce vehicle speeds in fog-prone areas and to reduce vehicle speeds on exit ramps. Other potential applications include horizontal curves, tunnels, merge areas, and construction work zones.

The majority of IPM systems observed operated in steady-burn state once activated; flash and chase features were more common in systems intended to provide warning (in one case, chase sequences were used to provide guidance through multiple-turn lane maneuvers).

Specific to halogen light sources, halogen lamps reportedly experienced frequent water condensation and broken filaments. Applying more generally to all IPM system marker types, frequent light source failures were consistently reported over all applications. Failures were generally attributed to environmental factors (e.g., water, dirt, and debris buildup) or traffic impacts. For markers located in the tire path of vehicles and particularly heavy vehicles, light source failure was particularly problematic. This condition is inherent in the design of IPM systems for multiple-turn lanes; vehicles traveling through the intersection are required to drive over a portion of the multiple-turn lane delineation. Ongoing light source failures can become costly if not included under a manufacturer’s warranty. Annual maintenance costs for one IPM system were estimated to be \$15,000, comprised largely of LED failure replacement costs. One jurisdiction reported significant delays in delivery of replacement parts.

IPMs that protrude above the ground have also experienced damage by street cleaners and snowplows. System manufacturers have moved to aluminum or stainless steel housing materials typically recessed into the pavement to address this issue. Recessed markers that also help to minimize damage from street cleaners and snowplows require frequent cleaning to eliminate dirt and debris from the lens surface. This requirement was frequently noted for the IPM systems observed in this synthesis effort. In some cases, the IPM system required cleaning (e.g., power washing) as frequently as once per month. Barrier- or post-mounted IPM systems do not require this same level of maintenance.

It was also noted that activities such as street repair or resurfacing require the IPM system to be removed and reinstalled or lost. This is not unique to IPM system applications but

challenges the longevity of any type of roadway instrumentation. Again, barrier- or post-mounted IPM systems are less likely to be affected by roadway repair or resurfacing activities.

IPM system costs can range significantly, anywhere from \$5,000 up to \$100,000. Factors affecting cost include the length and layout of the application and the subsequent number of markers required, specific features of the IPM system (e.g., unidirectional or bidirectional displays and operational modes), the availability and nature of power at the site (e.g., solar), the condition of the pavement and any remedial actions required before IPM system installation, and traffic control requirements. In general, implementing agencies do not consider IPM systems to be a “low-cost” alternative to traditional traffic control devices and suggest that use be limited to critical locations. Opportunities for federal funding to support IPM system implementation may be constrained by proprietary issues (i.e., FHWA typically requires system bids from three or more vendors; patented products may not be approved for widespread implementation).

Few formal evaluations have been performed to determine the effectiveness of IPM systems in enhancing roadway safety, operations, or aesthetics. Pedestrian crosswalk applications have been most frequently studied; IPM systems have generally been shown to increase vehicle driver awareness, increase vehicle yielding, reduce vehicle approach speeds, reduce vehicle and pedestrian conflicts, and reduce pedestrian wait times.

Considering broader applications of IPM systems, additional studies have generally shown a reduction in vehicle speeds, improved lane-tracking, increased road user awareness, and high public acceptance. More recent studies have been conducted in response to FHWA’s requirements for experimental status. Early results reported from these studies show promise but are generally based on limited data and, as such, cannot be considered conclusive.

Implementing agencies provided significant anecdotal information through this synthesis effort attesting to the effectiveness of IPM systems in enhancing various aspects of roadway safety, operations, or aesthetics depending on the nature of the application. A high overall degree of IPM system satisfaction was reported despite any installation or maintenance challenges encountered. Furthermore, implementing agencies noted a high level of public support for and acceptance of IPM systems.

Based on the information gathered through this synthesis effort, illuminated, active, IPM systems show potential for: (1) enhancing warning through school and construction zones, at highway–rail crossings, at horizontal curves, and during adverse weather; (2) enhancing guidance through multiple-turn lanes, at merge locations, and through tunnels; (3) enhancing regulation at intersection stop bars and where left turns are prohibited; and (4) enhancing illumination at vehicle and truck inspection points and environmentally sensitive areas. Direct benefits of IPM systems in each of these applications cannot be quantified conclusively because few acceptable evaluations of recent IPM system applications have been performed, and because inadequate installation, operation, and maintenance guidance is likely confounding system performance. As such, recommendations to accelerate successful applications of IPM systems relate to focused research, and evaluation and development of related standards and guidelines.

INTRODUCTION

PROBLEM STATEMENT

Various types of illuminated, active, in-pavement marker (IPM) systems are emerging that offer a range of designs and functional features intended to warn, guide, regulate, or provide illumination for road users. Compared with traditional retroreflective pavement markers (RRPMs), IPM systems can provide a greater level of information to the road user through the use of various marker color changes to indicate regulatory action (e.g., markers show red illumination when vehicles are required to stop), flash rates indicative of the level of hazard, or “chase” sequences directing the road user to reduce or increase speeds. These systems also offer the potential for increased visibility over traditional RRPMs, particularly through horizontal curves. RRPM systems function by reflecting light from a vehicle’s headlights. Hence, the entire extent of some horizontal curves cannot be illuminated by RRPMs. On the other hand, IPM markers can be designed to provide illumination from a wider range of viewing angles; giving a more consistent, complete, and clear indication of road curvature. For this synthesis effort, IPM systems also include lighted devices that are not “in-pavement” but are mounted on concrete barriers or sign posts.

Historically, IPM system use was limited to airport runway/taxiway or pedestrian crosswalk applications. More recently, IPM systems have been used to: (1) enhance warning through school and construction zones, at highway–rail crossings, at horizontal curves, and during adverse weather; (2) provide guidance through multiple-turn lanes, at merge locations, and through tunnels; (3) enhance regulation at intersection stop bars and where left turns are prohibited; and (4) enhance illumination at vehicle and truck inspection points and environmentally sensitive areas.

Although the number and breadth of IPM system applications has increased in recent years, it appears that little is known about the true effectiveness of these systems in enhancing roadway safety, operations, or aesthetics. Furthermore, it is evident that little guidance is available to support proper installation, operation, and maintenance of the systems.

OBJECTIVES

This synthesis report documents the current state of knowledge related to IPM system use and effectiveness. More specifically, the report documents: (1) the state of IPM technology,

including technology characteristics and standards and guidelines for use; (2) notable experiences from historical IPM system applications; and (3) detailed experiences from more recent IPM system applications, including system and facility characteristics, operation modes, installation and construction methods, maintenance requirements, system costs, and perceived and measured effectiveness.

Assimilated in this synthesis report, this information will help to accelerate successful applications and focus future research of IPM systems.

METHODOLOGY

Information to support this synthesis effort came from three primary sources:

- A review of published literature,
- A formal survey of transportation practitioners, and
- An informal survey of IPM system vendors and users.

Supplemental information was also provided by various NCHRP Synthesis Topic Panel members and through informal interviews with traffic engineers, researchers, and other industry professionals.

Literature Review

As a first step in this synthesis effort, a review of published literature was conducted. A full range of domestic and international IPM system applications, including airport and pedestrian crosswalk applications, were considered. Primary sources of literature included:

- Transportation Research Information System (TRIS);
- International Transport Research Documentation (ITRD) database, which includes transportation research of 23 countries; and
- Conference compendiums such as TRB’s annual meeting and ITE district and international meetings.

Not surprisingly, much of the published literature related to airport and pedestrian crosswalk applications. IPM systems are more widely implemented and have a longer history of use in these environments. Limited information was also uncovered related to the use of IPM systems during adverse weather.

Transportation Practitioner Survey

To supplement information obtained through the literature review and to capture a broader array of practical information related to IPM system use and effectiveness, a survey questionnaire was developed and distributed to numerous state and local traffic engineers. Specifically, the questionnaire was distributed to state traffic engineers from all 50 states, the District of Columbia, and Puerto Rico; traffic or public works engineers from the top 200 metropolitan statistical areas of the United States; and to the ITE Traffic Engineering Council Listserv. A total of 865 contacts were invited to complete the survey.

The survey questionnaire (see Appendix A) was designed to capture information for a wide range of potential IPM system applications (e.g., construction zones, highway–rail crossings, horizontal curves, adverse weather, multiple-turn lanes, merge locations, variable-width lanes, tunnels, intersection stop bars, left-turn restrictions, restricted and emergency use lanes, vehicle and truck inspection points, environmentally sensitive areas, and other applications). The survey questionnaire intentionally omitted pedestrian crosswalk applications to avoid duplication of previously documented findings.

Following brief introductory material describing the project background and objectives, survey respondents were asked to describe IPM system

- Applications in their jurisdiction (and the characteristics of the facility that hosts the IPM system),
- Technology and respective characteristics,
- Installation and construction methods and challenges,
- Operation modes,
- Maintenance requirements,
- Costs, and
- Perceived and measured effectiveness.

In an attempt to achieve a higher response rate and to expedite return, this survey was distributed electronically. Each contact was sent an invitation e-mail with a brief description of the synthesis project and instructions on how to locate and begin the survey. The online survey was designed with a gateway feature that allowed each invitee to log in to the survey using his or her e-mail address and a unique identification number (which was provided in the invitation e-mail). In addition, a persistence feature was used to allow the respondent to close the survey and return to it at a later time using the login information provided. The gateway and persistence features also allowed a respondent to forward the survey to another individual for full or partial completion.

Despite attempts to encourage response, only 62 of the 865 invited contacts completed the survey (7.2% response rate).

Of the 62 respondents, 47 indicated that they did not know of any IPM system applications within their agency's jurisdiction. An additional 10 respondents provided information regarding IPM system applications at pedestrian crosswalks. Only six contacts provided information about non-crosswalk applications of IPM systems. Although the low number of affirmative survey responses was disappointing, it was not surprising because IPM systems are still a relatively novel treatment for public roadways. A list of survey respondents is included in Appendix B.

Vendor Survey

To supplement the information obtained from both the literature review and the transportation practitioner questionnaire, a comprehensive informal survey of IPM vendors was conducted (a list of IPM system vendor contacts is included in Appendix C). The purpose of the vendor survey was twofold: (1) to identify additional IPM system applications that were not uncovered through the literature review or transportation practitioner survey, and (2) to provide detailed product information including technical specifications, operational performance, maintenance requirements, and system costs. In some cases, the vendor contacts were able to provide additional public agency transportation practitioner points of contact for specific applications. In addition, vendor contacts provided information about potential IPM system applications that are not yet field-tested but are in the conceptual stage.

Information obtained through this vendor survey may reflect an inherent bias. To minimize this bias, information was solicited from a wide range of vendors and tempered with information obtained by public agency transportation practitioners to the extent possible.

REPORT ORGANIZATION

Following the introductory information in this chapter, chapter two describes the state of IPM technology, including technology characteristics, standards, and guidelines for use, and notable experiences from historical IPM system applications. Chapter three details experiences from more recent IPM system applications, including system and facility characteristics, operation modes, installation and construction methods, maintenance requirements, and system costs, as well as perceived and measured effectiveness. Applications are categorized by their intent: to warn, to guide, to regulate, or to provide illumination for road users. Chapter four concludes the report with a summary of key findings and provides applicable recommendations based on the information obtained in this synthesis effort.

STATE OF THE TECHNOLOGY

This chapter describes the state of illuminated, active, IPM technology, including technology characteristics, standards and guidelines for use, and notable experiences from historical IPM system applications.

TECHNOLOGY CHARACTERISTICS

Both the physical characteristics (i.e., housing, illumination source, etc.) and the operational characteristics (i.e., system activation, operation mode, etc.) of IPM systems are described here.

Physical Characteristics

IPM systems generally comprise an illumination source surrounded by a protective housing and lens, a power source, and a system controller in a protective enclosure. The design and features of the various components may vary significantly depending on the type of application.

Illumination Source

Both incandescent/halogen lamps and light-emitting diodes (LED) have been commonly used as light sources in IPM systems. Laser and electroluminescence technology has also been considered for use; however, each has respective limitations preventing widespread application.

The earliest IPM systems, used primarily for airport runway/taxiway path lighting, relied on halogen lamps as the light source. Halogen lamps often experienced water condensation and broken filaments (most likely caused by heavy vehicle traffic over the units), resulting in a need for frequent replacement (Boyce and Van Derlofske 2002).

To overcome the noted shortcoming with halogen lamps, manufacturers moved toward the use of LEDs in traffic control and in-roadway applications. The use of LED technology in traffic control devices (e.g., hazard identification beacons, traffic signals, pedestrian signals, and dynamic message signs) spans several decades. Noted benefits of LED technology include lower power consumption, a smaller footprint, and less maintenance as compared with incandescent lamps (Finkel 1996). The useful life of an LED is purported to be up to 10 times the expected life of an incandescent lamp when used

in a flash mode. Baker (2002) reported an estimated expected life of 10 years and 3 years, respectively, for LEDs and halogen lamps.

In IPM system applications, the number of individual LEDs displayed in one direction can typically vary from 1 to 12. The LEDs are typically low-voltage, high-intensity sources, but many vendors offer the capability to adjust intensities using onboard photoelectric sensors or through external controllers depending on the ambient light characteristics (e.g., automatically dimming at night). This flexibility in luminous intensity, combined with low power consumption and extended useful life, has resulted in LEDs emerging as the favored light source for IPM systems.

Considering alternative light sources, Hagiwara et al. (1996) evaluated the use of laser beams to improve lane delineation in fog. Although laser beams provided sharply visible lines in fog, visibility is significantly affected by the amount of ambient lighting and the luminous intensity and viewing angle of the laser. Use of this technology also requires a mechanism to prevent road users from viewing the laser beams directly.

A second alternative light source that has received some focus is electroluminescence technology. This technology is energy efficient, but requires high voltage for operation. Patangia and Radnayake (2004, 2007) compared the performance of barrier-mounted LEDs with electroluminescence technology in enhancing night visibility for road users in work zones. During an initial phase of the study, Patangia and Radnayake (2007) found that, with a solar powered assembly, the LEDs outperformed the electroluminescence technology with respect to field hardiness and luminous intensity. Using a modified electroluminescence technology with a direct-mount solar unit, the LEDs continued to outperform the electroluminescence technology. In a road user survey, nearly three-quarters of respondents preferred the LEDs because of their brightness.

Housing and Lens

To minimize damage and subsequent replacement costs, light sources are encased in a protective housing. The housing typically measures no more than 6 in. along its largest dimension. Housing materials have commonly been made of plastic,

although newer markers are more frequently made of aluminum or stainless steel for improved durability. One vendor advertised a plastic housing that “self-healed” when deformed by a snowplow, although no field evidence was provided. Lens materials commonly include polycarbonate or boron and glass. Some vendors include a passive retroreflective lens (i.e., a prismatic surface that reflects external light sources) in addition to active illumination to provide fail-safe operation should the IPM system lose power.

Power Source

IPM systems can derive power to operate through hardwired electrical connections, inductive wireless connections, or through solar technology. Further, IPM systems can be configured in series or in parallel. Baker (2002) identified the following three primary power/installation combinations used by IPM system vendors:

- Series AC operation, which relies on halogen lamps (6.6 amp, 7 volts, 50 watt, or other light source) that are wired in series, equalizing voltage to each lamp (approximately 7 volts). Halogen lamps are extremely bright; in most installations, the lamps are dimmed to about 20% in faded light or dark conditions.
- Parallel inductive-powered low-voltage DC operation, which relies on high-intensity LEDs that are inductively powered from a buried cable; the power transfer occurs wirelessly from a buried conductor to the marker. The system voltage depends on the length of the cable; a 24-marker installation would require 1 amp, 20 volts.
- Parallel low-voltage DC operation, which relies on high-intensity LED (1.2 watts) with a system voltage ranging from 6 to 32 volts DC. In parallel, the system voltage is increased to compensate for voltage drop.

Power sources for IPM systems must comply with National Electrical Code (NEC). Most vendors have assessed their IPM systems and components for conformance to the NEC. Baker (2002) suggested the need for public agency oversight, citing NEC Articles 240, 250, 411, 620, 720, and 725 as they apply to IPM systems.

To date, hardwired electrical connections and inductive wireless connections have outperformed IPM systems relying on solar technology. Benefits of solar-powered IPM systems include the ease and flexibility of installation, particularly for remote areas. Green (2002) reported a cost for surface-mount, solar-powered markers featuring LED illumination ranging from approximately \$30 to \$80 each (2001 dollars). Disadvantages relate to the compromised luminous intensity (e.g., magnitude and consistency) when compared with hardwired or inductive IPM systems. Continued advancements in solar technology may make this a more viable IPM system power source in the future.

System Controller and Enclosures

IPM system controllers are typically housed in a protective cabinet or enclosure. For stand-alone IPM systems, the cabinet may contain a power and lighting control unit with a keypad and liquid crystal display (LCD), circuit breakers, an AC/DC transformer or a photoelectric sensor (as necessary), and slack cable. Battery backup capability is recommended. The cabinet is usually pole-mounted, but may also be located on the ground. A metal conduit connects the ground box and cabinet. If the IPM system is used in conjunction with other warning, guidance, regulatory, or illumination systems, the IPM system components could be housed in a traffic signal cabinet or other combined equipment enclosure.

Examples do exist for state-level standards and guidance related to IPM system enclosure requirements. The California Department of Transportation (Caltrans) provides the following specifications for in-roadway warning light (IRWL) equipment enclosures for crosswalk applications:

IRWL equipment enclosures shall be Type G controller cabinets, and shall be in accordance with Section 86 2.11, “Service,” of the Standard Specifications. The IRWL equipment enclosure shall be designed for outdoor use and have a dead front panel and hasp for padlocking of the cover. Painting of IRWL equipment enclosures shall be in accordance with Section 86 2.16, “Painting,” of the Standard Specifications. IRWL equipment enclosures shall contain a power supply, controller unit compatible with IRWL operation, flasher unit, circuit breakers, terminal blocks, wiring, and electrical components for operation of the IRWL system.

Installation

Installation of IPM systems generally includes placement of the electrical cable and conduit to power the system and placement of the markers. For placement of the electrical wires, a common method requires saw-cutting a 3/8 in. to 1/2 in. groove in the pavement. A larger cut is required to accommodate a larger-diameter conduit. The resulting saw cut should be clear of debris and moisture. The electrical cable and/or conduit is placed in the saw cut and typically covered with epoxy. For inductive IPM systems, both the conduit and node assembly are placed in the saw cut and sealed with epoxy. It is important to provide enough depth to the saw cut to adequately recess and protect the electrical conduit. Individual solar-powered IPM units do not require burying of cable or conduit.

Various methods are used for placement of markers. Markers can be recessed in the pavement through coring or milling methods. Markers can also be affixed directly to the pavement surface using various adhesives. Recessed markers are less prone to pop-offs but require additional effort during the installation process. In cold regions, where snowplowing is seasonally required, use of recessed markers is necessary. Also, the performance of marker adhesives, particularly in unusually cold or hot temperatures, can have a significant effect on pop-off frequency. Each IPM system vendor provides

more detailed installation instructions that are tailored to its specific product.

Operational Characteristics

IPM systems provide significant flexibility in operation. Operational characteristics described here relate to system activation and modes of operation (e.g., steady burn versus Flashing and chase sequences).

System Activation

Activation of IPM systems relies on either manual methods, where the system is activated directly by the user, or passive methods, where the system is activated automatically through some type of sensor input.

Manual activation is most commonly achieved, particularly for pedestrian crosswalk applications, through a push-button system. An example of a manual push-button system is provided in Figure 1. Signage is placed in proximity to the push button to alert the pedestrian that action is required to activate the system. Although push-button systems are often favored by public agencies because of their low cost, it was anecdotally reported that pedestrians will only use a push-button system 60% of the time (M. Harrison, personal communication, July 2007). Additionally, the use of a push-button system makes pedestrians more aware of the system, possibly giving the pedestrian a false sense of security when crossing the roadway.



FIGURE 1 Push-button activation system for smart crosswalks (Courtesy: LightGuard Systems, Inc.).

Historically, a broader array of methods has been used to provide passive activation of IPM systems including:

- In-ground sensors,
- Motion sensors,
- Visual image video detection systems (VIVDS),
- In-pavement loop detectors,
- Integration with traffic control devices, and
- Road-weather information systems (RWIS).

A common type of in-ground sensor, also used for pedestrian crosswalk applications, includes pressure mats with piezoelectric sensors (see Figure 2). When the piezoelectric sensors are compressed by the presence of a pedestrian, the IPM system is activated. The pedestrian may or may not be aware that the system has been activated by the pressure mat.

An alternative to in-ground sensors, motion sensors, may also be used to detect pedestrians entering or in a crosswalk. Motion sensors use light, radar, ultrasonic sound waves, infrared waves, or microwaves to detect motion in a predefined area. A common motion sensor system uses rigid, upright posts or bollards and projected light across crosswalk entrances (see Figure 3). A set of two bollards is placed on each side of the entrance to a crosswalk. Each bollard contains either a light transmitter or sensor or both devices to detect movement between the posts. When a pedestrian steps between the bollards, the beam of light is broken, signaling activation of the IPM system. Multiple beams of light projected between the bollards can be used to help determine the direction of travel of the pedestrian.

VIVDS, capable of sensing a change in the background image of a particular view, provide a more sophisticated passive activation system. In pedestrian crossing applications, a sensor detects a change in pixel configuration when a pedestrian enters the viewfinder of a video detection unit. This subsequently alerts the IPM system that a pedestrian is waiting



FIGURE 2 Pressure mat activation system (Courtesy: SmartStud Systems).



FIGURE 3 Bollard motion sensor activation system (*Courtesy: LightGuard Systems, Inc.*).

to cross. These systems are more commonly used to detect vehicles on traffic signal approaches. To date, their use for IPM system activation has been limited.

Similarly, in-pavement loop detectors have been more commonly used in more traditional vehicle detection applications such as detecting vehicles on traffic signal approaches and detecting vehicles on main lanes or entry ramps. This technology can also be used to detect a vehicle's presence or speed as it approaches an IPM system. Speed-dependent IPM system applications include horizontal curves, tunnels, freeway exit or entry ramps, merge areas, or construction work zones.

IPM systems have the potential to enhance the regulatory ability of other traffic control devices including traffic signals, heavy-rail or light-rail warning signals, or school-zone flasher systems.

RWIS have been used to activate IPM systems in response to adverse weather conditions. The intention of RWIS/IPM systems is to detect and alert road users of weather conditions that can limit sight distance or pose a significant driving hazard. Such systems have been most commonly used to mitigate the effects of fog, ice, or snow.

Depending on the application, each activation type has distinct advantages and disadvantages. Manual activation methods typically cost the least, but require action from the road user to be effective. Passive activation methods are more discrete, neither alerting the road user to the system nor providing a false sense of security; however, they may suffer a high frequency of "false positives" and "misses."

Pedestrian crosswalk experience suggests that motion sensors using microwave technology suffer a higher rate of false positives, particularly during rainy conditions (Huang 2000; Boyce and Van Derlofske 2002). Boyce and Van Derlofske

(2002) attributed an increase in vehicle speed and vehicle-pedestrian conflicts over time to false activation of the microwave-based motion sensor activation system and recommended installation of a manual activation system. Conversely, Whitlock and Weinberger (1998) recommended a passive activation system over an existing manual push-button system. Bollard activation systems, using projected light, have shown greater success. Huang et al. (1999) reported a 100% activation rate when pedestrians were present.

Operation Modes

Depending on the manufacturer, IPM systems offer a range of features that have the potential to enhance roadway operations. Marker color changes can be used to indicate regulatory action required by the road user (i.e., markers show red illumination when vehicles are required to stop). Varying flash rates (including steady burn) can indicate the level of hazard, and "chase" sequences can direct the road user to reduce or increase speeds.

Common IPM system marker colors include white, amber, red, green, and blue. Using LED illumination technology, IPM system markers can illuminate the same color in all directions, can alternate colors (i.e., all markers show red illumination when vehicles are required to stop but return to green or white when vehicles are permitted to travel), or can illuminate two different colors by direction (i.e., to indicate wrong way travel with white in one direction and red in the other).

IPM systems can be operated in a steady-burn state or in a flashing mode, continuously or intermittently. The flashing mode may be triggered by a detected hazard (i.e., when upstream speed sensors detect a vehicle traveling too fast for a curve or when RWIS detects fog conditions) and may, depending on the manufacturer, provide an adjustable increasing flash rate consistent with increasing danger (as long as the flash rate remains within an acceptable range).

More sophisticated IPM systems offer forward or reverse "chase" sequencing (i.e., adjacent markers are sequentially illuminated giving the effect of moving light along the path). This feature is intended to improve speed-related roadway operations by pacing traffic at a consistent and appropriate speed for conditions. Chase sequencing has been used to maintain or reduce vehicle speeds in fog-prone areas and to reduce vehicle speeds on exit ramps. Other potential applications for chase sequencing include horizontal curves, tunnels, merge areas, or construction work zones.

When IPM systems are operated in a flash or chase mode, the frequency must operate below 5 flashes per second or more than 30 flashes per second. The flash rate should not be between 5 and 30 flashes per second owing to the possibility of inducing epileptic seizures in some individuals.

STANDARDS AND GUIDELINES FOR USE

Given the novelty of IPM system use on public roadways, little direction in the form of standards or guidelines is available to support proper installation, operation, and maintenance of the systems. At the federal level, the *Manual on Uniform Traffic Control Devices (MUTCD)* (2004) provides standards, guidance, options, and support for traffic control devices in the United States. State officials either wholly adopt the standards defined in the *MUTCD* or develop unique state-level standards. Some countries outside of the United States have developed their own IPM system standards and guidelines.

Federal Standards and Guidelines

Although the *MUTCD* provides significant general guidance related to traffic control devices (e.g., signs, markings, and highway traffic signals), this reference contains few explicit standards, guidance, or options for IPM system use. Federal standards and guidelines for the installation, operation, and maintenance of IPM systems were developed as recently as 2000, with a focus on pedestrian crosswalk applications. The *MUTCD* defines “in-roadway lights” as: “A special type of highway traffic signal installed in the roadway surface to warn road users that they are approaching a condition on or adjacent to the roadway that might not be readily apparent and might require the road users to slow down and/or come to a stop” (*MUTCD*, Section 4A-3, 2004).

Section 4L.01 Application of In-Roadway Lights of the *MUTCD* states that “in-roadway lights shall not exceed a height of 0.75 inches above the roadway surface” but provides more flexibility in flash rates, stating that “the flash rate for in-roadway lights may be different from the flash rate of standard beacons” (*MUTCD*, Section 4L.01, 2004).

Specific to pedestrian crosswalk applications, “Section 4L.02 In-Roadway Warning Lights at Crosswalks” of the *MUTCD* contains standards related to the installation and operation of IPM systems. In summary, IPM systems shall

- Be installed only at marked crosswalks with applicable warning signs (not at crosswalks controlled by YIELD signs, STOP signs, or traffic control signals);
- Be installed on both sides of the crosswalk, spanning its entire length;
- Initiate operation based on pedestrian actuation and cease operation at a predetermined time after the pedestrian actuation or, with passive detection, after the pedestrian clears the crosswalk;
- Display a flashing yellow signal indication, with a flash rate of not less than 50 and not more than 60 flash periods per minute (flash rates between 5 and 30 flashes per second might induce epileptic seizures and shall not be used);
- Be installed to meet minimum spacing requirements:
 - A minimum of two lights on the approach side of the crosswalk on one-lane, one-way roadways;

- A minimum of three lights on both sides of the crosswalk on two-lane roadways; and
- A minimum of one light per lane on both sides of the crosswalk on roads with more than two lanes; and
- Be installed in the area between the outside edge of the crosswalk line and 10 ft from the outside edge of the crosswalk, facing away from the crosswalk if unidirectional or away from and across the crosswalk if bidirectional (an optional, additional yellow light indication visible to pedestrians in the crosswalk is permitted to indicate to pedestrians that the in-roadway lights are indeed flashing as they cross the street).

Additional guidance provided in this section relates to pedestrian walking speeds and the subsequent period of IPM system operation. A normal walking speed of 4 ft per second or less should be used, depending on the nature of the pedestrian population (e.g., a high proportion of elderly or wheelchair-bound pedestrians suggests a lower walking speed and longer period of IPM system operation). Furthermore, depending on the length of the crosswalk and presence of a median, sufficient width for pedestrians to wait and median-mounted pedestrian actuators may be required. In addition, Section 4L.02 recommends installing the IPM system markers in the center of each travel lane out of the normal vehicle tire path.

For non-crosswalk applications of IPM systems, experimental approval may be sought and granted by the FHWA. One benefit of IPM system implementation under FHWA “experimental” status includes a reduced risk of liability for the requesting agency (i.e., in the event of deaths, injuries, or property damage, attributable to a nonstandard device or application). Additionally, improved evaluation can lead to changes in the *MUTCD* and widespread benefits to agencies and motorists.

Note that Section 4L of the *MUTCD* classifies IPM systems as a type of traffic signal rather than a pavement marker, delineator, illumination source, etc. This classification is likely attributable to the nature of the application considered; at pedestrian crosswalks, IPM systems function to alternately stop or permit traffic to proceed depending on pedestrian presence. Similarly, a highway traffic signal alternately stops or permits traffic to proceed depending on vehicle or pedestrian presence. Other types of IPM system applications, such as horizontal curve or adverse weather warning, multiple-turn lane or tunnel guidance, or vehicle and truck inspection point illumination may be more appropriately categorized as pavement marking, delineator, or illumination source, respectively. In Section 1A.13 of the *MUTCD*, which provides a broader definition of terms, IPM systems are explicitly defined as *not* being highway traffic signals. This breadth of IPM system application and subsequent function suggests a similar required breadth in related standards and guidelines. Table 1 summarizes *MUTCD* chapters or sections that currently provide some related direction or would require future modification to better address IPM system use.

TABLE 1
APPLICABLE *MUTCD* STANDARDS AND GUIDANCE

Applicable <i>MUTCD</i> Standards and Guidance	
Warning	
School zones	<ul style="list-style-type: none"> • 7B.11 School Speed Limit Assembly • 7C.03 Crosswalk Markings
Construction zones	<ul style="list-style-type: none"> • 6D.03 Worker Safety Considerations • 6F.73 Raised Pavement Markers
Highway-rail crossings	<ul style="list-style-type: none"> • 8B.06 Turn Restrictions During Preemption • 8B.21 Stop Lines
Horizontal curves	<ul style="list-style-type: none"> • 10C.23 Pavement Markings • 3D.02 Delineator Design • 3D.03 Delineator Application • 5E.03 Edge Line Markings
Adverse weather	
Guidance	
Multiple-turn lanes	<ul style="list-style-type: none"> • 3D.02 Delineator Design • 3D.03 Delineator Application
Merge locations	<ul style="list-style-type: none"> • 3D.02 Delineator Design • 3D.03 Delineator Application
Tunnels	<ul style="list-style-type: none"> • 3D.02 Delineator Design • 3D.03 Delineator Application • 5E.04 Delineators
Regulation	
Intersection stop bars	<ul style="list-style-type: none"> • 8B.21 Stop Lines
Left-turn restrictions	<ul style="list-style-type: none"> • 8B.06 Turn Restrictions During Preemption
Illumination	
Vehicle/truck inspection points	None
Environmentally sensitive areas	None

State-Level Standards and Guidelines

Preceding the standards developed for inclusion in the *MUTCD*, Caltrans first issued guidelines and standards for the installation of IPM systems in 1998, again with a focus on pedestrian crosswalk applications. The development of these standards and guidelines followed several years of IPM system testing and evaluation. Current standards and guidelines have been updated to reflect and reference changes in the *MUTCD*. Example language related to IPM system operation follows:

Flasher units for IRWLs shall be installed in IRWL equipment enclosures. Flasher units shall indicate when the IRWL is activated. The flash rate shall be between 50 and 60 flashes per minute. The flash rate and period for the IRWL shall conform with Chapter 4L of the California *MUTCD*. The flash rate shall conform to the requirements in Section 8.3.3 of the National Electrical Manufacturers Association Standards Publications No. TS 1 *Traffic Control System*. The minimum pedestrian crossing time shall be based on a walking speed of 4 feet per second.

International Standards and Guidelines

One of the more comprehensive guides for IPM system use, *Recommendation for Use of Active Marking*, was published by the Province of Noord-Holland in the Netherlands in 2005. This guide details: (1) appropriate applications of IPM systems; (2) the advantages and disadvantages of these systems; (3) various functional and technical requirements including light source and housing, light color, light intensity, aperture angles, and placement; and (4) a decision tree to de-

termine the appropriateness of IPM systems compared with conventional marking, delineation, and illumination systems. This guide also includes a detailed example application of these principles at a horizontal curve section.

Applications

The Dutch suggest that IPM systems are appropriate for use in any situation where road user lane-tracking ability could be enhanced, and are particularly beneficial at horizontal curves. The Dutch guidelines recognize that because of the inherent low-light yield capability, IPM systems are not recommended for determining the position of the road user in relation to other vehicles, recognizing foreign objects on the road surface, or recognizing vehicles or people.

Advantages and Disadvantages

Advantages of IPM systems, as reported by the Dutch, include increased traffic safety, increased road user comfort, reduced light pollution and carbon dioxide emissions, the potential for installation in remote areas (not connected to an electrical grid) through the use of solar technology, elimination of the need for transition segments (low-light output requires no adaptation time for the road user when changing from illuminated to nonilluminated segments, or vice versa), reduced residual materials at the end of the life cycle as compared with conventional lighting, and typically lower costs as compared with conventional lighting.

Disadvantages of IPM systems include the need to close the road completely during construction or maintenance if the IPM system is installed along the centerline (construction or maintenance of conventional lighting systems typically allow one lane to remain open), the loss of IPM system components when the road surface is repaired or removed, and potentially higher costs as compared with conventional lighting if hardwired IPM systems are installed on multiple lane roadways (*Recommendation . . . 2005*).

Functional and Technical Requirements

With respect to light sources and housings for IPM systems, the Dutch provide the following recommendations (*Recommendation . . . 2005*):

- Light sources should have a lifespan equaling at least that of conventional pavement marking equipment, and preferably that of road surfaces; “only LED technology currently meets this criteria.”
- The protective housing should be composed of high-quality synthetic material, which can be milled out at the end of its lifespan or with replacement of the asphalt; the supplier must demonstrate that the housing has a durability lasting at least 20 years.
- After installation, a malfunctioning light source should be replaced easily, without drilling or milling. The light source’s sensitivity for pollution from its surroundings must be minimal; the absence of sharp joints and edges prevents the gathering of dirt and dust and increases the self-cleaning effect of rain or tire traffic.
- Supply and mounting of light source(s), electronic parts, and housings as separate components ease replacement when a failure occurs, reduces waste, and provides the potential to reuse parts that have a longer lifespan than the road surface.

With respect to light color, the Dutch require the color of the IPM system marker to be the same as that of the existing (passive) marking.

The desired light intensity depends on where the IPM system is used and is influenced by the maximum road user perception distance (with an assumed preview of 15 s) and the presence and intensity of the surrounding lighting. The Dutch recommend the following light intensities based on surrounding lighting conditions:

- 500 millicandelas in complete darkness or with low diffused lighting;
- 1000 millicandelas when background lighting is present; and
- 2000 millicandelas when combined with or near conventional lighting.

The light yield from an IPM system can be relatively low. Enough light must be emitted to make the marker visible at a

great distance, but not so much light that the driver is unable to see other road users or obstacles in front of him or her. In situations where surrounding lighting is present, a higher light intensity must be used than in situations where it is almost completely dark.

Aperture angle, defined as the angle indicating the width of a light beam, is an important factor in IPM system applications along horizontal curves. As the radius tightens, the road user’s view through the curve becomes smaller, making it necessary to place more markers in a certain section of the road so that the path of the curve becomes recognizable. If the radius is small (less than 1,968 ft for one-lane roadways or greater than 3,281 ft for two-lane roadways), it is also necessary to direct the markers at the oncoming traffic (an alternative is to increase the aperture angle, but this compromises the light yield). The Dutch recommend using a 12-degree horizontal aperture angle and a 10-degree (minimum 8-degree, maximum 12-degree) vertical aperture angle for optimal visibility over the complete IPM system-equipped curve section.

When placing the IPM system markers in the pavement, the Dutch define two maximum height requirement conditions. The maximum height over the road surface is 0.20 in. for horizontal curves with mixed traffic (i.e., cars, mopeds, and motorcycles) and 0.39 in. for horizontal curves with car traffic only.

When positioning IPM systems on the pavement surface, markers are always installed along the outside edgeline of one-way roadways, regardless of the number of lanes. For two-way roadways, the markers are placed along the centerline of the roadway. The Dutch recommend placing the IPM system markers directly on (or in) the existing passive marking or immediately beside it to maintain the delineation of the roadway (*Recommendation . . . 2005*).

The marker spacing is the most important variable factor when implementing an IPM system. The desirable distance between markers is affected by the visibility of the locale, the radius of the roadway, and the maximum travel speed. On a straight road section the maximum speed limit is the only factor that determines the distance between the markers. The Dutch recommend various speed-based marker distances ranging from approximately 82 ft at 20 mph to approximately 325 ft at 75 mph.

To determine appropriate marker spacing along a horizontal curve, the Dutch provide the following relationship:

$$KL = \left[\frac{(R + 0.5 * B)}{N} \right] * \arccos \left[\frac{(R - 0.5 * B - S)}{(R + 0.5 * B)} \right]$$

where:

KL is the marker distance in radians,

R is the radius of the curve measured to the centerline of the lane curve in meters,

B is the width of the lane in meters,

S is the distance between the edgeline and the obstacles on the inside curve in meters, and
 N is the required minimum number of markers visible to the road user; a minimum N of 5 is recommended.

Bringing all of these principles together, the Dutch provide a detailed example application for a horizontal curve section. The reader is referred to the original citation for details (*Recommendation* . . . 2005).

Finally, the Dutch developed a multistep decision tree to support implementation decisions related to IPM systems. In summary, this multistep process

- Distinguishes between roads that are already lit and unlit,
- Investigates the potential to remove or omit conventional lighting if IPM systems are installed,
- Investigates the potential to reduce the energy consumption and environmental interference if IPM systems are installed,
- Determines the cost-effectiveness of the IPM system and determines acceptability, and
- Investigates the potential to “switch off” conventional lighting under favorable traffic and weather circumstances (i.e., as a cost-effective alternative to IPM system installation).

HISTORICAL APPLICATIONS

As mentioned previously, IPM systems were first used to provide path guidance for airport runways and taxiways and later emerged as an enhanced warning tool for pedestrian crosswalks. Although the technology characteristics and subsequent costs of IPM systems have changed significantly since these earlier applications, a review of experiences related to IPM system installation and maintenance may provide valuable precautionary information for new system installations. In addition, a review of observed IPM system effectiveness may support decision making for related applications. For instance, it might be inferred that intersection stop bars equipped with IPM systems may experience similar benefits related to reduced vehicle approach speeds and increased vehicle compliance as those observed for pedestrian crosswalks.

Airport Runways and Taxiways

Published information related to the use of IPM systems on airport runways and taxiways focused predominantly on the evolution of technology from tungsten bulbs, which were expensive to install and maintain, to LED light sources, which were found to be less expensive to install and operate. A few studies were uncovered that focused on the performance of IPM systems in airport applications.

As early as 1978, Douglas investigated the use of green lights installed in the runway surface on the extended taxiway

centerline marking for lighting both high-speed and low-speed exits. This method had not yet been adopted in the United States because of concern over the possibility of mistaking a low-speed exit for a high-speed exit. To address these concerns, the author recommended: (1) modifying the type L-829 signs located at exits from the runway to increase their conspicuousness, (2) improved shielding to taxiway edge lights, (3) use of asymmetric instead of symmetric lenses on straight stretches, (4) dimming of taxiway edge lights to reduce the “sea-of-blue” effect, and (5) use of high-efficiency retroreflective paint to mark the turn-offs to the exit taxiway to improve nighttime guidance. A system of pulsating blue lights at the entrance to the exit taxiway throat also showed promise (Douglas 1978).

More than 15 years later, Katz and Paprocki (1994) developed and tested the performance of a prototype enhanced visual taxiway identification system, consisting of a segment of green lights imbedded within the conventional runway centerline lighting system at the FAA William J. Hughes Technical Center. Results of the effort indicated that the system may be expected to provide enhanced and effective identification of taxiway exit locations at minimal cost.

At the same facility, Gallagher (2001) evaluated the use of LED light strips with a focus on pilot and lighting personnel perceptions. The LED light strips augmented painted surface markings, which were still deemed necessary for daytime and inclement weather conditions. Gallagher found that all but one participant rated the LED light strips as a valuable augmentation to the painted surface markings.

Most recently, Patterson (2004) reported specific operational problems attributable the use of runway guard lights installed at hold lines at the Chicago O’Hare International Airport. In this application, a series of alternate flashing, yellow, unidirectional, in-pavement lighting fixtures are equally spaced along a runway holding position. These markings are intended to be visible only to aircraft approaching the hold position from the taxiway. In some instances, however, pilots have reported that the lights are visible from the opposite side of the fixtures (i.e., to aircraft exiting the runway) resulting in false guidance information to the pilots. No information was provided regarding how this issue was resolved.

These limited reported experiences suggest important findings related to directional illumination, luminous intensity, and supplemental use of surface markings. Installation, maintenance, and cost information was not uncovered (except for the earliest types of IPM systems). The transferability of this latter information is likely more limited given differences in vehicles and vehicle operating characteristics between roadway and airport environments.

Pedestrian Crosswalks

Commonly referred to as “flashing crosswalks,” IPM systems for pedestrian crosswalk applications include the basic



FIGURE 4 “Smart crosswalk system” (Courtesy: LightGuard Systems, Inc.).

components of: (1) IPMs, (2) an AC or solar power source, and (3) a manual push-button or passive activation system (see Figure 4). Over time, and with expanded IPM system implementation, various installation, operation, and maintenance challenges have been identified.

As noted previously, some passive activation systems, particularly those relying on microwave detectors, have experienced higher rates of false positives and misses. A passive activation bollard system in San Jose, California, malfunctioned as a result of vandalism (Malek 2001). Of more concern, citizens in Santa Monica, California, are reporting a false sense of pedestrian security, which, when combined with a high rate of system malfunction, has purportedly led to multiple pedestrian–vehicles crashes and one resulting death (Ericksen 2007).

A greater variety of maintenance challenges have been identified. Specific to halogen light sources, halogen lamps

reportedly experienced frequent water condensation and broken filaments. Applying more generally to all IPM system marker types, recessed markers require frequent cleaning to eliminate dirt and debris from the lens surface. In-pavement markers that protrude above the ground have experienced damage by street cleaners and snowplows (in at least one application, the damage did not prevent the light from remaining operational) (Malek 2001). Manufacturers moved to aluminum or stainless steel housing materials to address this issue. Activities such as street repair or resurfacing require the IPM system to be removed and reinstalled or lost.

Challenges related to system settlement have also been reported; over time and under traffic load, the markers are pressed further into the pavement, eventually damaging the power supply conduit and causing system failure (Ericksen 2007). City officials in Santa Monica suggest that the use of portland concrete cement instead of asphalt concrete pavement would address this challenge (Ericksen 2007).

City officials in Santa Monica, California, also report significant delays in receiving system parts (e.g., replacement lights) when system failures do occur. These reported delays differ between independent suppliers. One supplier attributed delays to the discontinuance of the product, whereas another attributed delays to pending product improvements that would result in a brighter, and more robust, marker and a backlog of replacement orders resulting from a minor engineering design change (Ericksen 2007).

For pedestrian crosswalk applications, IPM system costs have ranged from \$5,000 to \$100,000 per application. Factors affecting cost include the length and layout of the application and the subsequent number of markers required; specific features of the IPM system (e.g., unidirectional or bidirectional displays and operational modes); the availability and nature (e.g., solar) of power at the site; the condition of the pavement and any remedial actions required before IPM system installation;

TABLE 2
BENEFITS OF IN-PAVEMENT WARNING LIGHTS AT CROSSWALKS

Measure	Author	Comments
Enhanced Driver Awareness	Huang et al. (1999)	Actuated flashing provides an advantage over continuous flashing More effective than overhead beacon, especially at night
	Malek (2001)	
Increased Vehicle Yielding	Boyce and Van Derlofske (2002)	Particularly beneficial during adverse weather
	Whitlock and Weinburger (1998)	
Reduced Vehicle Speeds	Huang et al. (1999)	17.8% to 16.2% reduction in maximum speed 27.2% to 25.2% reduction in average speed 16.3% to 14.0% reduction in 85th percentile speed
	Boyce and Van Derlofske (2002)	
Reduced Vehicle/Pedestrian Conflicts	Prevedouros (2000)	Reduced number of vehicles entering crosswalk while pedestrian waiting 50.5% reduction (26.7 s to 13.2 s)
	Huang et al. (1999)	
Lower Pedestrian Wait Times	Boyce and Van Derlofske (2002)	

and traffic control requirements. A broader range of costs is anticipated for the emerging IPM system applications intended to enhance guidance, regulation, and illumination.

Regarding the effectiveness of IPM systems in pedestrian crosswalk applications, the results are generally favorable although the quality of prior study designs has been criticized. Few studies have directly measured the effect of IPM systems on pedestrian crosswalk safety; the infrequency of crashes and the time duration required to achieve an adequate sample preclude direct measurement. Instead, prior studies have considered various surrogate safety measures including enhanced driver awareness, increased vehicle yielding, reduced vehicle speeds, or reduced vehicle–pedestrian conflicts (defined as a

vehicle and a pedestrian in a crosswalk at the same time). A single study was identified that considered the effect of IPM systems on pedestrian crosswalk operation (i.e., in reducing pedestrian wait times). Table 2 summarizes previous studies investigating the effectiveness of IPM systems at pedestrian crosswalks.

Despite individual study limitations, a positive trend in IPM system effectiveness in enhancing pedestrian crosswalk safety and operation can be observed. In-pavement marker systems have generally been shown to increase vehicle driver awareness, increase vehicle yielding, reduce vehicle approach speeds, reduce vehicle–pedestrian conflicts, and reduce pedestrian wait times in this type of application.

APPLICATIONS OF IN-PAVEMENT MARKER TECHNOLOGY

This chapter details experiences from recent IPM system applications, including documentation of system and facility characteristics, operation modes, installation and construction methods, maintenance requirements, system costs, and perceived and measured effectiveness. Applications are categorized by their function: to warn, guide, regulate, or provide illumination for road users. Table 3 lists novel IPM system applications, identified primarily through the transportation practitioner survey and the IPM system vendor survey.

WARNING

With the primary intent to warn road users, IPM systems have been implemented—as an isolated system or in combination with other warning devices—in school zones, in construction zones, at highway–rail crossings, along horizontal curves, and in areas that experience frequent adverse weather.

School Zones

As a natural outgrowth of pedestrian crosswalk applications, IPM systems have recently been implemented to provide supplemental warning in school zones.

Risner Elementary School, Edmond, Oklahoma

In 2000, the city of Edmond, Oklahoma, installed an IPM system at the Orvis Risner Elementary School to augment flashing school zone beacons that are activated during specific periods in the morning and afternoon. Yellow IPM system markers are placed along the double yellow centerline through the school zone (see Figure 5). The first installation had the markers spaced at a distance of 50 ft; subsequent installations have reduced the marker spacing to 25 ft.

The IPM system is activated 30 min before, and deactivated 10 min after, classes begin in the morning. In the afternoon, the system is activated 10 min before, and deactivated 30 min after classes end. The system operates in constant flash mode when activated.

Because the times of operation are only during daylight hours, the city had engaged the system vendor to enhance the luminous intensity of the markers in daylight conditions.

Some issues related to water penetration and subsequent electrical failures were reported with this system. Also, a recent ice storm required contractors to “blade” the streets, resulting in the accidental removal of the IPM system markers.

Costs for the original system, installed before the 2000–2001 school year, totaled \$38,000. The city of Edmond budgets \$55,000 each year for school zone improvements, which now include IPM systems, as well as signalized countdown pedestrian crossings and real-time, radar-based driver feedback speed signs (T. Minnick, personal communication, Aug. 8, 2007).

To measure the effectiveness of the IPM system in enhancing school zone safety, vehicle speed data were collected before the system was installed and seven months after the activation of the system. The incidence of speeding in the school zone was approximately 30% before the installation of the IPM system and dropped to 19% after the installation. Additionally, a survey was conducted to determine how parents, police, teachers, and bus and daycare van drivers reacted to the IPM system. The survey showed that 95% of the respondents had noticed the IPM system, 93% believed the IPM system increases awareness of the school zone, and 89% believed the system improves safety in the school zone (*Speeding . . .* 2002).

Construction Zones

Various Locations—Iowa, Kansas, Missouri, and Nebraska

In 1999, a collaborative study of smart work-zone technology was performed by the State Departments of Transportation in Iowa, Kansas, Missouri, and Nebraska (the Midwest Smart Work Zone Deployment Initiative) (Meyer 2000b). One of the technologies tested during the deployment initiative was an IPM system.

During the deployment, the westbound lanes of I-70 in Kansas were closed and two-way traffic was redirected to the two eastbound lanes, approximately 10 miles east of Salinas, Kansas. An IPM system was used to delineate the general traffic lanes and the crossover traffic lanes from the westbound side of I-70. The IPM system markers were installed using a “temporary” asphalt adhesive at a distance of 50 ft apart for approximately 1,200 ft (M. Harrison, personal

TABLE 3
SUMMARY OF NOVEL TECHNOLOGY APPLICATIONS

Application		Source
Warning		
School zones	<ul style="list-style-type: none"> Orvis Risner Elementary School; Edmond, Oklahoma 	Vendor survey
Construction zones	<ul style="list-style-type: none"> Various Locations; Kansas, Nebraska, Iowa, and Missouri 	Vendor survey
Highway-rail crossings	<ul style="list-style-type: none"> Paramount Boulevard at Rosecrans Avenue; Paramount, California 	Vendor survey
Horizontal curves	<ul style="list-style-type: none"> Interstate 95 at State Road 84; Fort Lauderdale, Florida I-126 at Greystone Boulevard; Columbia, South Carolina FM 127; Mount Pleasant, Texas US 59 at Loop 151 Flyover; Texarkana, Texas N200 between Overveen and Bloemendaal; Province of Noord-Holland, the Netherlands A4226 (Five Mile Lane); Vale of Glamorgan, Wales, United Kingdom 	Vendor survey Transportation practitioner survey Vendor survey Vendor survey Vendor survey Vendor survey
Adverse weather	<ul style="list-style-type: none"> I-526, Cooper River Bridge; Charleston, South Carolina Various Locations; Virginia 	Vendor survey Vendor survey
Guidance		
Multiple-turn lanes	<ul style="list-style-type: none"> SH 99 at Arch Road, Single-Point Urban Interchange; Stockton, California Wabash Avenue at Veterans Parkway; Springfield, Illinois. 	Transportation practitioner survey Vendor survey
Merge locations	<ul style="list-style-type: none"> Route 46; Totoda Burrow, Wayne Township, New Jersey 	Vendor survey
Tunnels	<ul style="list-style-type: none"> McClure Tunnel; Santa Monica, California Wilson Tunnel, Route 63 (Likelike Highway); Honolulu, Hawaii Tunnel #1, SR 20 between Newhalem and Diablo; Washington 	Vendor survey Transportation practitioner survey Internal leads
Regulation		
Intersection stop Bars	<ul style="list-style-type: none"> Disneyland Drive near Disneyland Resort; Anaheim, California 2nd Street at Adams Street; Coquille, Oregon West Alabama Street at the Galleria; Houston, Texas Various Locations along METRORail Line; Houston, Texas Various Locations along METRORail Line; Houston, Texas 	Vendor survey Vendor survey Vendor survey Internal leads Internal leads
Left-turn restrictions		
Illumination		
Vehicle/truck inspection points	<ul style="list-style-type: none"> Vandenberg Air Force Base; Santa Barbara County, California 	Vendor survey
Environmentally sensitive areas	<ul style="list-style-type: none"> SR A1A, Boca Raton, Florida N513 Highway; Castricum, Province of Noord-Holland, the Netherlands 	Vendor survey Vendor survey

communication, July 2007). Amber lights were used to delineate the left edge, placed just beyond the edgeline, and white lights were used to delineate the right edge, also placed just beyond the edgeline. The lights operated in a steady-burn mode (Meyer 2000a, b).



FIGURE 5 School zone IPM system application in Edmond, Oklahoma (Courtesy: SmartStud Systems).

In addition to the IPM system, a safety warning system (SWS) was deployed before activation of the IPM system. The SWS warned drivers of the work zone through a recorded message transmitted from a radar signal to select radar detectors and other in-vehicle receivers.

The evaluation was intended to determine if the use of the IPM systems, in combination with SWS, reduced speeds and improved lane-keeping in the work zone. Vehicle speeds through the work zone were collected: (1) before the implementation of either system, (2) after the activation of the SWS, and (3) after the activation of the IPM system (in simultaneous operation with the SWS).

Following activation of the IPM system, a statistically significant decrease in the mean and 85th percentile speeds was observed. A nighttime speed reduction of more than 6 mph was recorded for both passenger cars and trucks. Additionally, a 7% decrease was noted for drivers exceeding the posted speed limit (29% to 22%). Researchers noted that the devices that were the most effective based on the

quantitative data collected were the speed display and the hardwired (as compared with solar) IPM system (Meyer 2000a).

Lane-keeping is also important in a construction zone because it helps prevent lane crossovers and subsequent head-on collisions. The lane-keeping benefit of the IPM system was measured using pneumatic tubes placed partially in the roadway. The tubes were configured in such a way to track whether a vehicle encroached on the centerline or right line by three feet, two feet, or one foot. If a vehicle did not activate any of these tubes, it was assumed that the vehicle was traveling in the middle of the designated lane. The percentage of vehicles within one foot of the inside edge decreased from 8.9% to 5.2%, indicating that vehicles were traveling closer to the middle of the lane while in the construction zone (Meyer 2000a). This reduction proved to be statistically significant.

One challenge to IPM system use in construction zones is the ability to supply and route adequate power cables. The use of solar-powered IPM systems was investigated in this same study. Unlike the hardwired systems, the solar-powered IPM systems did not produce statistically significant results because the lighting was reportedly too dim (E. Meyer, personal communication, July 26, 2007).

Highway–Rail Crossings

Paramount Boulevard at Rosecrans Avenue, Paramount, California

The highway–rail crossing at the intersection of Paramount Boulevard and Rosecrans Avenue in Paramount, California, is atypical because the railroad crosses diagonally across the intersection and not just across one approach. The intersection was too wide for regular railroad crossing gates and the typical railroad crossing lights would have visually blocked the existing traffic signal faces. Sight distance issues were caused by a building on one corner. An IPM system was identified as a suitable alternative warning device at this location (see Figures 6 and 7).

Eighty-five red LED IPM system markers were used in the application. More markers were required here than at an intersection with a 90 degree railroad crossing because the markers must be seen from all four approaches.

The rail line is a spur trap that services a refinery, with trains crossing once or twice per day (i.e., a daily delivery in and out). The trains do not travel at high speeds, but rather at approximately 5 mph. Traffic volumes at the intersection are high; approximately 30,000 vehicles per day eastbound and westbound and 20,000 vehicles per day northbound and southbound. Additionally, there are approximately 400 high school and middle school students who walk through this intersection each day.



FIGURE 6 Paramount Boulevard at Rosecrans Avenue, Paramount, California.

When the train approaches, it must receive a green indication on the tracks before proceeding through the intersection. When the train has a green indication, all vehicle traffic approaches receive a red indication and the IPM markers begin flashing with a red illumination. Typically, all rail activity occurs during daylight hours; the illuminated markers appear bright enough for all approaches.

Few operational issues were reported with the system based on four years of operation. Only one instance of an electrical short circuit was reported; 66 of the markers temporarily lost power. Occasional power washing by city street crews is required for the system (B. Pagett, personal communication, July 23, 2007).

For this application, the IPM system was originally approved by the California Public Utilities Commission and FHWA as a demonstration project. The system cost between \$55,000 and \$60,000.



FIGURE 7 At-grade highway–rail crossing IPM system application, Paramount, California (Courtesy: LightGuard Systems, Inc.).

No formal evaluation of IPM system effectiveness has been performed. Anecdotally, the Paramount city engineer noted that no crashes have occurred at the intersection since the installation (predeployment crash data were not available) and that the school crossing guards have reacted positively to the system.

Horizontal Curves

In-pavement marker systems offer the potential for increased visibility over traditional RRPMS through horizontal curves. RRPMS function by reflecting light from a vehicle's headlights. Hence, the entire extent of some horizontal curves cannot be illuminated by RRPMS. On the other hand, IPM markers can be designed to provide illumination from a wider range of viewing angles; giving a more consistent, complete, and clear indication of road curvature. A number of horizontal curve IPM system applications were identified.

Interstate 95 at State Road 84, Fort Lauderdale, Florida

In November 2004, the Florida Department of Transportation (FDOT) installed an IPM system on the exit ramp from southbound I-95 to westbound State Road (SR) 84. The intersection has been the site of several crashes attributable to high vehicle exit speeds from I-95 and the sharp, 90 degree turn required for traffic to enter onto SR 84 (see Figures 8 and 9).

The IPM system is activated when a vehicle is detected traveling at 45 mph or greater on the I-95 exit ramp. The IPM system operates in a reverse chase sequence (i.e., toward the vehicle), giving a driver the sense that he is traveling at a faster

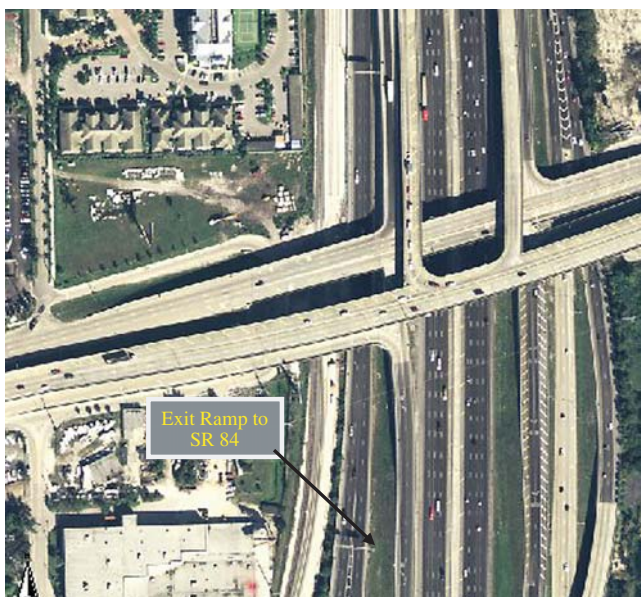


FIGURE 8 Exit ramp from I-95 to SR 84, Fort Lauderdale, Florida.



FIGURE 9 Horizontal curve IPM system application, Fort Lauderdale, Florida (Courtesy: Florida Department of Transportation).

speed. As the driver slows, the chase sequence slows. The IPM system markers extend through the entrance to SR 84 to provide added warning of the curvature at this location (G. Soles, personal communication, July 26, 2007).

The IPM system at this location has experienced a number of setbacks to effective operation. Lightning strikes, maintenance crew familiarity with the IPM system, power supply issues, and pavement resurfacing activity have prevented continuous successful operation for periods longer than six months.

The IPM system was struck by lightning twice within a two-month period, motivating the vendor to install additional grounding for the system. Next, a maintenance crew, unfamiliar with the power supply system, reconnected the power supply incorrectly to a night timer causing the lights to function only at night. The lights were restored to 24-h function, but another storm caused an electrical malfunction in the system. The system was repaired and upgraded with addressable chips by the vendor; FDOT reported significant improvement in system performance after the installation of addressable chips.

The IPM system was also compromised during recent road resurfacing activities. The contractor was provided a map and verbal direction where the IPM system loops, lights, and wiring were installed, but the system was still accidentally damaged by the contractor's milling machine. In this instance, the system was very hard to repair because the milling damage to the cabling was under the surface and difficult to detect. After the system was restored following resurfacing, another lighting strike hit. The system was restored but, in July 2007, was again reported as being without power.

Unfortunately, no automatic feedback system is available to provide information regarding system failure or real-time status. Malfunctions are often reported to FDOT by the Florida Highway Patrol and Road Ranger motorist assistance program drivers.

Despite the technical issues that the system has incurred, FDOT believes the system is very effective and important for enhancing safety on the exit ramp. According to FDOT, the IPM system markers are very sturdy and are capable of being driven over by semi-trucks with no apparent damage. FDOT has also received positive feedback from the public regarding the system. Once IPM system operation has stabilized (i.e., successfully operating continuously for at least six months), FDOT will formally evaluate its effectiveness. Data reflecting conditions before IPM system installation have been previously collected for comparison.

I-126 at Greystone Boulevard, Columbia, South Carolina

At the exit ramp to Greystone Boulevard from I-126 near Columbia, South Carolina, road users were observed traversing a horizontal curve with excess speed, leading to frequent run-off-the-road crashes into traffic control devices intended to warn the driver (e.g., chevron signing along the curve). An IPM system was implemented at this location to increase the visibility of the curve (see Figure 10).

For a distance of 200 ft, IPM system markers were attached directly to the surface of the roadway using butyl pads. The markers consist of two LEDs for illumination, but also provide passive guidance through a reflectorized lens (similar to an RRPM). The IPM system is solar-powered; each marker is activated internally by a photocell and operates during low-light times. Once activated, the units flash at a rate of approximately 60 to 80 times per minute.



FIGURE 10 I-126 at Greystone Boulevard, Columbia, South Carolina.



FIGURE 11 Horizontal curve IPM system application (daylight), Mount Pleasant, Texas (Courtesy: TxDOT Atlanta District).

Each marker cost approximately \$55, with a total of 13 units installed (\$715) and installation was performed by South Carolina DOT (SCDOT) personnel. The IPM system is likely too new (installed one month ago at the time of this report) to report any operational or maintenance related issues or to provide substantive perceptions of effectiveness. Personnel from SCDOT did indicate that 2 of the 13 chevron signs on the curve have been hit by vehicles since the recent installation of the IPM system. No information was provided regarding the frequency of crashes prior to IPM system installation for comparison (A. Leaphart, personal communication, July 2007).

Farm-to-Market 127, Mount Pleasant, Texas

The Texas DOT (TxDOT) had a problematic horizontal curve on Farm-to-Market (FM) 127 outside of Mount Pleasant, Texas. The curve is in a rural area with no safety lighting; road users were frequently leaving the road and running into traffic control devices intended to warn the driver (e.g., chevron signing along the curve). To enhance curve delineation, IPM system markers were mounted on the chevron sign posts (a hole was drilled in the chevron's pipe and the marker was bolted to the post using antitheft bolts) (see Figures 11 and 12).



FIGURE 12 Horizontal curve IPM system application (night), Mount Pleasant, Texas (Courtesy: TxDOT Atlanta District).

The original IPM system that was installed at this location was solar-powered. The observed luminous intensity was often less than desired owing to large trees in the area that were preventing the solar panels from receiving enough light to adequately charge the system.

To remedy these issues, in 2006, the IPM system was modified and hardwired to an AC power source. Luminous intensity has appeared to improve following this modification; TxDOT personnel noted that during night operation the markers are “super bright,” but can still be seen reasonably well during the day, because of the shadows cast from surrounding trees.

The IPM system operates 24 hours per day and is activated when an upstream radar detector, located on an advance warning sign, detects a vehicle traveling faster than the posted advisory speed of 35 mph. When the system is activated, the IPM system markers on the chevron sign posts flash with the advisory speed beacons.

The installation and equipment cost approximately \$15,000 for this application. Personnel from TxDOT remarked that that the system is not a low-cost solution, but is applicable to the most critical problematic locations (C. Ibarra, personal communication, Aug. 3, 2007).

Other than the issues identified previously related to power source (hardwired versus solar), no issues related to installation, operation, or maintenance were reported for this system. A few incidents of vandalism (e.g., markers stolen) have occurred.

Overall, TxDOT personnel assess the IPM system positively, but note that familiar road users do not reduce speeds for the curve because the locals know how to traverse the curve. Operational impacts for unfamiliar motorists may be most important. No formal evaluation has been performed to determine the effectiveness of the IPM system in improving safety at this site.

U.S. 59 at Loop 151 Flyover, Texarkana, Texas

After the TxDOT Atlanta District experienced perceived success with the IPM system application on FM 127, an additional candidate location was identified. The flyover from U.S. 59 onto Loop 151 in Texarkana, Texas, had a long history of road users impacting the ramp barriers. This flyover ramp is also in a fog-prone area.

For this installation, IPM system markers were installed on the right-side concrete barrier of the curve (see Figures 13 and 14). The installation is approximately one-half mile long. The markers were bolted directly to the barrier using antitheft bolts. The IPM system is activated by a photocell and is illuminated when the ambient light begins to dim. Once the system is acti-



FIGURE 13 Horizontal curve IPM system application (close-up view), Texarkana, Texas (Courtesy: TxDOT Atlanta District).

vated, the lights operate on a steady burn until the ambient light is bright enough to turn off the photocell.

The IPM system at this location has experienced some challenges since implementation, but TxDOT is working with the manufacturer to remedy issues with the system. One challenge with this installation was the physical length (one-half mile) and the power requirements of each marker. Each marker requires 21 volts to operate, and ensuring enough voltage is available to illuminate the last sets of markers along the line was difficult because of power consumption along the cable. In response, the manufacturer developed special power reduction modules that adjust the initial 33-volt input to the required 21 volts per marker. At the end of the half-mile installation, no additional power reduction is necessary to achieve the required 21-volt power. Personnel from TxDOT suggested that this installation would have been easier if a power supply had been provided at each end of the line. The IPM system cost \$56,000 for an approximate half-mile length of roadway, which included equipment and installation.



FIGURE 14 Horizontal curve IPM system application, Texarkana, Texas (Courtesy: TxDOT Atlanta District).



FIGURE 15 Horizontal curve IPM system application (aesthetic view), Texarkana, Texas (Courtesy: TxDOT Atlanta District).

A formal evaluation of the effectiveness of this IPM system has not been done. Anecdotally, TxDOT personnel report fewer tire marks on the barriers at this location than before. Additionally, TxDOT personnel believe that the markers add to the aesthetics of the flyover (see Figure 15) (C. Ibarra, personal communication, Aug. 3, 2007).

N200 between Overveen and Bloemendaal, Province of Noord-Holland, the Netherlands

Limited information was available regarding an IPM system implemented in the Province of Noord-Holland along N200 in the Netherlands. N200 is a four-lane, divided roadway characterized by a high degree of curvature. IPM system markers are installed on the outside edge of each curve (see Figure 16). The benefits of this system are purported to be increased safety and an energy reduction of more than 90% when compared with conventional overhead illumination (Astucia Traffic Safety Systems 2007b).



FIGURE 16 Horizontal curve IPM system application, Province of Noord-Holland, the Netherlands (Courtesy: Astucia Traffic Safety Systems).

A4226 (Five Mile Lane), Vale of Glamorgan, Wales, United Kingdom

Five Mile Lane—a narrow rural roadway—is characterized by a high degree of curvature. In response to an elevated crash rate, several mitigating treatments were implemented including a speed limit reduction, deployment of mobile and permanent speed cameras, supplemental road markings and signage, and pavement resurfacing with high-skid-resistance material. In July 2002, an IPM system was installed to enhance delineation on the centerline of this two-lane roadway (see Figure 17).

It was noted that in the three years after the IPM system was installed, crash rates were reduced by 72% when compared with the three years prior to installation. It was believed that the increased visibility in the curved sections contributed to the reduction in crashes (Astucia Traffic Safety Systems 2007c).

Adverse Weather

The effectiveness of IPM systems in enhancing safety and operations during adverse weather conditions has been the subject of international and domestic study.

In a laboratory setting in Australia, Styles (2004a) considered the activation performance of environmentally triggered IPM systems. Thirteen light-sensitive, five temperature-sensitive, and seven moisture-sensitive markers were tested according to their response to fading light, fog, and low temperature. Based on these tests, it was noted that the markers will perform their intended illuminating tasks: (1) before ice formation, (2) upon formation of moisture on their surface, and (3) in advance of light intensity levels falling below levels that are present with good street lighting.



FIGURE 17 Horizontal curve IPM system application, Wales, United Kingdom (Courtesy: Astucia Traffic Safety Systems).

In Japan, Munehiro et al. (2006) examined the required luminous intensity of IPM systems in fog conditions. They evaluated LED marker characteristics during day and night conditions, asking 20 subjects to subjectively evaluate glare, visibility, and safety of test deployments of varying LED intensities. They found that the desired luminous intensities of 1000 candelas (cd) for daytime and 70 cd for nighttime were acceptable for IPM systems during fog conditions.

In a related study, Hagiwara et al. (2001) investigated the luminous intensity of LEDs in snow conditions and reported difficulty in relying on illuminated markers for tracking during snowstorms, particularly during daylight snowstorm conditions. Markers would have to be spaced closely to contrast with the background light levels and the increased scatter of light during these events.

Domestically, Whitlock and Weinberger (1998) noted that flashing amber lights significantly enhance driver awareness during adverse weather conditions for IPM systems implemented at pedestrian crosswalks (1998).

Practical experience related to IPM system effectiveness during adverse weather is described here.

I-526, Cooper River Bridge, Charleston, South Carolina

In 1992, the SCDOT installed an IPM system on the Cooper River Bridge as a result of a review of environmental impacts potentially caused by fog created by a nearby paper mill (Potash and Brown 1988). The IPM system, intended to provide longer-range delineation of the road beyond the range of vehicle headlights, was just one of five measures selected for implementation. Other measures include dynamic message signs, closed-circuit television cameras, environmental sensors, and a control and communications infrastructure (Goodwin 2003).

An IPM system originally designed for airport runway lighting was used. System markers are placed every 110 ft along the edgelines of the bridge. The IPM system is manually activated by a remote traffic management center (TMC). Weather sensors located on the bridge alert the TMC when fog conditions exist. The TMC verifies the condition by camera or with an on-site inspection. When visibility conditions reach less than 750 ft, the edgeline markers are illuminated. The markers are operated in a steady-burn state (R. Clark, personal communication, Aug. 13, 2007). In light fog, every other marker is illuminated (i.e., a marker spacing of 220 ft); in heavy fog, all markers are illuminated (i.e., marker spacing of 110 ft).

Frequent light source failures have proven challenging and costly for this system. Additionally, the slope of the bridge results in sand and other sediment build-up on the markers (on the downslope), leading to reduced luminous intensity,

overheating, and subsequent failure. Street sweepers also cause debris build-up; the units must be periodically cleaned (approximately once per month) to function properly. System costs were not available for this location.

No formal evaluations have been performed to determine the effectiveness of this IPM system, but a representative from SCDOT notes that favorable comments regarding the system were received from the public following implementation.

Various Locations, State of Virginia

Sections of I-64 and I-77 in Virginia are prone to heavy fog. An early IPM system, on a 5.8-mile segment of I-64, was implemented in 1976, and continually operated until 1997, when the system was upgraded. Upgrades included brighter edgeline markers (previously, incandescent lights were used), new visibility sensors, and 10 DMSs.

A before-and-after evaluation of the 1976 IPM system on I-64 showed a decrease in crashes from 40 (four fog-related) to 31 crashes (one fog-related) in a 19-month period. After the system upgrades in 1997, another 19-month before-and-after study examined crash rates. Again, a decrease in crashes was observed, from 60 (five fog-related) to 54 crashes (two fog-related) (Lynn et al. 2002). The statistical significance of these observed changes was not reported.

Most recently, the Virginia Transportation Research Council (VTRC) has proposed using several different systems, including IPM systems with chase sequence capabilities to reflect variable speed limits, to help prevent crashes in fog-prone areas. In February 2007, the Virginia legislature enabled this application by passing legislation that allows use of variable speed limits. The VTRC also recommends investigation of IPM system effectiveness for pacing vehicles in fog and warning road users of tailgating vehicles (S. Shergold, personal communication, July 26, 2007).

GUIDANCE

With the primary intent to guide road users, IPM systems have been implemented at multiple-turn lanes, merge locations, and tunnels.

The general effectiveness of IPM systems in enhancing road user guidance was investigated by Styles (2004b). Lateral placement, speed, brake use, high-beam headlight use, and travel on (or over) the centerline were considered for a two-lane roadway in Australia. Styles observed that driver distance from the centerline increased significantly (+2.44 in. and +3.07 in.) at two of four test locations. Travel farther from the centerline increases the distance between oncoming vehicles and was surmised to lead to fewer head-on collisions. At the other two test locations, the distance to the centerline decreased (−1.99 in. and −2.46 in.), but only the latter

decrease was statistically significant at the 90% confidence level. Researchers concluded that the clearer delineation of the centerline may make road users more comfortable traveling closer to the centerline, in contrast to traveling closer to what may be a more poorly delineated roadway edge. The study further concluded that brake use and high-beam headlight use were not significantly affected owing to the IPM system, but some reduction in speed (ranging from -0.75 to -1.93 mph) was observed in a before-and-after review of the IPM system installation.

Multiple-Turn Lanes

IPM systems have the potential to enhance lane-tracking during multiple-turn-lane maneuvers and subsequently reduce the occurrence of sideswipe crashes.

SH 99 at Arch Road, Single-Point Urban Interchange, Stockton, California

In Stockton, California, an IPM system was implemented to enhance two-lane, left-turn operations from all approaches of the Arch Road at State Highway 99 (SH 99) intersection (see Figure 18). This intersection is a single-point urban interchange with average daily traffic of 14,000 vehicles.

The IPM system consists of white LED markers mounted flush with the pavement surface. The system is hardwired for both communications and power, both of which run in an underground conduit. Each marker is individually spliced to the power source to provide easy access for replacement.

The IPM system is activated during the left-turn phase of the traffic signal. The markers define the lane line of the two left-turn lanes and illuminate in a forward chase sequence, giving road users a sense of motion and providing positive directional guidance. The markers remain illuminated until the entire curve is lit; the chase sequence then repeats. The



FIGURE 18 Multiple-turn lane IPM system application, Stockton, California (Courtesy: Caltrans).

system operates 24 hours per day (G. Tsutsumi, personal communication, July 2007). The system was originally test operated in two different modes: (1) steady-burn, and (2) forward chasing. The forward chase sequence was perceived to be more effective in keeping traffic moving and, hence, is the only mode of operation used currently.

Frequent LED failures, likely resulting from intersection traffic under normal operation and particularly from vibrations produced by heavy trucks, occur about once every two to three months. The manufacturer is working with the city to minimize these failures. No real-time, remote failure feedback is available for this system. Failures are noted from field observation, from remote visual inspection using nearby closed-circuit cameras, or through public feedback.

The initial installation of the IPM system was reported to cost approximately \$75,000, with annual maintenance costs of approximately \$15,000 per year. The maintenance costs are primarily attributable to the frequent LED failures. Additionally, large sections of the intersection must be closed to service the system.

No formal evaluation has been conducted to determine the effectiveness of the IPM system in improving road user guidance through this intersection. The city of Stockton has, however, received positive public feedback regarding the IPM system.

Wabash Avenue at Veterans Parkway, Springfield, Illinois

In 2004, the Illinois DOT (IDOT) installed an IPM system at the intersection of Wabash Avenue at Veterans Parkway in Springfield, Illinois (see Figure 19). The IPM system was intended to provide a more permanent means to delineate the



FIGURE 19 Multiple-turn lane IPM system application, Springfield, Illinois (Courtesy: SmartStud Systems).

lanes at this busy intersection, compared with dashed pavement markings that fade within a matter of months.

Left-turn delineation for dual left-turn lanes is provided at all approaches. When the left-turn phase is activated, the white LED markers illuminate and operate in a steady burn through the turn phase and approximately three to four seconds after the phase. Marker visibility is described as acceptable during daylight, but superior at night. The system operates 24 h a day. Similar to experiences in Stockton, California, the primary issues with this IPM system have included LED failure. Two full replacements of markers (but not cabling) have occurred since the initial installation owing to the large number of LED failures. Although the system was under warranty and replacement costs were assumed by the manufacturer, IDOT still had to provide costly and disruptive traffic control through the intersection (K. Armstrong, personal communication, Aug. 16, 2007). The entire cost for this system, including traffic control, was approximately \$120,000.

According to IDOT, the IPM system has improved traffic control at the intersection by better delineating the dual left-turn lanes at each approach. This effect has not been confirmed through formal evaluation, however. Significant positive feedback, including several favorable editorials published in local newspapers, was received after the installation of the system.

Merge Locations

At merge locations, IPM systems have the potential to enhance lane-tracking for road users, particularly if the merge maneuver is complicated by curvilinear roadway geometrics.

Route 46, Totowa Burrow, Wayne Township, New Jersey

In 2006, the New Jersey DOT (NJDOT) installed an IPM system on Route 46, in Totowa Burrow, Wayne Township, New Jersey (see Figures 20–22). This IPM system was intended to assist road users with lane delineation at an entry ramp merge location within a curve. System markers were used to delineate centerlines and edgelines and to depict an arrow on the pavement at the merge location. The IPM system operates in a steady-burn state 24 hours per day. The lights are visible during daylight hours and dimmed at night.

Installation issues have challenged the effective operation of this IPM system. The general roadway contractor was not familiar with either the IPM product or installation procedures. Channels to house the cables connecting the markers were not placed deep enough into the pavement, eventually exposing the cables to traffic and the environment. This led to early cable fatigue and failure and subsequent whole system failures. Challenges also existed related to the design of the “merge” arrow as road users had difficulty determining



FIGURE 20 Merge location IPM system application, Wayne Township, New Jersey (*Courtesy: HIL-Tech, Ltd.*).



FIGURE 21 Merge location IPM system application (arrow view), Wayne Township, New Jersey (*Courtesy: HIL-Tech, Ltd.*).



FIGURE 22 Merge location IPM system application (taper view), Wayne Township, New Jersey (*Courtesy: HIL-Tech, Ltd.*).

that the lighted object is an arrow until he or she is immediately in proximity to the arrow.

Despite these installation challenges, NJDOT personnel consider the IPM system to be very effective and recommended its use in fog-prone areas or other locations needing additional roadway delineation. IPM systems were only recommended for the most critical locations, however, because of the system cost. Specific IPM system costs were not readily available from NJDOT; system installation was included as a construction change order on a larger project.

Tunnels

IPM systems used in tunnels can provide guidance and additional roadway illumination for road users. Such systems have been shown to be more effective at night; the tunnel environment is similar to night conditions. IPM systems can be particularly beneficial when a road user enters a dark tunnel from a fully lit daytime environment.

These IPM systems have been used extensively in European tunnels and their effectiveness in improving safety and operation has been the subject of much study.

The average travel speed through tunnels has been shown to increase slightly, whereas speed limit violations decreased following implementation of IPM systems (Eigentler 2005). One explanation for the increased average speed is that road users may feel more comfortable driving in the tunnel. Additionally, road users more commonly maintained a two-second or more headway distance in higher-density traffic following implementation of IPM systems.

Another study conducted by Ruhr University in Bochum examined the use of IPM systems in three different tunnels in Germany (Eigentler 2005). The study measured speed through the tunnel and distances maintained from the side of the tunnel. In addition, road users were surveyed after they exited the tunnel. Trucks changed their lane-tracking to travel in the rightmost portion of the lane following IPM system implementation. A small increase in average speed, leading to a smoother speed progression through the tunnel, was also observed. Road users were better able to adjust from the open road environment to the tunnel environment without slowing down. This is an operational advantage in that decreases in speed at the tunnel entrance can cause a sufficient disruption in the traffic flow, leading to major congestion in heavy traffic.

Austria was the first country to approve guidelines for IPM system use in tunnel applications in its *Guidelines for Tunnel Equipment* (Eigentler 2005). After a 1999 fire disaster, the Tauern Tunnel reopened with an IPM system to help guide road users through the tunnel. In Norway, fire agencies are promoting use of IPM systems in tunnels; in emergency situa-

tions, the IPM system could provide escape or evacuation route delineation regardless of the direction of traffic.

Domestically, IPM systems have been recently implemented in tunnels in the states of California, Hawaii, and Washington.

McClure Tunnel, Santa Monica, California

In October 2003, an IPM system was installed in the McClure Tunnel, where I-10 meets the Pacific Coast Highway in Santa Monica, California. The IPM was installed on the center median barrier to delineate the center of the tunnel and guide road users through a sharp curve (see Figure 23).

The tunnel environment limits opportunities for self-cleaning of IPM units (i.e., through rainfall); however, the barrier mount also limits dirt and debris build-up on the IPM system markers. Caltrans personnel report infrequent maintenance activity, resulting only when vehicles hit the center median barrier and dislodge the IPM system electrical wires or conduit. The IPM system cost was reported to be between \$60,000 and \$70,000; the length of the tunnel and the distance between markers was not reported.

Caltrans personnel purport enhanced visibility for road users and a reduction in crashes as a result of the IPM system, but a formal evaluation has not been done to support these findings (G. Toor, personal communication, July 27, 2007).

Wilson Tunnel, Route 63 (Likelike Highway), Honolulu, Hawaii

In May 2006, the Hawaii DOT (HDOT) implemented an IPM system in the eastbound Wilson Tunnel on Route 63 outside of Honolulu (see Figures 24 and 25). The intention of



FIGURE 23 Tunnel IPM system application, Santa Monica, California (Courtesy: SmartStud Systems).



FIGURE 24 Wilson Tunnel (inside the tunnel), Route 63, Honolulu, Hawaii (*Courtesy: Hawaii DOT*).

the IPM system was to provide lane guidance and reduce crashes; the system provides a guidance and warning function both inside the tunnel and outside at the tunnel exit.

The subject roadway consists of two one-way tunnels, each with two 12-ft lanes and sidewalks. The length of each tunnel is approximately 2,700 ft. The average daily traffic for both directions in the tunnel is 29,500 vehicles, with a posted speed limit of 35 mph (A. Takeshita, personal communication, Aug. 13–15, 2007).

IPM markers are mounted within the double-white center lane lines and on the right edgeline in the eastbound tunnel only. The white LED markers are operated in a steady-burn state 24 hours per day.

To date, there have been no reported failures with the markers or system. Failure detection does not occur automatically, but is detected through inspection by the HDOT maintenance



FIGURE 25 Wilson Tunnel (exit from the tunnel), Route 63, Honolulu, Hawaii (*Courtesy: Hawaii DOT*).

crews or through public notifications. The initial cost of the system was \$70,000, which is comparable to the system costs reported for the Santa Monica, California, IPM system tunnel application. Although no formal evaluation of effectiveness has been performed, HDOT reported a perceived improvement in tunnel operation and safety as a result of the IPM system.

Tunnel # 1, SR-20 between Newhalem and Diablo, Washington

In July 2005, the Washington State DOT (WSDOT) implemented an IPM system in Tunnel #1 on State Route 20, between Newhalem and Diablo (see Figure 26). The IPM system implementation was motivated by a desire for increased safety through added delineation inside the tunnel, particularly for road users crossing from bright daylight conditions into the dark tunnel.

At this location, the roadway has two lanes (one lane in each direction) and a width of 30 ft (including shoulders) inside the tunnel. The tunnel is 630 ft in length. The average daily traffic for both directions of travel through the tunnel is 1,500 vehicles per day, and the posted speed limit is 45 mph.

The IPM system markers are placed along the centerline for the length of the tunnel. The yellow LED markers operate in a steady-burn state when activated either by vehicle loop detectors at each tunnel approach or by push buttons for bicyclists entering the tunnel. Installation required a saw cut into the concrete for the inductive power line. In addition, a 6- to 10-in.-wide strip of pavement surface was milled down for a length of about 18 in. in front of and behind each marker (see Figure 27) allowing the marker to be recessed from the traffic lane surface to help avoid damage from snowplows.

Some maintenance is required to clean the individual markers every three to six months as debris and dirt on the



FIGURE 26 Tunnel IPM system application, between Newhalem and Diablo, Washington (*Courtesy: WSDOT*).



FIGURE 27 Tunnel IPM system application (milled pavement view), between Newhalem and Diablo, Washington (Courtesy: WSDOT).

markers hinder their visibility over time. To date, there have been no reported failures with the markers or system. Failure detection does not occur automatically, but is detected through inspection by the WSDOT maintenance crews or through motorist notifications. The total system cost was estimated as \$100,000. Ongoing annual costs associated with system maintenance are approximately \$1,000. The operation and safety of the facility have improved with the addition of the IPM, WSDOT believes, although no formal evaluation is available (G. Baghai, personal communication, Aug. 3–7, 2007).

REGULATION

IPM systems have been implemented in combination with other regulatory devices at intersection stop bars and for left-turn restrictions to enhance regulation of road users.

Intersection Stop Bars

IPM systems implemented at intersection stop bars can be integrated with traffic signals or other control devices to enhance regulation of road users.

Disneyland Drive near Disneyland Resort, Anaheim, California

An IPM system intersection stop-bar application on Disneyland Drive in Anaheim, California, was credited with reducing crashes from 14 in a six-month period prior to implementation to 6 in the six-month period following implementation. The system was also credited with reducing red light running and increasing stop-bar adherence (Kaku Associates, Inc. 2002).

2nd Street at Adams Street, Coquille, Oregon

In Coquille, Oregon, in 2006, the intersection of 2nd Street and Adams Street—a four-way stop-controlled intersection—was modified from an all-red flashing signal to an IPM system stop-bar application with lighted stop signs on all approaches (see Figure 28). The IPM system and stop signs for any approach illuminate when a vehicle is detected traveling at least 5 mph approaching the intersection.

Challenges to successful IPM system operation in stop-bar applications include sensor failure and adherence to the pavement. Marker adherence issues have been attributed to fully loaded logging trucks running directly over the light systems in Coquille, Oregon (unnamed city staff member, personal communication, July 23, 2007). Despite these issues, the IPM system is viewed as beneficial, enhancing the visibility of the four-way stop control. Both daytime and nighttime operations are considered to be effective. The system cost was approximately \$40,000; maintenance is covered under a manufacturer warranty.

West Alabama Street at the Galleria Shopping Mall, Houston, Texas

Under FHWA's experimental designation, an IPM system was implemented at a signalized pedestrian crossing that connects two sections of the Galleria Mall at West Alabama Street. The IPM system is illuminated during the yellow and red phases of the traffic signal and matches the signal's color indications. The markers used in this application have five amber LEDs and five red LEDs. When the traffic signal provides a yellow indication, the amber LEDs illuminate in a steady-burn state (see Figure 29). When the traffic signal provides a red indication, the red LEDs illuminate, also in a steady-burn state (see Figure 30). When the traffic signal shows a green indication, the IPM system is deactivated.



FIGURE 28 Intersection stop-bar IPM system application, Coquille, Oregon (Courtesy: LightGuard Systems, Inc.).



FIGURE 29 Stop-bar application Amber Phase, Alabama Street at Galleria, Houston, Texas.

Initially there were problems with electrical “shorts” in the IPM system; however, this was attributed to initial system wiring rather than equipment failure. Once resolved, few additional maintenance issues were reported. As with other applications, it was noted that the IPM system markers do collect dirt and debris and require occasional high-pressure water cleaning (tunnel-like conditions under the pedestrian bridge prevents rain from self-cleaning the markers) (R. Taube, personal communication, July 23, 2007). Decreased luminous intensity was also noted with the IPM system markers. This is likely attributable to the reduced number of LEDs per illumination phase (i.e., 5 yellow or red LEDs per illumination rather than the more typical 10). The total cost for this IPM system was approximately \$45,000, comprising material costs of \$30,000 and installation costs of \$15,000 (P. English, personal communication, July 23, 2007). The effectiveness of the IPM system at this location was measured at two different times following implementation: (1) initially following system implementation, and (2) following extended implementation

to better determine lasting system effects over time (TEDSI Infrastructure Group 2004a, b). When compared with the “before” conditions, the following changes were observed after IPM system implementation:

- Pedestrian compliance with the signal increased by 17% initially following implementation and by 19% following extended implementation.
- Motorist noncompliance with the signal decreased by 23% initially following implementation and by 25% following extended implementation.
- Red-light running decreased by 50% initially following implementation and by 77% following extended implementation.
- Stop-bar violations (i.e., the number of vehicles encroaching over the stop bar) decreased by 6% initially following implementation and by 26% following extended implementation.

Note that in each case the IPM system effectiveness was observed to increase rather than decrease over time, although the time period for measurement following extended implementation was not reported (e.g., three months, six months, and one year).

Various Locations along METRORail Line, Houston, Texas

In 2006, The Houston Metropolitan Transit Authority of Harris County, Texas (METRO) implemented an IPM system at an intersection stop bar in the Houston central business district, specifically at the intersection of Jefferson Street and Main Street (see Figure 31). Only the Jefferson Street approach was initially equipped with the IPM system. Jefferson Street is a five-lane, one-way, eastbound street that intersects the METRORail line at Main Street. The motivation for this implementation was to increase road user awareness of the traffic



FIGURE 30 Stop-bar application Red Phase, Alabama Street at Galleria, Houston, Texas.



FIGURE 31 Intersection stop-bar IPM system application, Jefferson Street at Main Street Houston, Texas.

signal and the onset of a red indication, to subsequently reduce the incidence of red-light running on streets intersecting the rail line. The Jefferson Street approach served as the initial test site.

The IPM system at this location is configured in a linear layout with two offset rows of red LED markers. The spacing of IPM markers in each row is approximately one foot, but the offset of the markers between the two rows effectively presents a six-inch spacing. The IPM system is activated in a steady-burn state when the eastbound traffic signal indication for the Jefferson Street approach changes to red. The IPM system is deactivated when the traffic signal operates in an all-red flashing mode.

This IPM system uses an inductive loop power source, eliminating the need for the markers to be hardwired directly to the power source. The installation of the system involved cutting a groove in the pavement to place the inductive power loop, coring the pavement to install the power nodes, and adhering the markers to the pavement surface above the nodes.

Reported issues with the performance of this IPM system include a lack of marker adherence to the pavement (i.e., a high frequency of pop-offs) and a loss of luminous intensity over time (W. Langford, personal communication, 2007).

As with the IPM system application at West Alabama Street at the Galleria Shopping Mall in Houston, Texas, the Jefferson Street at Main Street IPM system was deployed with FHWA's experimental approval. As part of this process, semi-annual reports are required to document the effectiveness of the application under experiment. The first report provided information on driver comprehension, traffic operations (including red-light running and violations of the right-turn-on-red prohibition), and vehicle crashes (Tydlacka and Voigt 2006).

Driver comprehension studies were conducted in April 2006 with 103 individuals who drive in and around Houston and specifically, along the METRORail line. The participants were shown a selection of video clips (some of which contained computer-animated renditions of the proposed intersection stop-bar IPM system application in the active state) and asked to complete a survey after viewing the videos. These comprehension studies were completed before the IPM system was activated in the field. The driver comprehension studies showed that nearly 90% of respondents stated that the first characteristic they noticed about the intersection was the IPM system at the stop bar. More than 80% believed that the purpose of the system was to tell drivers where to stop for the traffic signal. It was concluded that most drivers noticed the IPM system and associated the IPM system with the traffic signal (based on computer-animated renditions of the proposed IPM system).

The initial operational analysis was supported by three days of data prior to IPM system implementation and one day of early "after" data following implementation. The results

showed a minor reduction in red-light running (from 9 per day to 8 per day), but a major reduction (more than 50%) in right-turn-on-red maneuvers (from 47 per day to 18 per day). Similar findings were observed when these changes were normalized to reflect violations per 1,000 cycles or violations per 10,000 vehicles (Tydlacka and Voigt 2006).

Crash frequency was also monitored before and following IPM system activation. One year of crash data before IPM system implementation and six months of data following implementation were considered. A reduction from two to zero eastbound crashes was observed after the IPM system was implemented. The short observation period and infrequent crash occurrence limits further conclusions related to the crash reduction potential of the IPM system at this site. These findings related to driver comprehension, traffic operations, and vehicle crashes at Jefferson Street are preliminary but promising. Evaluations are still ongoing.

Given the promise of the initial IPM system at Jefferson Street, a second street that approaches Main Street—Gray Street—was equipped with an intersection stop-bar IPM system at Main Street. This intersection was also equipped with LED-bordered backplates installed behind the traffic signal faces. Figure 32 depicts both the IPM system intersection stop-bar application and the LED-bordered backplates. When the traffic signal indication changes to red, the IPM system and the LED-bordered backplates are concurrently illuminated in a red, steady-burn state. Evaluations of the effectiveness of these combined systems are ongoing.

Most recently, Houston METRO has implemented several additional IPM systems at intersection stop bars (as well as LED-bordered backplates) along Main Street and the light rail line. Two different types of IPM systems were used across these locations, requiring different installation techniques, power delivery methods, and operating modes (i.e., flashing).



FIGURE 32 Intersection stop-bar IPM system with LED-bordered backplates, West Gray Street at Main Street, Houston, Texas.

One of the IPM systems is designed such that each marker flashes consistently, but individual markers flash with left and right sides alternating. Table 4 summarizes current intersection stop-bar IPM system and LED-bordered backplate applications currently in use by Houston METRO.

Left-Turn Restrictions

Left-turn restrictions are typically conveyed to road users through static regulatory signing. IPM systems have the potential to enhance road user awareness of turn prohibitions, and offer more flexibility in operations related to time-of-day or transit-priority restrictions.

Various Locations along METRORail Line, Houston, Texas

A segment of Houston's METRORail light rail is centered on Fannin Street running in the former median portion of the roadway. Along this corridor, left-turn movements are prohibited in both northbound and southbound directions along Fannin Street (within the Texas Medical Center) when a train is approaching. Despite this left-turn restriction, a number of crashes have occurred involving left-turn movements by road users. To reinforce the turn restriction, Houston METRO first installed a dynamic lane control assignment system (see Figures 33–35). A "Red X" indicates that left-turn movements are prohibited; a "Green Arrow" indicates that left-turn movements are allowed and a "Train Approaching" sign provides additional warning to road users ("METRORail . . ." 2007). These overhead-



FIGURE 33 Active "X" for do not enter left turn lane on X, Houston, Texas (Courtesy: Houston METRO).

mounted dynamic signs are linked to the traffic signal controller. When a train approaches from either direction, the "Green Arrow" is replaced with a "Red X" and the "Train Approaching" sign is illuminated ("Walking . . ." 2007).

To supplement this dynamic lane control assignment system, Houston METRO in 2006 implemented an IPM system on the northbound and southbound approaches of Fannin Street at Dryden Street (see Figures 36 and 37).

A single row of red IPM system markers is placed along the lane line between the left-turn lane and the left through

TABLE 4
INTERSECTION STOP-BAR IPM SYSTEMS AND LED-BORDERED BACKPLATES
IN HOUSTON, TEXAS

Location Along Main Street	IPM System	LED Backplates	Implementation Date
Jefferson Street (eastbound)	✓	✓	March 2006 (IPM System) August 2007 (LED Backplates)
Gray Street (westbound)	✓	✓	October 2006 (IPM System) June 2007 (LED Backplates)
McGowen Street (east/westbound)	✓		November 2006
Webster Street (eastbound)	✓		February 2007
Dallas Street (eastbound)	✓		May 2007
Commerce Street (westbound)		✓	June 2007
Walker Street (westbound)	✓		June 2007
Elgin Street (east/westbound)	✓		June 2007
Alabama Street (east/westbound)	✓		June 2007
Pierce Street (eastbound)	✓	✓	July 2007 (IPM System) February 2007 (LED Backplates)



FIGURE 34 Active “Arrow” for permitted access left-turn lane, Houston, Texas (Courtesy: Houston METRO).

lane in both the northbound and southbound directions. The markers are spaced approximately 5 ft apart and extend from the beginning of the left-turn bay through the Dryden intersection. The system is activated in a steady-burn state when the dynamic lane control assignment indicates a “Red X.”

The installation of the system involved cutting a groove in the pavement to place the inductive power loop, coring the pavement to install the power nodes, and adhering the markers to the pavement surface above the nodes.

Not unique to this application, power supply issues were encountered early in IPM system operation but have since been resolved. On more than one occasion, the system was without power owing to a suspected manufacturing defect in the power supply. Also, marker adhesion has been problematic; some markers were dislodged from the pavement and were lost or destroyed by traffic. Once the missing markers were replaced with stronger adhesive, the system has operated with few to no problems (W. Langford, personal communication, 2007).



FIGURE 35 Train approaching sign (flashes on train approach).



FIGURE 36 Left-turn restriction IPM system application (not active), Houston, Texas.

As with the previous IPM system applications in Houston, Texas, this IPM system was implemented with FHWA’s experimental approval. As part of this process, semi-annual reports are required to document the effectiveness of the application under experiment. The first report provided information on driver comprehension, traffic operations (including violations of the prohibited left-turn maneuver), and vehicle crashes.

Conducted simultaneously with the previously described driver comprehension studies for IPM system intersection stop-bar applications, the driver comprehension studies for this application were conducted in April 2006 with 103 individuals who drive in and around Houston and, specifically, the Texas Medical Center. The participants were shown a selection of video clips (some of which contained computer-animated renditions of the proposed IPM system in the active state) and asked to complete a survey after they viewed the videos. These comprehension studies were completed before the IPM system was activated on Fannin Street. The results of this



FIGURE 37 Left-turn restriction IPM system application (active), Houston, Texas.

study indicated that approximately 82% of the respondents understood the meaning of the IPM system to be “do not enter the left lane.” Only 50%, however, thought that the IPM system signaled that a train was coming. Respondents were also shown an image with the IPM system and an overhead “Train Approaching” sign, yet 18% did not include “a train is coming” or “do not turn left” in their response. The driver comprehension study concluded that although most drivers understood that the purpose of the IPM system was to restrict access to the left-turn lane, some road users may be challenged to determine when a train is approaching or when they are allowed to enter the left-turn lane using the current dynamic lane control assignment and IPM system.

The operational analysis for this combined dynamic lane control assignment and IPM system application considered five specific violation types:

1. Type 1 LT Violator—Vehicle enters left-turn lane against the “Red X” of the dynamic left-turn lane control signal and completes left turn.
2. Type 2a LT Violator—Vehicle completes left turn from lane other than left-turn lane against the “Red X” of the dynamic left-turn lane control signal.
3. Type 2b LT Violator—Vehicle completes left turn from lane other than left-turn lane with the “Green Arrow” of the dynamic left-turn lane control signal.
4. LT Violator/Bailout—Vehicle enters left-turn lane against the “Red X” of the dynamic left-turn lane control signal and does not complete the left turn.
5. Bailout—Vehicle enters the left-turn lane legally with the “Green Arrow” of the dynamic left-turn lane control signal and does not complete the left turn, continuing straight on Fannin Street.

Three days of data prior to IPM system implementation and one day of early “after” data following implementation supported this operational analysis. The results showed a consistent trend in violations; total violations were either the same or slightly higher than before when measured shortly after implementation. The number of Type 1 violators (i.e., vehicle enters left-turn lane against the “Red X” of the dynamic left-turn lane control signal and completes left turn) per 10,000 vehicles was observed to decrease, however, for each direction. These results should be viewed as preliminary and should take into account the short observation period (i.e., one day) following IPM system implementation (Tydlacka and Voigt 2006).

The crash analysis at this site was inconclusive owing to an infrequency of observed crashes (no left-turn vehicle/train crashes occurred at this location in the year before IPM system implementation or in the six months following implementation) and the abbreviated observation period following IPM system implementation. Although no significant reduction in crashes could be attributed to IPM system implementation at this site, left-turn vehicle/train crashes have shown a consistent annual decline over time.

ILLUMINATION

With a primary intent to provide an alternate source of illumination, IPM systems have been implemented at vehicle and truck inspection points and in environmentally sensitive areas, potentially affected by light pollution attributable to conventional overhead roadway lighting systems.

Vehicle and Truck Inspection Points

At locations where safety and security is of heightened concern (e.g., international border crossings and military facilities), IPM systems have the potential to enhance the monitoring capabilities of officials at these locations through improved illumination.

Vandenberg Air Force Base, Santa Barbara County, California

Because of their upward light projection, IPM systems have been used by monitoring inspectors to better view the undercarriages of entering and exiting vehicles (see Figure 38). Most contacts interviewed for this synthesis effort declined to divulge details about these systems for security reasons; a representative from Vandenberg Air Force Base did confirm the use of IPM systems at two different locations. No additional information regarding the installation, operation, maintenance, cost, or effectiveness of these IPM systems was available.

Environmentally Sensitive Areas

Light pollution, attributable to conventional overhead roadway lighting systems, has prompted the use of IPM systems as an alternative source of illumination at a number of locations deemed to be environmentally sensitive.



FIGURE 38 Vehicle and truck inspection point IPM system application (Courtesy: Traffic Safety Corporation).

SR A1A, Boca Raton, Florida

In Boca Raton, Florida, sea turtle hatchlings are instinctively drawn to the ocean by the reflection of light from the sky on the water's surface. Along State Route A1A, the installation of overhead artificial roadway lighting confused the hatchlings, drawing them inland (instead of toward the ocean) where they became dehydrated, preyed upon, and even run over by vehicles. In 2001, FDOT initiated an experimental demonstration project to test the use of IPM systems as an alternate illumination source with the intent of preserving the sea turtle hatchlings (see Figure 39).

A one-half-mile section of SR A1A, adjacent to the beach and the city's Spanish River Park, was selected as the demonstration site. The existing overhead roadway lights were deactivated and combined bollard lighting and IPM systems were implemented. The alternative light sources were physically lower in height than the sea dunes adjacent to the roadway to prevent light from reaching the beach. The alternate light system is only used during the sea turtle mating season (from May to October), and is photo-sensitive, illuminating at dusk.

Not unique to this application, marker adhesion was reported as initially problematic at this location; the adhesive used to hold the markers in place would release in Florida's high summer temperatures. This issue was fully resolved by the manufacturer. The control cabinet was also struck by lightning and has since been replaced with a stronger, grounded box.

Although no IPM system costs were directly reported, a resurfacing project is planned for SR A1A that will provide continued use of the existing half-mile IPM system and extend the system for an additional half-mile. The cost of the combined resurfacing/IPM system project is \$500,000 (A. Broadwell, personal communication, July 26, 2007).



FIGURE 39 Environmentally sensitive area IPM system application SH A1A Boca Raton, Florida (Courtesy: SmartStud Systems).

Two separate studies were done by the University of Florida to determine the effectiveness of the combined bollard lighting and IPM systems, considering both the turtle hatchlings and the general public. The hatchlings study revealed a 99% decrease in hatchling disorientation attributable to the alternative light system. In the public acceptance study, the majority of the public was in favor of the project and agreed that the alternative light system was adequate for roadway usage. Older road users, however, were observed to be less receptive to the alternative light system. No changes in crash characteristics were observed as a result of the alternative lighting (Ellis and Washburn 2003).

N513 Highway, Castricum, Province of Noord-Holland, the Netherlands

Along the N513 Highway in the Province of Noord-Holland, the Netherlands, an IPM system was implemented as an alternative to overhead roadway lighting to address safety concerns in an environmentally sensitive location. At this location, bicyclists returning from the adjacent beach and conservation area frequently cross the N513 highway. The proximity of the conservation area precluded use of conventional overhead roadway lighting to increase the visibility of the bicyclists as they crossed the highway.

In 2003, solar-powered IPM system markers were placed along the centerline of the roadway for a distance of approximately 180 ft on both sides of the bicycle crossing (see Figure 40). Inductive loops are used to activate the IPM system as vehicles approach the crossing area.

The Dutch reported a 99.2% savings in energy and minimal impacts on wildlife as a result of the IPM system. In addition, no fatalities or injuries have been reported since the installation of this system. No information was provided, however, regarding safety levels before IPM system implementation to



FIGURE 40 Environmentally sensitive area IPM system application, Province of Noord-Holland, the Netherlands (Courtesy: Astucia Traffic Safety Systems).

determine whether this result is notable (Astucia Traffic Safety Systems 2007a).

CONCEPTUAL APPLICATIONS

While investigating existing IPM systems, several conceptual applications of IPM systems were uncovered including:

- Fire station exit warning systems;
- Toll booth open/closed operational status;

- High-occupancy-vehicle lane open/closed operational status, entrance and exit lane delineation, enforcement areas, and reversible lanes;
- Parking garage guidance to open spaces; and
- Airport gate lead-ins.

These potential applications of IPM systems are still in the conceptual stage and have not yet been field-tested to determine their ability to enhance safety, operations, or aesthetics under these conditions.

CONCLUSIONS

Various types of illuminated, active, in-pavement marker (IPM) systems are emerging that offer a range of designs and functional features intended to warn, guide, regulate, or provide illumination for road users. Although the number and breadth of IPM system applications has increased in recent years, little has been documented about the effectiveness of these systems in enhancing roadway safety, operations, or aesthetics. Furthermore, little guidance is available to support proper planning, installation, operation, and maintenance of the systems.

This synthesis report documents the current state of knowledge related to IPM system use and effectiveness. More specifically, this report documents: (1) the state of IPM technology, including technology characteristics and standards and guidelines for use; (2) notable experiences from historical IPM system applications; and (3) detailed experiences from recent IPM system applications, including system and facility characteristics, operation modes, installation and construction methods, maintenance requirements, system costs, and perceived and measured effectiveness. Assimilated in this synthesis report, this information will help to accelerate successful applications and focus future research of IPM systems.

This chapter provides a summary of key findings and presents applicable suggestions based on the information obtained in this synthesis effort.

SUMMARY OF KEY FINDINGS

Key findings related to IPM system applications, technology characteristics, installation and construction methods, operation modes, maintenance requirements, costs, and perceived and measured effectiveness are summarized here. Given the relative novelty of IPM system use on public roadways, little direction in the form of standards or guidelines is available to support proper installation, operation, and maintenance of the systems. At the federal level, the *Manual on Uniform Traffic Control Devices (MUTCD)* (2004) provides significant general guidance related to traffic control devices (e.g., signs, markings, and highway traffic signals), but contains few explicit standards, guidance, or options for IPM system use and focuses exclusively on pedestrian crosswalk applications.

Applications

Historically, IPM system use was limited to airport runway/taxiway or pedestrian crosswalk applications. More recently, IPM systems have been used to enhance:

- Warning through school and construction zones, at highway–rail crossings, at horizontal curves, and during adverse weather;
- Guidance through multiple-turn lanes, at merge locations, and through tunnels;
- Regulation at intersection stop bars and where left turns are prohibited; and
- Illumination at vehicle and truck inspection points and environmentally sensitive areas.

Technology Characteristics

Generally, IPM systems consist of an illumination source surrounded by a protective housing and lens, a power source, and a system controller in a protective enclosure. The design and features of the various components may vary significantly depending on the type of application. None of the IPM systems observed provided automatic notification of system failure; instead, failures were detected through remote surveillance, on-site inspection, or public reports. Should this capability be added to IPM systems, the design and use of this feature could be guided by related Intelligent Transportation Systems (ITS) standards.

Illumination Source

Both incandescent/halogen lamps and light-emitting diodes (LED) have been commonly used as light sources in IPM systems. Laser and electroluminescence technology has also been considered for use; however, each has respective limitations preventing widespread applications. Flexibility in color and luminous intensity, low power consumption, and extended useful life, has resulted in LED emerging as the favored light source for IPM systems.

For the IPM systems observed, several issues related to the luminous intensity of the light source were identified. Compromised luminous intensity was reported during daylight operation as compared with nighttime operation at several

sites. In addition, luminous intensity was reportedly lower for IPM systems relying on solar technology, as opposed to hardwired or inductive systems. Although not confirmed through measurement, a decrease in luminous intensity was also reported over time. Last, an increased capability in color features (i.e., utilizing more than one color per marker) reduces the number of LEDs illuminated simultaneously and hence reduces the luminous intensity of the marker.

Housing and Lens

Housing materials, typically measuring no more than 6 in. along the largest dimension, have commonly been made of plastic, although newer markers are more frequently made of aluminum or stainless steel for improved durability. Lens materials commonly include polycarbonate or boron/glass. Some vendors include a passive retroreflective lens (i.e., a prismatic surface that reflects external light sources) in addition to active illumination to provide fail-safe operation should the IPM system lose power.

Power Source

IPM systems can derive power to operate through hardwired electrical connections, inductive wireless connections, or solar technology. To date, hardwired electrical connections and inductive wireless connections have outperformed (i.e., higher luminous intensity, more consistent operation) IPM systems relying on solar technology. Benefits to solar-powered IPM systems include the ease and flexibility of installation, particularly for remote areas. Continued advancements in solar technology may make this a more viable IPM system power source in the future.

System Controller and Enclosures

The IPM system controllers are typically housed in a protective cabinet or enclosure. For lightning protection, a ground box with copper ground rod is typically located near the cabinet/enclosure. In electrical storm-prone areas, lightning protection for IPM systems is especially important.

Installation and Construction Methods

Each IPM system vendor provides more detailed installation instructions tailored to its specific product.

For placement of the electrical cable and/or conduit, a common method requires saw-cutting a 3/8 in. to 1/2 in. groove in the pavement for cable-only installations (a larger cut is required to accommodate a larger-diameter conduit). The electrical conduit is placed in the saw cut and typically covered with epoxy. For inductive IPM systems, both the conduit and node assembly are placed in the saw cut and sealed with epoxy. It is important to provide enough depth to

the saw cut to adequately recess and protect the electrical cable and/or conduit. Individual unit solar-powered IPM systems do not require this installation step.

Several of the observed IPM systems noted power supply issues following installation. A few of these instances were attributable to a manufacturer defect. Power supply issues were more commonly attributed, however, to a lack of familiarity with installation procedures by the contractor or poor quality control during installation (e.g., water penetration).

Markers can be recessed in the pavement through coring or milling methods or affixed directly to the pavement surface. Recessed markers are less prone to “pop-offs” but require additional effort during the installation process. In cold regions, where snowplowing is frequent, use of recessed markers is necessary. Also, the performance of marker adhesives, particularly in unusually cold or hot temperatures, can have a significant effect on pop-off frequency. In most instances, manufacturers have been able to significantly reduce the occurrence of pop-offs through the use of alternate adhesive; however, this action generally only follows a period of poor IPM system performance.

As observed in this synthesis effort, markers can also be placed on concrete barriers, sign posts, etc. IPM systems that use barrier- or post-mounted markers experienced significantly fewer pop-offs.

Based on pedestrian crosswalk experience, a high frequency of system failures in a single jurisdiction was attributable to marker settlement and subsequent power supply issues in asphalt concrete pavements. This issue was purportedly avoidable if the IPM systems were installed in portland concrete cement pavement. Although the IPM systems observed in this synthesis effort included a range of pavement materials, no additional information was uncovered that described the comparative performance of IPM systems that were installed in either portland concrete cement or asphalt concrete pavements.

Additionally, no consistent standard for IPM system marker spacing was observed within similar applications. Between applications, marker spacing was generally observed to increase as traffic speeds increased.

Operation Modes

System Activation

Activation of IPM systems relies on either manual methods, where the system is activated directly by the road user (e.g., a push-button system) or passive methods, where the system is activated automatically through some type of sensor input. Passive activation can be provided through in-ground sensors, motion sensors, visual image video detection systems, in-pavement loop detectors, integration with traffic control

devices, and road-weather information systems. Manual activation methods are typically lowest in cost, but require action from the road user to be effective. Passive activation methods are more discrete, but may suffer a high frequency of false positives and misses, particularly when using microwave technology.

Additional IPM system activation methods observed in this synthesis effort included timer-based activation (in the case of a school zone) and ambient light-sensitive activation through the use of photoelectric cells to detect dusk (for activation) and dawn (for deactivation).

The nature of IPM system activation depends somewhat on the intended function of the system and the characteristics of the environment in which it is placed. Systems that are intended to guide road users are often operated continuously, particularly those in high-traffic environments. Conversely, IPM systems that are intended to warn, regulate, or provide illumination are more commonly operated intermittently, in response to a detected hazard or regulatory action, or to minimize environmental effects and energy consumption.

Modes of Operation

Depending on the manufacturer, IPM systems offer a range of features that have the potential to enhance roadway operations. Marker color changes can be used to indicate regulatory action required by the road user (e.g., markers show red illumination when vehicles are required to stop). Varying flash rates (including steady burn) can indicate the level of hazard. Also, “chase” sequences can direct the road user to reduce or increase speeds.

Common IPM system marker colors include white, amber, red, green, and blue. Using LED illumination technology, IPM system markers can illuminate the same color in all directions, can alternate colors consistently (i.e., all markers show red illumination when vehicles are required to stop, but return to green or white when vehicles are permitted to travel), or can illuminate two different colors by direction (i.e., to indicate wrong way travel). Use of multiple colors in the IPM system marker reduces the luminous intensity for any single illumination (i.e., a marker that contains 10 total LEDs would illuminate 5 LEDs of one color followed by 5 LEDs of another color).

IPM systems can be operated in a steady-burn state or in a flashing mode, consistently or intermittently. The flashing mode may be triggered by a detected hazard (e.g., when upstream speed sensors detect a vehicle traveling too fast for a curve or when a road-weather information system detects fog conditions) and may, depending on the manufacturer, provide an adjustable increasing flash rate consistent with increasing danger (as long as the flash rate remains within an

acceptable range). All other times, the IPM system may show steady or no illumination.

More sophisticated IPM systems offer forward or reverse chase sequencing (i.e., adjacent markers are sequentially illuminated giving the effect of moving light along the path). This feature is intended to improve speed-related roadway operations by pacing traffic at consistent and appropriate speeds for conditions. Chase sequencing has been used to maintain or reduce vehicle speeds in fog-prone areas and to reduce vehicle speeds on exit ramps. Other potential applications include horizontal curves, tunnels, merge areas, or construction work zones.

In the IPM systems observed, use of white, amber, and red markers were noted, most commonly as single-color configurations, although some of the markers provided dual-color illumination to coincide with the red and amber traffic signal indications. The majority of IPM systems observed operated in steady-burn state once activated; flash and chase features were more common in systems intended to provide warning (in one case, chase sequences were used to provide guidance through multiple-turn lane maneuvers).

Maintenance Requirements

Specific to halogen light sources, halogen lamps reportedly experienced frequent water condensation and broken filaments. Applying more generally to all IPM system marker types, frequent light source failures were consistently reported over all applications. Failures were generally attributed to environmental factors (e.g., water, dirt, and debris build-up) or traffic impacts. For markers located in the tire path of vehicles and particularly heavy vehicles, light source failure was particularly problematic. This condition is inherent in the design of IPM systems for multiple-turn lanes; vehicles traveling through the intersection are required to drive over a portion of the multiple-turn lane delineation. Ongoing light source failures can become costly if not included under a manufacturer’s warranty. Annual maintenance costs for one IPM system were estimated to be \$15,000, comprised largely of LED failure replacement costs. One jurisdiction reported significant delays in delivery of replacement parts.

System markers that protrude above the ground have also experienced damage by street cleaners and snowplows. System manufacturers have moved to aluminum or stainless steel housing materials typically recessed into the pavement to address this issue. Recessed markers that also help to minimize damage from street cleaners and snowplows require frequent cleaning to eliminate dirt and debris from the lens surface. This requirement was frequently noted for the IPM systems observed in this synthesis effort. In some cases, the IPM system required cleaning (e.g., power washing) as frequently as once per month. Barrier- or post-mounted IPM systems do not require this same level of maintenance.

It was also noted that activities such as street repair or resurfacing require the IPM system to be removed and reinstalled or lost. This is not unique to IPM system applications, but challenges the longevity of any type of roadway instrumentation. Again, barrier- or post-mounted IPM systems are less likely to be affected by roadway repair or resurfacing activities.

Costs

Costs for IPM system applications range significantly, from \$5,000 to \$100,000. Factors affecting cost include the length and layout of the application and the subsequent number of markers required; specific features of the IPM system (e.g., unidirectional or bidirectional displays and operational modes); the availability and nature (e.g., solar) of power at the site; the condition of the pavement and any remedial actions required before IPM system installation; and traffic control requirements. In general, implementing agencies do not consider IPM systems to be a “low-cost” alternative to traditional traffic control devices and suggest that their use be limited to critical locations. Opportunities for federal funding to support IPM system implementation may be constrained by proprietary issues (i.e., FHWA typically requires system bids from three or more vendors; patented products may not be approved for widespread implementation).

Perceived and Measured Effectiveness

Few formal evaluations have been performed to determine the effectiveness of IPM systems in enhancing roadway safety, operations, or aesthetics. Pedestrian crosswalk applications have been most frequently studied; IPM systems have generally been shown to increase vehicle driver awareness, increase vehicle yielding, reduce vehicle approach speeds, reduce vehicle/pedestrian conflicts, and reduce pedestrian wait times.

Considering broader applications of IPM systems, additional studies have generally shown a reduction in vehicle speeds, improved lane-tracking, increased road user awareness, and high public acceptance. More recent studies have been conducted in response to FHWA’s requirements for experimental status. Early results reported from these studies show promise but are generally based on limited data and, as such, cannot be considered conclusive.

Implementing agencies provided significant anecdotal information through this synthesis effort purporting the effectiveness of IPM systems in enhancing various aspects of roadway safety, operations, or aesthetics depending on the nature of the application. A high overall degree of IPM system satisfaction was reported despite any installation or maintenance challenges encountered. Further, implementing agencies noted a high level of public support for and acceptance of IPM systems.

SUGGESTIONS

Based on the information gathered through this synthesis effort, illuminated, active, IPM systems show potential for enhancing: (1) warning through school and construction zones, at highway–rail crossings, at horizontal curves, and during adverse weather; (2) guidance through multiple-turn lanes, at merge locations, and through tunnels; (3) regulation at intersection stop bars and where left turns are prohibited; and (4) illumination at vehicle and truck inspection points and environmentally sensitive areas. Direct benefits of IPM systems in each of these applications cannot be quantified conclusively because few acceptable evaluations of recent IPM system applications have been performed, and a lack of installation, operation, and maintenance guidance is likely confounding system performance. As such, suggestions to focus future research and accelerate successful applications of IPM systems fall into two categories: (1) research and evaluation and (2) standards and guidelines.

Research and Evaluation

- Development of a robust and standardized methodology for evaluating IPM systems would help to ensure that some level of consistency is achieved in the evaluation of these treatments. The functional breadth of more recent IPM system applications (i.e., to warn, guide, regulate, or provide illumination) requires an adaptable methodology that encompasses a wide range of performance measures.
- Agencies that currently operate IPM systems are encouraged to evaluate their effectiveness and document subsequent findings so that others can benefit from their experiences. In lieu of a standardized evaluation methodology, agencies could focus on obtaining a sufficiently large data sample over a reasonable observation period to enhance the credibility of their findings.
- Additional research, with the following focus, could support subsequent development of IPM system guidelines and standards:
 - Equipment specifications addressing the illumination source, housing and lens, power source, system controller and enclosure;
 - Operational specifications addressing system activation, marker color, marker flash rates, and chase sequences;
 - Installation methods including system layout and spacing;
 - Maintenance requirements;
 - Human factors (e.g., effects of glare and comprehension); and
 - Safety (e.g., overdriving and collision with nonilluminated objects).
- Development of an Internet-based clearinghouse could support exchange of practical information (e.g., installation lessons learned, annual maintenance costs, and

warranty recommendations) regarding IPM system use among public agencies.

Standards and Guidelines

- An expanded breadth and depth of coverage of IPM systems within the *MUTCD* is encouraged. The breadth of IPM system application and subsequent function suggests a similar required breadth in related standards and guidelines.
- Warrants are likely not required or appropriate for IPM systems; IPM systems typically supplement existing traffic control treatments and/or devices.
- Methods to describe the relationship between IPM systems and other ITS devices and systems and promote their use within ITS architectures and planning efforts could be beneficial in encouraging implementation. These methods could consider how IPM systems would interface with communications protocols and other equipment, and how they could provide feedback to transportation system operators to report operational status.

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GLOSSARY

Addressable chip: A computer chip added to a device to allow a computer system to identify, locate, or control that device directly.

Ambient light: Total illumination of an area without additional lighting sources.

Aperture angle: The angle indicating the width of a light beam.

Bidirectional: An undivided roadway with two opposing directions of travel. A device with two faces such that the desired effect of the device is obtained with each face (i.e., a retroreflective pavement marker).

Bollard: A thick post.

Candela (cd): Basic unit of luminous intensity.

Centerline: The pavement marking line that bisects two opposing directions of travel.

Cone of vision: A person's field of view. A driver's lateral vision, typically adequate up to 20 degrees on each side.

Delineation: Pavement markings separating adjacent lanes of traffic.

Diode: An electronic device that restricts current flow.

Edgeline: A pavement marking line on the right side of the right lane.

Electroluminescence: Direct conversion of electrical energy to light by a solid phosphor subjected to an alternating electric field.

Flashing crosswalk: Pedestrian crosswalk with in-pavement markers installed to provide additional warning.

Guide: Something that serves to direct or indicate.

Halogen lamp: A tungsten filament enclosed in a quartz pocket with halogen gas surrounding it.

Illuminate: To provide or brighten with light.

Incandescent bulb: A bulb with a tungsten filament that, when heated substantially, emits light.

In-pavement markers (IPM): An object that is placed inside (buried in) or on the surface of the pavement to provide guidance to road users.

In-roadway lights: Defined in the *MUTCD* as "... special types of highway traffic signals installed in the roadway surface to warn road users that they are approaching a condition on or adjacent to the roadway that might not be readily apparent and might require the road users to slow down and/or come to a stop. This includes, but is not necessarily limited to, situations warning of marked school crosswalks, marked midblock crosswalks, marked crosswalks on uncontrolled approaches, marked crosswalks in advance of roundabout intersections ..."

Inside lane: The furthest left lane of a group of adjacent lanes with the same direction of travel.

Lane line: A pavement marking that delineates a line between two adjacent lanes with the same directions of travel.

Laser beam: Highly amplified and coherent radiation of one or more discrete frequencies of light focused into a straight line.

Light-emitting diode (LED) source: Diode in which light emitted at a p-n junction is proportional to the bias current; color depends on the material used.

Luminance level: The intensity of light per unit area of its source.

Luminous intensity: Level of which light is emitted from a source. It is a measure of the wavelength-weighted power emitted by a light source in a particular direction.

Manual activation: A method of device activation in which a human turns on a switch.

Mid-block, uncontrolled crosswalk: A crosswalk not at a roadway intersection and without a stop sign or traffic signal at the crosswalk.

NEC: National Electrical Code. A standard for the safe installation of electrical wiring.

Outside lane: The furthest right lane of a group of adjacent lanes with the same direction of travel.

Passive detection/activation: A method of device activation in which a human does not turn on a switch, but something else activates the device.

Pavement marking: Paint, retroreflective pavement markers, in-pavement markers, or other raised pavement markers used on a roadway.

Photoelectric: Affected by a light source.

Regulate: To control or direct using a set of rules typically enforced by a government agency.

Respondents: Participants who replied to the survey administered.

Retroreflective pavement marker (RRPM): An object with a surface that reflects the light of a vehicle's headlight back to the source, which is placed on a pavement surface.

Road user: A motor vehicle operator, bicycle rider, pedestrian, or person utilizing another personal mode of travel who is using a roadway system.

Unidirectional: An object, marking, or device that faces only one way.

Warn: To signal prudence or a danger.

APPENDIX A

Survey Questionnaire

Survey Response Sequence

Question 1—Answered once by each respondent

Question 2—Answered once by each respondent

For each “yes” in Question 2, each respondent will be led through the following sequence of questions (*):

Affirmative Application 1 (e.g., intersection stop bars)

Location #1:

- Facility characteristics questions
- Technology type and characteristics questions
- Installation and construction methods questions
- Operation questions
- Maintenance questions
- Costs questions
- Benefits questions

*Each question is coded with question number, application type, and location number. For example, 2—ISB1 is the second question related to intersection stop bars at location 1.

Location #2 (and every subsequent location):

- Facility characteristics questions (same)
- Technology type and characteristics questions (same)
- Installation and construction methods questions (same)
- Operation questions (same)
- Maintenance questions (same)
- Costs questions (same)
- Benefits questions (same)

Affirmative Application 2 (e.g., multiple-turn lanes)

Location #1 (*):

- Facility characteristics questions
- Technology type and characteristics questions
- Installation and construction methods questions
- Operation questions
- Maintenance questions
- Costs questions
- Benefits questions

*As currently drafted, question sets above would be defined a little differently for each of the application types. Many of the questions may be modified to be more generic and standard across application types; facility characteristics will likely have to include some distinct questions by application.

Location #2 (and every subsequent location)

- Facility characteristics questions (same)
- Technology type and characteristics questions (same)
- Installation and construction methods questions (same)
- Operation questions (same)
- Maintenance questions (same)
- Costs questions (same)
- Benefits questions (same)

Process is repeated until information is gathered for each affirmative application type and unique location.

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM SYNTHESIS OF HIGHWAY PRACTICE 38-13

ILLUMINATED, ACTIVE, IN-PAVEMENT MARKER SYSTEMS

SURVEY QUESTIONNAIRE

Several different types of illuminated pavement markers exist and there are numerous ways to install and operate them. These devices are currently being used to guide, warn, and regulate road users with the intention of improving safety, operations, and visibility of both the roadway and regulatory devices. Although they may be installed in any number of surfaces, this investigation will focus on actively operated, illuminated markers installed on a pavement or roadway barrier surface (i.e., concrete barrier).

Illuminated, active, in-pavement marker systems (IPMs) can be useful tools for providing guidance and warning to road users, but not all transportation professionals know the best practice for installing, activating, and using them. Consequently, the National Cooperative Highway Research Council (NCHRP), as part of its synthesis series (Project 20-5, Topic 38-13), is conducting this survey to identify and summarize the state of the practice of illuminated, active, in-pavement marker systems (IPMs).

TELL US ABOUT YOURSELF

Name: _____
 Title: _____
 Agency: _____
 Division: _____
 City: _____
 Street Address: _____
 State: _____
 Zip Code: _____
 Telephone: _____
 Fax: _____
 E-mail: _____

1. Is there anyone else, either within your agency or in another agency or jurisdiction, who is actively using illuminated, active in-pavement marker systems that we should contact?

☐ Yes ☐ No

If yes, please provide contact information. _____

TELL US ABOUT THE USE OF ILLUMINATED, ACTIVE IN-PAVEMENT MARKER SYSTEMS IN YOUR <STATE> <LOCALE>

2. In your <state> <locale>, have illuminated, active in-pavement marker systems been used at any of the following locations? (Check all that apply.)

<input type="checkbox"/> Yes	<input type="checkbox"/> No	Intersection stop bars
<input type="checkbox"/> Yes	<input type="checkbox"/> No	Multiple-turn lanes
<input type="checkbox"/> Yes	<input type="checkbox"/> No	Merging areas
<input type="checkbox"/> Yes	<input type="checkbox"/> No	Freight rail/light rail crossings or guideways
<input type="checkbox"/> Yes	<input type="checkbox"/> No	Truck inspection points
<input type="checkbox"/> Yes	<input type="checkbox"/> No	Tunnels
<input type="checkbox"/> Yes	<input type="checkbox"/> No	Curves
<input type="checkbox"/> Yes	<input type="checkbox"/> No	Restricted/emergency use lanes
<input type="checkbox"/> Yes	<input type="checkbox"/> No	Variable-width lanes (e.g., narrowing lane widths to increase capacity)
<input type="checkbox"/> Yes	<input type="checkbox"/> No	Adverse weather areas
<input type="checkbox"/> Yes	<input type="checkbox"/> No	Construction zones
<input type="checkbox"/> Yes	<input type="checkbox"/> No	Environmentally sensitive areas (e.g., replacing or supplementing street lighting)
<input type="checkbox"/> Yes	<input type="checkbox"/> No	Other _____

For each “yes” indicated above and each unique location of installation, respondents will be asked to complete the following set of questions related to facility characteristics, technology type and characteristics, installation/construction methods, operation, maintenance, costs, and benefits.

INTERSECTION STOP BARS

You have indicated that IPMs have been used at intersection stop bars in your <state> <locale>. You will have the opportunity to describe each of the intersection stop bars in your <state> <locale> equipped with IPMs. Considering one location at a time, please provide the following information.

Location #1

Facility Characteristics

1. ISB1 Can you provide a brief description of the intersection stop-bar location (i.e., street name, street intersection, city, etc.)?
2. ISB1 Is the roadway facility constructed of ☐ concrete or ☐ asphalt at the intersection stop-bar location?
3. ISB1 How many total intersection legs exist at the intersection stop-bar location?
4. ISB1 How many intersection legs are equipped with IPMs?
5. ISB1 How many approach lanes exist at the intersection stop-bar location?
6. ISB1 What is the average approach volume for the roadway at the intersection stop-bar location?
7. ISB1 What is the posted speed limit for the roadway at the intersection stop-bar location?
8. ISB1 When was the application deployed and activated?
9. ISB1 Is the IPM still active? If not, when was it removed or deactivated?

Technology Type and Characteristics

10. ISB1 Who is the manufacturer of the IPM at this location?
11. ISB1 What is the size/shape of the individual markers?
12. ISB1 Is the method of illumination ☐ LED or ☐ other?
13. ISB1 What is the illumination output or angle?
14. ISB1 What marker colors are used? ☐ White ☐ Green ☐ Red ☐ Blue ☐ Yellow ☐ Other
15. ISB1 Are the colors ☐ static or ☐ dynamically sequenced?
16. ISB1 Is the ☐ illumination static or ☐ flashing? If flashing, what flash rate is used?
17. ISB1 If multiple rows of pavement markers were used, was the layout aligned (:::) or alternating (.:.)?
18. ISB1 Is the power source ☐ solar, ☐ hardwired, or ☐ battery only?
19. ISB1 Is the communication method ☐ wireline or ☐ wireless?
20. ISB1 What is the age of the technology?
21. ISB1 Are the markers mounted ☐ in-ground, top flush with the pavement, ☐ protruding from the surface of the pavement, or ☐ other?

Installation and Construction Methods

22. ISB1 When first installing the IPM at this location, did you follow any design standards and specifications (i.e., *MUTCD*), special provisions, standard drawings/details, or supplemental policies and guidance? ☐ Yes ☐ No
If yes, may we get a copy?
23. ISB1 Was the wiring placed using ☐ underground conduit, ☐ pavement saw cut, or ☐ other?
24. ISB1 In your opinion, do you think that the installation and construction methods used were adequate to ensure successful system performance? ☐ Yes ☐ No
If no, please explain.

Operation

25. ISB1 Is the IPM at this location operated ☐ on-demand, ☐ during the daytime only, ☐ during the nighttime only, ☐ continuously, or ☐ other?
26. ISB1 What is the method of activation? ☐ Passive detection (e.g., microwave, motion sensors, video detection, light trip beam) ☐ Activation by RWIS or speed sensors ☐ Integration with traffic control devices ☐ Other
27. ISB1 Does the IPM provide or supplement a regulatory function? ☐ Yes ☐ No
If yes, are violations of the IPM actively enforced? ☐ Yes ☐ No

Maintenance

28. ISB1 Which, if any, type(s) of failure did you experience with the IPM at this location? ☐ Individual LED failure ☐ Cracking
☐ Marker came free from pavement ☐ Flicker/loose connection ☐ Power system ☐ No failures
29. ISB1 What are the measured failure rates (if available) for the IPM at this location?
30. ISB1 What is the method of notification if a failure is detected? ☐ Automatic feedback from the IPM ☐ Public input
☐ Observation/inspection by your agency ☐ Other
31. ISB1 In your opinion, how would you rate the durability of the IPM at this location? ☐ Very good ☐ Good ☐ Neutral ☐ Poor
☐ Very poor
32. ISB1 In your opinion, how would you rate the adhesion of the IPM at this location? ☐ Very good ☐ Good ☐ Neutral ☐ Poor
☐ Very poor
33. ISB1 Please describe any other maintenance issues related to the IPM at this location.

Costs

34. ISB1 What were the initial costs of the IPM at this location including hardware and installation?
35. ISB1 What are the ongoing annual costs of the IPM at this location including operation and maintenance?

Benefits

36. ISB1 In your opinion, has the IPM at this location improved the operation of the facility? ☐ Yes ☐ No
37. ISB1 Has the IPM at this location resulted in any unexpected operational challenges? ☐ Yes ☐ No
If yes, please describe?
38. ISB1 Have these unexpected changes in operations been formally measured and/or documented in an evaluation report?
☐ Yes ☐ No
If yes, may we get a copy?
39. ISB1 In your opinion, has the IPM at this location improved the safety of the facility? ☐ Yes ☐ No
40. ISB1 Has the IPM at this location resulted in any unexpected safety challenges (i.e., sudden braking, changes in crash patterns or types)? ☐ Yes ☐ No
If yes, please describe?
41. ISB1 Have these suspected changes in safety been formally measured and/or documented in an evaluation report?
☐ Yes ☐ No
If yes, may we get a copy?
42. ISB1 Has improper activation of the IPM at this location posed any challenges?

Is there another intersection stop-bar location that you'd like to describe?

If yes, respondent is returned to Question 1. ISB1 (which is now 1. ISB2 for location 2) under Facility Characteristics and asked to complete all 42 questions for the second location. If no, respondent is directed to a set of similar questions for new application type.

MULTIPLE-TURN LANES

You have indicated that illuminated, active in-pavement marker systems have been used at multiple-turn lane locations in your <state> <locale>. You will have the opportunity to describe each of the multiple-turn lane locations in your <state> <locale> equipped with illuminated, active in-pavement marker systems. Considering one location at a time, please provide the following information.

Location #1

Facility Characteristics

1. MTL1 Can you provide a brief description of the multiple-turn lane location (i.e., street name, street intersection, city, etc.)?
2. MTL1 Is the roadway facility constructed of ☐ concrete or ☐ asphalt at the multiple-turn lane location?
3. MTL1 How many multiple-turn lanes exist at this location?
4. MTL1 Is the turning movement to the ☐ left or to the ☐ right?
5. MTL1 What is the lane width in feet at the multiple-turn lane location?
6. MTL1 What is the average approach volume for the roadway at the multiple-turn lane location?
7. MTL1 What is the posted speed limit for the roadway at the multiple-turn lane location?

Technology Type and Characteristics

8. MTL1 Who is the manufacturer of the illuminated, active in-pavement marker system at this location?
9. MTL1 What is the size/shape of the individual markers?
10. MTL1 Is the method of illumination ☐ LED or ☐ other?
11. MTL1 What is the illumination output or angle?
12. MTL1 What marker colors are used? ☐ White ☐ Green ☐ Red ☐ Blue ☐ Yellow ☐ Other
13. MTL1 Are the colors ☐ static or ☐ dynamically sequenced?
14. MTL1 Is the ☐ illumination static or ☐ flashing? If flashing, what flash rate is used?
15. MTL1 If multiple rows of pavement markers were used, was the layout aligned (:::) or alternating (.:.)?
16. MTL1 Is the power source ☐ solar, ☐ wired, or ☐ battery only?
17. MTL1 Is the communications method ☐ wireline or ☐ wireless?
18. MTL1 What is the age of the technology?
19. MTL1 Are the markers mounted ☐ in-ground flush with the pavement, ☐ on the surface of the pavement, or ☐ other?

Installation and Construction Methods

20. MTL1 When first installing the illuminated, active in-pavement marker system at this location, did you follow any design standards and specifications (i.e., *MUTCD*), special provisions, standard drawings/details, supplemental policies and guidance? ☐ Yes ☐ No
If yes, may we get a copy?
21. MTL1 Was the wiring placed using ☐ underground conduit, ☐ pavement saw cut, or ☐ other?
22. MTL1 In your opinion, do you feel that the installation and construction methods used were adequate to ensure successful system performance?

Operation

23. MTL1 Is the illuminated, active in-pavement marker system at this location operated ☐ on-demand, ☐ during the daytime only, ☐ during the nighttime only, ☐ continuously, or ☐ other?
24. MTL1 What is the method of activation? ☐ Passive detection (e.g., microwave, motion sensors, video detection, light trip beam)
☐ Activation by RWIS or speed sensors ☐ Integration with traffic control devices ☐ Other
25. MTL1 Is this location actively enforced? ☐ Yes ☐ No

Maintenance

26. MTL1 Which, if any, type(s) of failure did you experience with the illuminated, active in-pavement marker system at this location? ☐ Individual LED failure ☐ Cracking ☐ Marker came free from pavement ☐ Flicker/loose connection
☐ Power system
27. MTL1 What are the measured failure rates (if available) for the illuminated, active in-pavement marker system at this location?
28. MTL1 Describe the method of notification if a failure is detected?
29. MTL1 In your opinion, how would you rate the durability of the illuminated, active in-pavement marker system at this location?
☐ Very good ☐ Good ☐ Neutral ☐ Poor ☐ Very poor
30. MTL1 In your opinion, how would you rate the adhesion of the illuminated, active in-pavement marker system at this location?
☐ Very good ☐ Good ☐ Neutral ☐ Poor ☐ Very poor
31. MTL1 Please describe any other maintenance issues related to the illuminated, active in-pavement marker system at this location.

Costs

32. MTL1 What were the initial costs of the illuminated, active in-pavement marker system at this location, including hardware and installation?
33. MTL1 What are the ongoing annual costs of the illuminated, active in-pavement marker system at this location, including operation and maintenance?

Benefits

34. MTL1 In your opinion, has the illuminated, active in-pavement marker system at this location improved the operation of the facility? ☐ Yes ☐ No
35. MTL1 Has the illuminated, active in-pavement marker system at this location resulted in any unexpected operational challenges?
☐ Yes ☐ No
If yes, please describe?

36. MTL1 Have these suspected changes in operations been formally measured and/or documented in an evaluation report?
☐ Yes ☐ No
 If yes, may we get a copy?
37. MTL1 In your opinion, has the illuminated, active in-pavement marker system at this location improved the safety of the facility? ☐ Yes ☐ No
38. MTL1 Has the illuminated, active in-pavement marker system at this location resulted in any unexpected safety challenges (i.e., sudden braking)? ☐ Yes ☐ No
 If yes, please describe?
39. MTL1 Have these suspected changes in safety been formally measured and/or documented in an evaluation report?
☐ Yes ☐ No
 If yes, may we get a copy?
40. MTL1 Has improper activation of the illuminated, active in-pavement marker system at this location posed any challenges?

Is there another multiple-turn lane location that you would like to describe?

If yes, respondent is returned to Question 1. MTL1 (which is now 1. MTL2 for location 2) under Facility Characteristics and asked to complete all 40 questions for the second location. If no, respondent is directed to set of similar questions for new application type.

MERGING AREAS

You have indicated that illuminated, active in-pavement marker systems have been used at merging areas in your <state> <locale>. You will have the opportunity to describe each of the merging areas in your <state> <locale> equipped with illuminated, active in-pavement marker systems. Considering one location at a time, please provide the following information.

Location #1

Facility Characteristics

1. MA1 Can you provide a brief description of the merging area location (i.e., entrance/exit ramp, interchange, city, etc.)?
2. MA1 Is the roadway facility constructed of ☐ concrete or ☐ asphalt at the merging area location?
3. MA1 How many total roadway lanes (including both directions) exist at the merging area location?
4. MA1 What is the total length of the merging area in feet?
5. MA1 What is the average annual daily traffic (AADT) for the roadway at the merging area location?
6. MA1 Is the primary merging activity to the ☐ left, ☐ right, or ☐ both?
7. MA1 What is the posted speed limit for the roadway at the merging area location?

Technology Type and Characteristics

8. MA1 Who is the manufacturer of the illuminated, active in-pavement marker system at this location?
9. MA1 What is the size/shape of the individual markers?
10. MA1 Is the method of illumination ☐ LED or ☐ other?
11. MA1 What is the illumination output or angle?
12. MA1 What marker colors are used? ☐ White ☐ Green ☐ Red ☐ Blue ☐ Yellow ☐ Other
13. MA1 Are the colors ☐ static or ☐ dynamically sequenced?
14. MA1 Is the illumination ☐ static or ☐ flashing? If flashing, what flash rate is used?
15. MA1 If multiple rows of pavement markers were used, was the layout aligned (:::) or alternating (···)?
16. MA1 Is the power source ☐ solar, ☐ wired, or ☐ battery only?
17. MA1 Is the communications method ☐ wireline or ☐ wireless?
18. MA1 What is the age of the technology?
19. MA1 Are the markers mounted ☐ in-ground flush with the pavement, ☐ on the surface of the pavement, or ☐ other?

Installation and Construction Methods

20. MA1 When first installing the illuminated, active in-pavement marker system at this location, did you follow any design standards and specifications (i.e., *MUTCD*), special provisions, standard drawings/details, or supplemental policies and guidance? ☐ Yes ☐ No
 If yes, may we get a copy?
21. MA1 Was the wiring run using ☐ underground conduit, ☐ pavement saw cut, or ☐ other?

22. MA1 In your opinion, do you think that the installation and construction methods used were adequate to ensure successful system performance?

Operation

23. MA1 Is the illuminated, active in-pavement marker system at this location operated ☐ on-demand, ☐ during the daytime only, ☐ during the nighttime only, ☐ continuously, or ☐ other?
24. MA1 What is the method of activation? ☐ Passive detection (e.g., microwave, motion sensors, video detection, light trip beam) ☐ Activation by RWIS or speed sensors ☐ Integration with traffic control devices ☐ Other
25. MA1 Is this location actively enforced? ☐ Yes ☐ No

Maintenance

26. MA1 Which, if any, type(s) of failure did you experience with the illuminated, active in-pavement marker system at this location? ☐ Individual LED failure ☐ Cracking ☐ Marker came free from pavement, ☐ Flicker/loose connection ☐ Power system
27. MA1 What are the measured failure rates (if available) for the illuminated, active in-pavement marker system at this location?
28. MA1 Describe the method of notification if a failure is detected?
29. MA1 In your opinion, how would you rate the durability of the illuminated, active in-pavement marker system at this location? ☐ Very good ☐ Good ☐ Neutral ☐ Poor ☐ Very poor
30. MA1 In your opinion, how would you rate the adhesion of the illuminated, active in-pavement marker system at this location? ☐ Very good ☐ Good ☐ Neutral ☐ Poor ☐ Very poor
31. MA1 Please describe any other maintenance issues related to the illuminated, active in-pavement marker system at this location.

Costs

32. MA1 What were the initial costs of the illuminated, active in-pavement marker system at this location, including hardware and installation?
33. MA1 What are the ongoing annual costs of the illuminated, active in-pavement marker system at this location, including operation and maintenance?

Benefits

34. MA1 In your opinion, has the illuminated, active in-pavement marker system at this location improved the operation of the facility? ☐ Yes ☐ No
35. MA1 Has the illuminated, active in-pavement marker system at this location resulted in any unexpected operational challenges? ☐ Yes ☐ No
If yes, please describe?
36. MA1 Have these suspected changes in operations been formally measured and/or documented in an evaluation report? ☐ Yes ☐ No
If yes, may we get a copy?
37. MA1 In your opinion, has the illuminated, active in-pavement marker system at this location improved the safety of the facility? ☐ Yes ☐ No
38. MA1 Has the illuminated, active in-pavement marker system at this location resulted in any unexpected safety challenges (i.e., sudden braking)? ☐ Yes ☐ No
If yes, please describe?
39. MA1 Have these suspected changes in safety been formally measured and/or documented in an evaluation report? ☐ Yes ☐ No
If yes, may we get a copy?
40. MA1 Has improper activation of the illuminated, active in-pavement marker system at this location posed any challenges?

Is there another merging area location that you would like to describe?

If yes, respondent is returned to Question 1. MA1 (which is now 1. MA2 for location 2) under Facility Characteristics and asked to complete all 40 questions for the second location. If no, respondent is directed to set of similar questions for new application type.

RAIL CROSSING OR RAIL GUIDEWAY

You have indicated that illuminated, active in-pavement marker systems have been used at rail crossing locations in your <state> <locale>. You will have the opportunity to describe each of the rail crossing locations in your <state> <locale> equipped with illuminated, active in-pavement marker systems. Considering one location at a time, please provide the following information.

Location #1**Facility Characteristics**

1. RC1 Can you provide a brief description of the rail crossing or guideway location (i.e., street name, street intersection, city, etc.)?
2. RC1 Is the roadway facility constructed of ☐ concrete or ☐ asphalt at the rail crossing or guideway location?
3. RC1 How many total roadway lanes (including both directions) exist at the rail crossing or guideway location?
4. RC1 What is the total length of the rail crossing (i.e., width of roadway including lane, shoulder, and median widths) or rail guideway in feet?
5. RC1 What is the average annual daily traffic (AADT) for the roadway at the rail crossing or guideway location?
6. RC1 What is the train volume for this crossing or guideway location?
7. RC1 What is the posted speed limit for the roadway at the rail crossing or guideway location?

Technology Type and Characteristics

8. RC1 Who is the manufacturer of the illuminated, active in-pavement marker system at this location?
9. RC1 What is the size/shape of the individual markers?
10. RC1 Is the method of illumination ☐ LED or ☐ other?
11. RC1 What is the illumination output or angle?
12. RC1 What marker colors are used? ☐ White ☐ Green ☐ Red ☐ Blue ☐ Yellow ☐ Other
13. RC1 Are the colors ☐ static or ☐ dynamically sequenced?
14. RC1 Is the illumination ☐ static or ☐ flashing? If flashing, what flash rate is used?
15. RC1 If multiple rows of pavement markers were used, was the layout aligned (:::) or alternating (.:.)?
16. RC1 Is the power source ☐ solar, ☐ wired, or ☐ battery only?
17. RC1 Is the communications method ☐ wireline or ☐ wireless?
18. RC1 What is the age of the technology?
19. RC1 Are the markers mounted ☐ in-ground flush with the pavement, ☐ on the surface of the pavement, or ☐ other?

Installation and Construction Methods

20. RC1 When first installing the illuminated, active in-pavement marker system at this location, did you follow any design standards and specifications (i.e., *MUTCD*), special provisions, standard drawings/details, or supplemental policies and guidance? ☐ Yes ☐ No
If yes, may we get a copy?
21. RC1 Was the wiring run using ☐ underground conduit, ☐ pavement saw cut, or ☐ other?
22. RC1 In your opinion, do you think that the installation and construction methods used were adequate to ensure successful system performance?

Operation

23. RC1 Is the illuminated, active in-pavement marker system at this location operated ☐ on-demand, ☐ during the daytime only, ☐ during the nighttime only, ☐ continuously, or ☐ other?
24. RC1 What is the method of activation? ☐ Passive detection (e.g., microwave, motion sensors, video detection, light trip beam) ☐ RWIS or speed sensors ☐ Integration with traffic control devices ☐ Other
25. RC1 Is this location actively enforced? ☐ Yes ☐ No

Maintenance

26. RC1 Which, if any, type(s) of failure did you experience with the illuminated, active in-pavement marker system at this location? ☐ Individual LED failure ☐ Cracking ☐ Marker came free from pavement ☐ Flicker/loose connection ☐ Power system
27. RC1 What are the measured failure rates (if available) for the illuminated, active in-pavement marker system at this location?
28. RC1 Describe the method of notification if a failure is detected?
29. RC1 In your opinion, how would you rate the durability of the illuminated, active in-pavement marker system at this location? ☐ Very good ☐ Good ☐ Neutral ☐ Poor ☐ Very poor
30. RC1 In your opinion, how would you rate the adhesion of the illuminated, active in-pavement marker system at this location? ☐ Very good ☐ Good ☐ Neutral ☐ Poor ☐ Very poor
31. RC1 Please describe any other maintenance issues related to the illuminated, active in-pavement marker system at this location.

Costs

32. RC1 What were the initial costs of the illuminated, active in-pavement marker system at this location, including hardware and installation?
33. RC1 What are the ongoing annual costs of the illuminated, active in-pavement marker system at this location, including operation and maintenance?

Benefits

34. RC1 In your opinion, has the illuminated, active in-pavement marker system at this location improved the operation of the facility?
☐ Yes ☐ No
35. RC1 Has the illuminated, active in-pavement marker system at this location resulted in any unexpected operational challenges?
☐ Yes ☐ No
If yes, please describe?
36. RC1 Have these suspected changes in operations been formally measured and/or documented in an evaluation report?
☐ Yes ☐ No
If yes, may we get a copy?
37. RC1 In your opinion, has the illuminated, active in-pavement marker system at this location improved the safety of the facility?
☐ Yes ☐ No
38. RC1 Has the illuminated, active in-pavement marker system at this location resulted in any unexpected safety challenges (i.e., sudden braking)? ☐ Yes ☐ No
If yes, please describe?
39. RC1 Have these suspected changes in safety been formally measured and/or documented in an evaluation report? ☐ Yes ☐ No
If yes, may we get a copy?
40. RC1 Has improper activation of the illuminated, active in-pavement marker system at this location posed any challenges?

Is there another rail crossing location that you would like to describe?

If yes, respondent is returned to Question 1. RC1 (which is now 1 RC2 for location 2) under Facility Characteristics and asked to complete all 40 questions for the second location. If no, respondent is directed to set of similar questions for new application type.

TRUCK INSPECTION POINTS

You have indicated that illuminated, active in-pavement marker systems have been used at truck inspection points in your <state> <locale>. You will have the opportunity to describe each of the truck inspection points in your <state> <locale> equipped with illuminated, active in-pavement marker systems. Considering one location at a time, please provide the following information.

Location #1

Facility Characteristics

1. TIP1 Can you provide a brief description of the truck inspection location (i.e., interchange, city, etc.)?
2. TIP1 Is the roadway facility constructed of ☐ concrete or ☐ asphalt at the truck inspection location?
3. TIP1 How many total roadway lanes (including both directions) exist at the truck inspection location?
4. TIP1 What is the total length of the truck inspection area in feet?
5. TIP1 What is the average annual daily traffic (AADT) for the roadway at the truck inspection location?
6. TIP1 What is the truck volume at this location?
7. TIP1 What is the posted speed limit for the roadway at the truck inspection location?

Technology Type and Characteristics

8. TIP1 Who is the manufacturer of the illuminated, active in-pavement marker system at this location?
9. TIP1 What is the size/shape of the individual markers?
10. TIP1 Is the method of illumination ☐ LED or ☐ other?
11. TIP1 What is the illumination output or angle?
12. TIP1 What marker colors are used? ☐ White ☐ Green ☐ Red ☐ Blue ☐ Yellow ☐ Other
13. TIP1 Are the colors ☐ static or ☐ dynamically sequenced?
14. TIP1 Is the illumination ☐ static or ☐ flashing? If flashing, what flash rate is used?
15. TIP1 If multiple rows of pavement markers were used, was the layout aligned (:::) or alternating (.:.)?
16. TIP1 Is the power source ☐ solar, ☐ wired, or ☐ battery only?
17. TIP1 Is the communications method ☐ wireline or ☐ wireless?

18. TIP1 What is the age of the technology?
 19. TIP1 Are the markers mounted ☐ in-ground flush with the pavement, ☐ on the surface of the pavement or ☐ other?

Installation and Construction Methods

20. TIP1 When first installing the illuminated, active in-pavement marker system at this location, did you follow any design standards and specifications (i.e., *MUTCD*), special provisions, standard drawings/details, or supplemental policies and guidance? ☐ Yes ☐ No
 If yes, may we get a copy?
 21. TIP1 Was the wiring run using ☐ underground conduit, ☐ pavement saw cut, or ☐ other?
 22. TIP1 In your opinion, do you think that the installation and construction methods used were adequate to ensure successful system performance?

Operation

23. TIP1 Is the illuminated, active in-pavement marker system at this location operated ☐ on-demand, ☐ during the daytime only, ☐ during the nighttime only, ☐ continuously, or ☐ other?
 24. TIP1 What is the method of activation? ☐ Passive detection (e.g., microwave, motion sensors, video detection, light trip beam) ☐ RWIS or speed sensors ☐ Integration with traffic control devices ☐ Other
 25. TIP1 Is this location actively enforced? ☐ Yes ☐ No

Maintenance

26. TIP1 Which, if any, type(s) of failure did you experience with the illuminated, active in-pavement marker system at this location?
☐ Individual LED failure ☐ Cracking ☐ Marker came free from pavement ☐ Flicker/loose connection ☐ Power system
 27. TIP1 What are the measured failure rates (if available) for the illuminated, active in-pavement marker system at this location?
 28. TIP1 Describe the method of notification if a failure is detected?
 29. TIP1 In your opinion, how would you rate the durability of the illuminated, active in-pavement marker system at this location?
☐ Very good ☐ Good ☐ Neutral ☐ Poor ☐ Very poor
 30. TIP1 In your opinion, how would you rate the adhesion of the illuminated, active in-pavement marker system at this location?
☐ Very good ☐ Good ☐ Neutral ☐ Poor ☐ Very poor
 31. TIP1 Please describe any other maintenance issues related to the illuminated, active in-pavement marker system at this location.

Costs

32. TIP1 What were the initial costs of the illuminated, active in-pavement marker system at this location, including hardware and installation?
 33. TIP1 What are the ongoing annual costs of the illuminated, active in-pavement marker system at this location, including operation and maintenance?

Benefits

34. TIP1 In your opinion, has the illuminated, active in-pavement marker system at this location improved the operation of the facility? ☐ Yes ☐ No
 35. TIP1 Has the illuminated, active in-pavement marker system at this location resulted in any unexpected operational challenges?
☐ Yes ☐ No
 If yes, please describe?
 36. TIP1 Have these suspected changes in operations been formally measured and/or documented in an evaluation report?
☐ Yes ☐ No
 If yes, may we get a copy?
 37. TIP1 In your opinion, has the illuminated, active in-pavement marker system at this location improved the safety of the facility?
☐ Yes ☐ No
 38. TIP1 Has the illuminated, active in-pavement marker system at this location resulted in any unexpected safety challenges (i.e., sudden braking)? ☐ Yes ☐ No
 If yes, please describe?
 39. TIP1 Have these suspected changes in safety been formally measured and/or documented in an evaluation report? ☐ Yes ☐ No
 If yes, may we get a copy?
 40. TIP1 Has improper activation of the illuminated, active in-pavement marker system at this location posed any challenges?

Is there another truck inspection point location that you would like to describe?

If yes, respondent is returned to *Question 1. TIP1* (which is now *1. TIP2* for location 2) under *Facility Characteristics* and asked to complete all 40 questions for the second location. If no, respondent is directed to set of similar questions for new application type.

TUNNELS

You have indicated that illuminated, active in-pavement marker systems have been used for tunnels in your <state> <locale>. You will have the opportunity to describe each of the tunnels in your <state> <locale> equipped with illuminated, active in-pavement marker systems. Considering one location at a time, please provide the following information.

Location #1

Facility Characteristics

1. T1 Can you provide a brief description of the tunnel location (i.e., tunnel name, intersection, city, etc.)?
2. T1 Is the roadway facility constructed of ☐ concrete or ☐ asphalt at the tunnel location?
3. T1 How many total roadway lanes (including both directions) exist at the tunnel location?
4. T1 What is the total length of the tunnel in feet?
5. T1 What is the average annual daily traffic (AADT) for the roadway at the tunnel location?
6. T1 What is the lane width in feet at the tunnel location?
7. T1 What is the posted speed limit for the roadway at the tunnel location?

Technology Type and Characteristics

8. T1 Who is the manufacturer of the illuminated, active in-pavement marker system at this location?
9. T1 What is the size/shape of the individual markers?
10. T1 Is the method of illumination ☐ LED or ☐ other?
11. T1 What is the illumination output or angle?
12. T1 What marker colors are used? ☐ White ☐ Green ☐ Red ☐ Blue ☐ Yellow ☐ Other
13. T1 Are the colors ☐ static or ☐ dynamically sequenced?
14. T1 Is the illumination ☐ static or ☐ flashing? If flashing, what flash rate is used?
15. T1 If multiple rows of pavement markers were used, was the layout aligned (:::) or alternating (.:.)?
16. T1 Is the power source ☐ solar, ☐ wired, or ☐ battery only?
17. T1 Is the communications method ☐ wireline or ☐ wireless?
18. T1 What is the age of the technology?
19. T1 Are the markers mounted ☐ in-ground flush with the pavement, ☐ on the surface of the pavement, or ☐ other?

Installation and Construction Methods

20. T1 When first installing the illuminated, active in-pavement marker system at this location, did you follow any design standards and specifications (i.e., *MUTCD*), special provisions, standard drawings/details, or supplemental policies and guidance?
☐ Yes ☐ No
If yes, may we get a copy?
21. T1 Was the wiring run using ☐ underground conduit, ☐ pavement saw cut, or ☐ other?
22. T1 In your opinion, do you think that the installation and construction methods used were adequate to ensure successful system performance?

Operation

23. T1 Is the illuminated, active in-pavement marker system at this location operated ☐ on-demand, ☐ during the daytime only, ☐ during the nighttime only, ☐ continuously, or ☐ other?
24. T1 What is the method of activation? ☐ Passive detection (e.g., microwave, motion sensors, video detection, light trip beam) ☐ RWIS or speed sensors, ☐ Integration with traffic control devices ☐ Other
25. T1 Is this location actively enforced? ☐ Yes ☐ No

Maintenance

26. T1 Which, if any, type(s) of failure did you experience with the illuminated, active in-pavement marker system at this location?
☐ Individual LED failure ☐ Cracking ☐ Marker came free from pavement ☐ Flicker/loose connection ☐ Power system
27. T1 What are the measured failure rates (if available) for the illuminated, active in-pavement marker system at this location?
28. T1 Describe the method of notification if a failure is detected?

29. T1 In your opinion, how would you rate the durability of the illuminated, active in-pavement marker system at this location?
☐ Very good ☐ Good ☐ Neutral ☐ Poor ☐ Very poor
30. T1 In your opinion, how would you rate the adhesion of the illuminated, active in-pavement marker system at this location?
☐ Very good ☐ Good ☐ Neutral ☐ Poor ☐ Very poor
31. T1 Please describe any other maintenance issues related to the illuminated, active in-pavement marker system at this location.

Costs

32. T1 What were the initial costs of the illuminated, active in-pavement marker system at this location, including hardware and installation?
33. T1 What are the ongoing annual costs of the illuminated, active in-pavement marker system at this location, including operation and maintenance?

Benefits

34. T1 In your opinion, has the illuminated, active in-pavement marker system at this location improved the operation of the facility?
☐ Yes ☐ No
35. T1 Has the illuminated, active in-pavement marker system at this location resulted in any unexpected operational challenges?
☐ Yes ☐ No
 If yes, please describe?
36. T1 Have these suspected changes in operations been formally measured and/or documented in an evaluation report? ☐ Yes ☐ No
 If yes, may we get a copy?
37. T1 In your opinion, has the illuminated, active in-pavement marker system at this location improved the safety of the facility?
☐ Yes ☐ No
38. T1 Has the illuminated, active in-pavement marker system at this location resulted in any unexpected safety challenges (i.e., sudden braking)? ☐ Yes ☐ No
 If yes, please describe?
39. T1 Have these suspected changes in safety been formally measured and/or documented in an evaluation report? ☐ Yes ☐ No
 If yes, may we get a copy?
40. T1 Has improper activation of the illuminated, active in-pavement marker system at this location posed any challenges?

Is there another tunnel location that you would like to describe?

If yes, respondent is returned to Question 1. T1 (which is now 1. T2 for location 2) under Facility Characteristics and asked to complete all 40 questions for the second location. If no, respondent is directed to set of similar questions for new application type.

CURVES

You have indicated that illuminated, active in-pavement marker systems have been used at curves in your <state> <locale>. You will have the opportunity to describe each of the curves in your <state> <locale> equipped with illuminated, active in-pavement marker systems. Considering one location at a time, please provide the following information.

Location #1

Facility Characteristics

1. C1 Can you provide a brief description of the curve location (i.e., roadway mile marker, city, etc.)?
2. C1 Is the roadway facility constructed of ☐ concrete or ☐ asphalt at the curve location?
3. C1 How many total roadway lanes (including both directions) exist at the curve location?
4. C1 What is the total length of the curve in feet?
5. C1 What is the degree of curvature of the curve?
6. C1 What is the average annual daily traffic (AADT) for the roadway at the curve location?
7. C1 What is the posted speed limit for the roadway at the curve location?

Technology Type and Characteristics

8. C1 Who is the manufacturer of the illuminated, active in-pavement marker system at this location?
9. C1 What is the size/shape of the individual markers?
10. C1 Is the method of illumination ☐ LED or ☐ other?
11. C1 What is the illumination output or angle?

12. C1 What marker colors are used? ☐ White ☐ Green ☐ Red ☐ Blue ☐ Yellow ☐ Other
13. C1 Are the colors ☐ static or ☐ dynamically sequenced?
14. C1 Is the illumination ☐ static or ☐ flashing? If flashing, what flash rate is used?
15. C1 If multiple rows of pavement markers were used, was the layout aligned (:::) or alternating (.:.)?
16. C1 Is the power source ☐ solar, ☐ wired, or ☐ battery only?
17. C1 Is the communications method ☐ wireline or ☐ wireless?
18. C1 What is the age of the technology?
19. C1 Are the markers mounted ☐ in-ground flush with the pavement, ☐ on the surface of the pavement, or ☐ other?

Installation and Construction Methods

20. C1 When first installing the illuminated, active in-pavement marker system at this location, did you follow any design standards and specifications (i.e., *MUTCD*), special provisions, standard drawings/details, or supplemental policies and guidance?
☐ Yes ☐ No
If yes, may we get a copy?
21. C1 Was the wiring run using ☐ underground conduit, ☐ pavement saw cut, or ☐ other?
22. C1 In your opinion, do you think that the installation and construction methods used were adequate to ensure successful system performance?

Operation

23. C1 Is the illuminated, active in-pavement marker system at this location operated ☐ on-demand, ☐ during the daytime only, ☐ during the nighttime only, ☐ continuously, or ☐ other?
24. C1 What is the method of activation? ☐ Passive detection (e.g., microwave, motion sensors, video detection, light trip beam), ☐ RWIS or speed sensors, ☐ Integration with traffic control devices, or ☐ Other
25. C1 Is this location actively enforced? ☐ Yes ☐ No

Maintenance

26. C1 Which, if any, type(s) of failure did you experience with the illuminated, active in-pavement marker system at this location?
☐ Individual LED failure ☐ Cracking ☐ Marker came free from pavement ☐ Flicker/loose connection ☐ Power system
27. C1 What are the measured failure rates (if available) for the illuminated, active in-pavement marker system at this location?
28. C1 Describe the method of notification if a failure is detected?
29. C1 In your opinion, how would you rate the durability of the illuminated, active in-pavement marker system at this location?
☐ Very good, ☐ Good ☐ Neutral ☐ Poor ☐ Very poor
30. C1 In your opinion, how would you rate the adhesion of the illuminated, active in-pavement marker system at this location?
☐ Very good ☐ Good ☐ Neutral ☐ Poor ☐ Very poor
31. C1 Please describe any other maintenance issues related to the illuminated, active in-pavement marker system at this location.

Costs

32. C1 What were the initial costs of the illuminated, active in-pavement marker system at this location, including hardware and installation?
33. C1 What are the ongoing annual costs of the illuminated, active in-pavement marker system at this location, including operation and maintenance?

Benefits

34. C1 In your opinion, has the illuminated, active in-pavement marker system at this location improved the operation of the facility? ☐ Yes ☐ No
35. C1 Has the illuminated, active in-pavement marker system at this location resulted in any unexpected operational challenges?
☐ Yes ☐ No
If yes, please describe?
36. C1 Have these suspected changes in operations been formally measured and/or documented in an evaluation report? ☐ Yes ☐ No
If yes, may we get a copy?
37. C1 In your opinion, has the illuminated, active in-pavement marker system at this location improved the safety of the facility?
☐ Yes ☐ No
38. C1 Has the illuminated, active in-pavement marker system at this location resulted in any unexpected safety challenges (i.e., sudden braking)? ☐ Yes ☐ No
If yes, please describe?

39. C1 Have these suspected changes in safety been formally measured and/or documented in an evaluation report? ☐ Yes ☐ No
If yes, may we get a copy?
40. C1 Has improper activation of the illuminated, active in-pavement marker system at this location posed any challenges?

Is there another curve location that you would like to describe?

If yes, respondent is returned to Question 1. C1 (which is now 1. C2 for location 2) under Facility Characteristics and asked to complete all 40 questions for the second location. If no, respondent is directed to set of similar questions for new application type.

RESTRICTED/EMERGENCY USE LANES

You have indicated that illuminated, active in-pavement marker systems have been used on restricted/emergency use lanes in your <state> <locale>. You will have the opportunity to describe each of the restricted/emergency use lanes in your <state> <locale> equipped with illuminated, active in-pavement marker systems. Considering one location at a time, please provide the following information.

Location #1

Facility Characteristics

1. REU1 Can you provide a brief description of the restricted/emergency use lane location (i.e., roadway, interchange, city, etc.)?
2. REU1 Is the roadway facility constructed of ☐ concrete or ☐ asphalt at the restricted/emergency use lane location?
3. REU1 How many total roadway lanes (including both directions) exist at the restricted/emergency use lane location?
4. REU1 What is the total length of the restricted/emergency use lane in feet?
5. REU1 What is the average annual daily traffic (AADT) for the roadway at the restricted/emergency use lane location?
6. REU1 What is the nature of the restriction at this location? ☐ Emergency use only ☐ Peak period use by select vehicles
☐ Directional use by time of day ☐ Other
7. REU1 What is the posted speed limit for the roadway at the restricted/emergency use lane location?

Technology Type and Characteristics

8. REU1 Who is the manufacturer of the illuminated, active in-pavement marker system at this location?
9. REU1 What is the size/shape of the individual markers?
10. REU1 Is the method of illumination ☐ LED or ☐ other?
11. REU1 What is the illumination output or angle?
12. REU1 What marker colors are used? ☐ White ☐ Green ☐ Red ☐ Blue ☐ Yellow ☐ Other
13. REU1 Are the colors ☐ static or ☐ dynamically sequenced?
14. REU1 Is the illumination ☐ static or ☐ flashing? If flashing, what flash rate is used?
15. REU1 If multiple rows of pavement markers were used, was the layout aligned (:::) or alternating (···)?
16. REU1 Is the power source ☐ solar, ☐ wired, or ☐ battery only?
17. REU1 Is the communications method ☐ wireline or ☐ wireless?
18. REU1 What is the age of the technology?
19. REU1 Are the markers mounted ☐ in-ground flush with the pavement, ☐ on the surface of the pavement, or ☐ other?

Installation and Construction Methods

20. REU1 When first installing the illuminated, active in-pavement marker system at this location, did you follow any design standards and specifications (i.e., *MUTCD*), special provisions, standard drawings/details, or supplemental policies and guidance? ☐ Yes ☐ No
If yes, may we get a copy?
21. REU1 Was the wiring run using ☐ underground conduit, ☐ pavement saw cut, or ☐ other?
22. REU1 In your opinion, do you think that the installation and construction methods used were adequate to ensure successful system performance?

Operation

23. REU1 Is the illuminated, active in-pavement marker system at this location operated ☐ on-demand, ☐ during the daytime only, ☐ during the nighttime only, ☐ continuously, or ☐ other?
24. REU1 What is the method of activation? ☐ Passive detection (e.g., microwave, motion sensors, video detection, light trip beam)
☐ RWIS or speed sensors ☐ Integration with traffic control devices ☐ Other
25. REU1 Is this location actively enforced? ☐ Yes ☐ No

Maintenance

26. REU1 Which, if any, type(s) of failure did you experience with the illuminated, active in-pavement marker system at this location? ☐ Individual LED failure ☐ Cracking ☐ Marker came free from pavement ☐ Flicker/loose connection ☐ Power system
27. REU1 What are the measured failure rates (if available) for the illuminated, active in-pavement marker system at this location?
28. REU1 Describe the method of notification if a failure is detected?
29. REU1 In your opinion, how would you rate the durability of the illuminated, active in-pavement marker system at this location?
☐ Very good ☐ Good ☐ Neutral ☐ Poor ☐ Very poor
30. REU1 In your opinion, how would you rate the adhesion of the illuminated, active in-pavement marker system at this location?
☐ Very good ☐ Good ☐ Neutral ☐ Poor ☐ Very poor
31. REU1 Please describe any other maintenance issues related to the illuminated, active in-pavement marker system at this location.

Costs

32. REU1 What were the initial costs of the illuminated, active in-pavement marker system at this location, including hardware and installation?
33. REU1 What are the ongoing annual costs of the illuminated, active in-pavement marker system at this location, including operation and maintenance?

Benefits

34. REU1 In your opinion, has the illuminated, active in-pavement marker system at this location improved the operation of the facility? ☐ Yes ☐ No
35. REU1 Has the illuminated, active in-pavement marker system at this location resulted in any unexpected operational challenges?
☐ Yes ☐ No
If yes, please describe?
36. REU1 Have these suspected changes in operations been formally measured and/or documented in an evaluation report?
☐ Yes ☐ No
If yes, may we get a copy?
37. REU1 In your opinion, has the illuminated, active in-pavement marker system at this location improved the safety of the facility?
☐ Yes ☐ No
38. REU1 Has the illuminated, active in-pavement marker system at this location resulted in any unexpected safety challenges (i.e., sudden braking)? ☐ Yes ☐ No
If yes, please describe?
39. REU1 Have these suspected changes in safety been formally measured and/or documented in an evaluation report?
☐ Yes ☐ No
If yes, may we get a copy?
40. REU1 Has improper activation of the illuminated, active in-pavement marker system at this location posed any challenges?

Is there another restricted/emergency use lane location that you would like to describe?

If yes, respondent is returned to Question 1. REU1 (which is now 1 REU2 for location 2) under Facility Characteristics and asked to complete all 40 questions for the second location. If no, respondent is directed to set of similar questions for new application type.

VARIABLE-WIDTH LANES (e.g., narrowing lane widths to increase capacity)

You have indicated that illuminated, active in-pavement marker systems have been used for variable lane widths in your <state> <locale>. You will have the opportunity to describe each of the variable lane width locations in your <state> <locale> equipped with illuminated, active in-pavement marker systems. Considering one location at a time, please provide the following information.

Location #1

Facility Characteristics

1. VW1 Can you provide a brief description of the variable-width lane location (i.e., street name, street intersection, city, etc.)?
2. VW1 Is the roadway facility constructed of ☐ concrete or ☐ asphalt at the variable-width lane location?
3. VW1 How many total roadway lanes (including both directions) exist at the variable-width lane location under the standard lane configuration?
4. VW1 How many total roadway lanes (including both directions) exist at the variable-width lane location under the narrowed lane configuration?

5. VW1 What is the total length of the variable-width lane in feet?
6. VW1 What is the average annual daily traffic (AADT) for the roadway at the variable-width lane location?
7. VW1 What is the posted speed limit for the roadway at the variable-width lane location?

Technology Type and Characteristics

8. VW1 Who is the manufacturer of the illuminated, active in-pavement marker system at this location?
9. VW1 What is the size/shape of the individual markers?
10. VW1 Is the method of illumination ☐ LED or ☐ other?
11. VW1 What is the illumination output or angle?
12. VW1 What marker colors are used? ☐ White ☐ Green ☐ Red ☐ Blue ☐ Yellow ☐ Other
13. VW1 Are the colors ☐ static or ☐ dynamically sequenced?
14. VW1 Is the illumination ☐ static or ☐ flashing? If flashing, what flash rate is used?
15. VW1 If multiple rows of pavement markers were used, was the layout aligned (:::) or alternating (··)?
16. VW1 Is the power source ☐ solar, ☐ wired, or ☐ battery only?
17. VW1 Is the communications method ☐ wireline or ☐ wireless?
18. VW1 What is the age of the technology?
19. VW1 Are the markers mounted ☐ in-ground flush with the pavement, ☐ on the surface of the pavement, or ☐ other?

Installation and Construction Methods

20. VW1 When first installing the illuminated, active in-pavement marker system at this location, did you follow any design standards and specifications (i.e., *MUTCD*), special provisions, standard drawings/details, or supplemental policies and guidance? ☐ Yes ☐ No
If yes, may we get a copy?
21. VW1 Was the wiring run using ☐ underground conduit, ☐ pavement saw cut, or ☐ other?
22. VW1 In your opinion, do you think that the installation and construction methods used were adequate to ensure successful system performance?

Operation

23. VW1 Is the illuminated, active in-pavement marker system at this location operated ☐ on-demand, ☐ during the daytime only, ☐ during the nighttime only, ☐ continuously, or ☐ other?
24. VW1 What is the method of activation? ☐ Passive detection (e.g., microwave, motion sensors, video detection, light trip beam) ☐ RWIS or speed sensors ☐ Integration with traffic control devices ☐ Other
25. VW1 Is this location actively enforced? ☐ Yes or ☐ No

Maintenance

26. VW1 Which, if any, type(s) of failure did you experience with the illuminated, active in-pavement marker system at this location? ☐ Individual LED failure ☐ Cracking ☐ Marker came free from pavement ☐ Flicker/loose connection ☐ Power system
27. VW1 What are the measured failure rates (if available) for the illuminated, active in-pavement marker system at this location?
28. VW1 Describe the method of notification if a failure is detected?
29. VW1 In your opinion, how would you rate the durability of the illuminated, active in-pavement marker system at this location? ☐ Very good ☐ Good ☐ Neutral ☐ Poor ☐ Very poor
30. VW1 In your opinion, how would you rate the adhesion of the illuminated, active in-pavement marker system at this location? ☐ Very good ☐ Good ☐ Neutral ☐ Poor ☐ Very poor
31. VW1 Please describe any other maintenance issues related to the illuminated, active in-pavement marker system at this location.

Costs

32. VW1 What were the initial costs of the illuminated, active in-pavement marker system at this location, including hardware and installation?
33. VW1 What are the ongoing annual costs of the illuminated, active in-pavement marker system at this location, including operation and maintenance?

Benefits

34. VW1 In your opinion, has the illuminated, active in-pavement marker system at this location improved the operation of the facility? ☐ Yes ☐ No

35. VW1 Has the illuminated, active in-pavement marker system at this location resulted in any unexpected operational challenges?
☐ Yes ☐ No
 If yes, please describe?
36. VW1 Have these suspected changes in operations been formally measured and/or documented in an evaluation report?
☐ Yes ☐ No
 If yes, may we get a copy?
37. VW1 In your opinion, has the illuminated, active in-pavement marker system at this location improved the safety of the facility?
☐ Yes ☐ No
38. VW1 Has the illuminated, active in-pavement marker system at this location resulted in any unexpected safety challenges (i.e., sudden braking)? ☐ Yes ☐ No
 If yes, please describe?
39. VW1 Have these suspected changes in safety been formally measured and/or documented in an evaluation report? ☐ Yes ☐ No
 If yes, may we get a copy?
40. VW1 Has improper activation of the illuminated, active in-pavement marker system at this location posed any challenges?

Is there another variable-width lane location that you would like to describe?

If yes, respondent is returned to Question 1. VW1 (which is now 1. VW2 for location 2) under Facility Characteristics and asked to complete all 40 questions for the second location. If no, respondent is directed to set of similar questions for new application type.

ADVERSE WEATHER AREAS

You have indicated that illuminated, active in-pavement marker systems have been used at adverse weather areas in your <state> <locale>. You will have the opportunity to describe each of the adverse weather areas in your <state> <locale> equipped with illuminated, active in-pavement marker systems. Considering one location at a time, please provide the following information.

Location #1

Facility Characteristics

1. AW1 Can you provide a brief description of the adverse weather location (i.e., roadway, mile-post range, city, etc.)?
2. AW1 Is the roadway facility constructed of ☐ concrete or ☐ asphalt at the adverse weather location?
3. AW1 How many total roadway lanes (including both directions) exist at the adverse weather location?
4. AW1 What is the total length of the adverse weather location in miles?
5. AW1 What is the average annual daily traffic (AADT) for the roadway at the adverse weather location?
6. AW1 What is the nature of the adverse weather? ☐ Fog ☐ Rain ☐ Smoke ☐ Other
7. AW1 What is the posted speed limit for the roadway at the adverse weather location?

Technology Type and Characteristics

8. AW1 Who is the manufacturer of the illuminated, active in-pavement marker system at this location?
9. AW1 What is the size/shape of the individual markers?
10. AW1 Is the method of illumination ☐ LED or ☐ other?
11. AW1 What is the illumination output or angle?
12. AW1 What marker colors are used? ☐ White ☐ Green ☐ Red ☐ Blue ☐ Yellow ☐ Other
13. AW1 Are the colors ☐ static or ☐ dynamically sequenced?
14. AW1 Is the illumination ☐ static or ☐ flashing? If flashing, what flash rate is used?
15. AW1 If multiple rows of pavement markers were used, was the layout aligned (:::) or alternating (···)?
16. AW1 Is the power source ☐ solar, ☐ wired, or ☐ battery only?
17. AW1 Is the communications method ☐ wireline or ☐ wireless?
18. AW1 What is the age of the technology?
19. AW1 Are the markers mounted ☐ in-ground flush with the pavement, ☐ on the surface of the pavement, or ☐ other?

Installation and Construction Methods

20. AW1 When first installing the illuminated, active in-pavement marker system at this location, did you follow any design standards and specifications (i.e., *MUTCD*), special provisions, standard drawings/details, or supplemental policies and guidance? ☐ Yes ☐ No
 If yes, may we get a copy?
21. AW1 Was the wiring run using ☐ underground conduit, ☐ pavement saw cut, or ☐ other?

22. AW1 In your opinion, do you think that the installation and construction methods used were adequate to ensure successful system performance?

Operation

23. AW1 Is the illuminated, active in-pavement marker system at this location operated ☐ on-demand, ☐ during the daytime only, ☐ during the nighttime only, ☐ continuously, or ☐ other?
24. AW1 What is the method of activation? ☐ Passive detection (e.g., microwave, motion sensors, video detection, light trip beam) ☐ RWIS or speed sensors ☐ Integration with traffic control devices ☐ Other
25. AW1 Is this location actively enforced? ☐ Yes ☐ No

Maintenance

26. AW1 Which, if any, type(s) of failure did you experience with the illuminated, active in-pavement marker system at this location? ☐ Individual LED failure ☐ Cracking ☐ Marker came free from pavement ☐ Flicker/loose connection ☐ Power system
27. AW1 What are the measured failure rates (if available) for the illuminated, active in-pavement marker system at this location?
28. AW1 Describe the method of notification if a failure is detected?
29. AW1 In your opinion, how would you rate the durability of the illuminated, active in-pavement marker system at this location? ☐ Very good ☐ Good ☐ Neutral ☐ Poor ☐ Very poor
30. AW1 In your opinion, how would you rate the adhesion of the illuminated, active in-pavement marker system at this location? ☐ Very good ☐ Good ☐ Neutral ☐ Poor ☐ Very poor
31. AW1 Please describe any other maintenance issues related to the illuminated, active in-pavement marker system at this location.

Costs

32. AW1 What were the initial costs of the illuminated, active in-pavement marker system at this location, including hardware and installation?
33. AW1 What are the ongoing annual costs of the illuminated, active in-pavement marker system at this location, including operation and maintenance?

Benefits

34. AW1 In your opinion, has the illuminated, active in-pavement marker system at this location improved the operation of the facility? ☐ Yes ☐ No
35. AW1 Has the illuminated, active in-pavement marker system at this location resulted in any unexpected operational challenges? ☐ Yes ☐ No
If yes, please describe?
36. AW1 Have these suspected changes in operations been formally measured and/or documented in an evaluation report? ☐ Yes ☐ No
If yes, may we get a copy?
37. AW1 In your opinion, has the illuminated, active in-pavement marker system at this location improved the safety of the facility? ☐ Yes ☐ No
38. AW1 Has the illuminated, active in-pavement marker system at this location resulted in any unexpected safety challenges (i.e., sudden braking)? ☐ Yes ☐ No
If yes, please describe?
39. AW1 Have these suspected changes in safety been formally measured and/or documented in an evaluation report? ☐ Yes ☐ No
If yes, may we get a copy?
40. AW1 Has improper activation of the illuminated, active in-pavement marker system at this location posed any challenges?

Is there another adverse weather area location that you would like to describe?

If yes, respondent is returned to Question 1. AW1 (which is now 1. AW2 for location 2) under Facility Characteristics and asked to complete all 40 questions for the second location. If no, respondent is directed to set of similar questions for new application type.

CONSTRUCTION ZONES

You have indicated that illuminated, active in-pavement marker systems have been used in construction zones in your <state> <locale>. You will have the opportunity to describe each of the construction zones in your <state> <locale> equipped with illuminated, active in-pavement marker systems. Considering one location at a time, please provide the following information.

Location #1

Facility Characteristics

1. CZ1 Can you provide a brief description of the construction zone location (i.e., street name, roadway name, city, etc.)?
2. CZ1 Were the illuminated in-pavement markers placed ☐ in the roadway, ☐ on jersey barriers, or ☐ in other area at the construction zone location?
3. CZ1 Were the illuminated in-pavement markers placed in or on ☐ concrete, ☐ asphalt, or ☐ other surface at the construction zone location?
4. CZ1 What was the total length of the construction zone in miles?
5. CZ1 What was the average annual daily traffic (AADT) for the roadway at the construction zone location?
6. CZ1 What was the duration of time that this construction zone was in effect?
7. CZ1 What is the posted speed limit for the roadway at the construction zone location?

Technology Type and Characteristics

8. CZ1 Who is the manufacturer of the illuminated, active in-pavement marker system at this location?
9. CZ1 What is the size/shape of the individual markers?
10. CZ1 Is the method of illumination ☐ LED or ☐ other?
11. CZ1 What is the illumination output or angle?
12. CZ1 What marker colors are used? ☐ White ☐ Green ☐ Red ☐ Blue ☐ Yellow ☐ Other
13. CZ1 Are the colors ☐ static or ☐ dynamically sequenced?
14. CZ1 Is the illumination ☐ static or ☐ flashing? If flashing, what flash rate is used?
15. CZ1 If multiple rows of pavement markers were used, was the layout aligned (:::) or alternating (···)?
16. CZ1 Is the power source ☐ solar, ☐ wired, or ☐ battery only?
17. CZ1 Is the communications method ☐ wireline or ☐ wireless?
18. CZ1 What is the age of the technology?
19. CZ1 Are the markers mounted ☐ in-ground flush with the pavement, ☐ on the surface of the pavement, or ☐ other?

Installation and Construction Methods

20. CZ1 When first installing the illuminated, active in-pavement marker system at this location, did you follow any design standards and specifications (i.e., *MUTCD*), special provisions, standard drawings/details, or supplemental policies and guidance? ☐ Yes ☐ No
If yes, may we get a copy?
21. CZ1 Was the wiring run using ☐ underground conduit, ☐ pavement saw cut, or ☐ other?
22. CZ1 In your opinion, do you think that the installation and construction methods used were adequate to ensure successful system performance?

Operation

23. CZ1 Is the illuminated, active in-pavement marker system at this location operated ☐ on-demand, ☐ during the daytime only, ☐ during the nighttime only, ☐ continuously, or ☐ other?
24. CZ1 What is the method of activation? ☐ Passive detection (e.g., microwave, motion sensors, video detection, light trip beam) ☐ RWIS or speed sensors ☐ Integration with traffic control devices ☐ Other
25. CZ1 Is this location actively enforced? ☐ Yes ☐ No

Maintenance

26. CZ1 Which, if any, type(s) of failure did you experience with the illuminated, active in-pavement marker system at this location?
☐ Individual LED failure ☐ Cracking ☐ Marker came free from pavement ☐ Flicker/loose connection ☐ Power system
27. CZ1 What are the measured failure rates (if available) for the illuminated, active in-pavement marker system at this location?
28. CZ1 Describe the method of notification if a failure is detected?
29. CZ1 In your opinion, how would you rate the durability of the illuminated, active in-pavement marker system at this location?
☐ Very good ☐ Good ☐ Neutral ☐ Poor ☐ Very poor
30. CZ1 In your opinion, how would you rate the adhesion of the illuminated, active in-pavement marker system at this location?
☐ Very good ☐ Good ☐ Neutral ☐ Poor ☐ Very poor
31. CZ1 Please describe any other maintenance issues related to the illuminated, active in-pavement marker system at this location.

Costs

32. CZ1 What were the initial costs of the illuminated, active in-pavement marker system at this location, including hardware and installation?

33. CZ1 What are the ongoing annual costs of the illuminated, active in-pavement marker system at this location, including operation and maintenance?

Benefits

34. CZ1 In your opinion, has the illuminated, active in-pavement marker system at this location improved the operation of the facility? ☐ Yes ☐ No
35. CZ1 Has the illuminated, active in-pavement marker system at this location resulted in any unexpected operational challenges? ☐ Yes ☐ No
If yes, please describe?
36. CZ1 Have these suspected changes in operations been formally measured and/or documented in an evaluation report? ☐ Yes ☐ No
If yes, may we get a copy?
37. CZ1 In your opinion, has the illuminated, active in-pavement marker system at this location improved the safety of the facility? ☐ Yes ☐ No
38. CZ1 Has the illuminated, active in-pavement marker system at this location resulted in any unexpected safety challenges (i.e., sudden braking)? ☐ Yes ☐ No
If yes, please describe?
39. CZ1 Have these suspected changes in safety been formally measured and/or documented in an evaluation report? ☐ Yes ☐ No
If yes, may we get a copy?
40. CZ1 Has improper activation of the illuminated, active in-pavement marker system at this location posed any challenges?

Is there another construction zone location that you would like to describe?

If yes, respondent is returned to Question 1. CZ1 (which is now 1. CZ2 for location 2) under Facility Characteristics and asked to complete all 40 questions for the second location. If no, respondent is directed to set of similar questions for new application type.

ENVIRONMENTALLY SENSITIVE AREAS (e.g., replacing or supplementing street lighting)

You have indicated that illuminated, active in-pavement marker systems have been used in environmentally sensitive areas in your <state> <locale>. You will have the opportunity to describe each of the environmentally sensitive areas in your <state> <locale> equipped with illuminated, active in-pavement marker systems. Considering one location at a time, please provide the following information.

Location #1

Facility Characteristics

1. ES1 Can you provide a brief description of the environmentally sensitive location (i.e., roadway, mile-post range, city, etc.)?
2. ES1 Is the roadway facility constructed of ☐ concrete or ☐ asphalt at the environmentally sensitive location?
3. ES1 How many total roadway lanes (including both directions) exist at the environmentally sensitive location?
4. ES1 What is the total length of the environmentally sensitive location in miles?
5. ES1 What is the average annual daily traffic (AADT) for the roadway at the environmentally sensitive location?
6. ES1 What is the nature of the environmental sensitivity at this location (e.g., reduce light pollution for natural habitat)?
7. ES1 What is the posted speed limit for the roadway at the environmentally sensitive location?

Technology Type and Characteristics

8. ES1 Who is the manufacturer of the illuminated, active in-pavement marker system at this location?
9. ES1 What is the size/shape of the individual markers?
10. ES1 Is the method of illumination ☐ LED or ☐ other?
11. ES1 What is the illumination output or angle?
12. ES1 What marker colors are used? ☐ White ☐ Green ☐ Red ☐ Blue ☐ Yellow ☐ Other
13. ES1 Are the colors ☐ static or ☐ dynamically sequenced?
14. ES1 Is the illumination ☐ static or ☐ flashing? If flashing, what flash rate is used?
15. ES1 If multiple rows of pavement markers were used, was the layout aligned (:::) or alternating (.:.)?
16. ES1 Is the power source ☐ solar, ☐ wired, or ☐ battery only?
17. ES1 Is the communications method ☐ wireline or ☐ wireless?
18. ES1 What is the age of the technology?
19. ES1 Are the markers mounted ☐ in-ground flush with the pavement, ☐ on the surface of the pavement, or ☐ other?

Installation and Construction Methods

20. ES1 When first installing the illuminated, active in-pavement marker system at this location, did you follow any design standards and specifications (i.e., *MUTCD*), special provisions, standard drawings/details, or supplemental policies and guidance?
☐ Yes ☐ No
 If yes, may we get a copy?
21. ES1 Was the wiring run using ☐ underground conduit, ☐ pavement saw cut, or ☐ other?
22. ES1 In your opinion, do you think that the installation and construction methods used were adequate to ensure successful system performance?

Operation

23. ES1 Is the illuminated, active in-pavement marker system at this location operated ☐ on-demand, ☐ during the daytime only, ☐ during the nighttime only, ☐ continuously, or ☐ other?
24. ES1 What is the method of activation? ☐ Passive detection (e.g., microwave, motion sensors, video detection, light trip beam) ☐ RWIS or speed sensors ☐ Integration with traffic control devices ☐ Other
25. ES1 Is this location actively enforced? ☐ Yes ☐ No

Maintenance

26. ES1 Which, if any, type(s) of failure did you experience with the illuminated, active in-pavement marker system at this location?
☐ Individual LED failure ☐ Cracking ☐ Marker came free from pavement ☐ Flicker/loose connection ☐ Power system
27. ES1 What are the measured failure rates (if available) for the illuminated, active in-pavement marker system at this location?
28. ES1 Describe the method of notification if a failure is detected?
29. ES1 In your opinion, how would you rate the durability of the illuminated, active in-pavement marker system at this location?
☐ Very good ☐ Good ☐ Neutral ☐ Poor ☐ Very poor
30. ES1 In your opinion, how would you rate the adhesion of the illuminated, active in-pavement marker system at this location?
☐ Very good ☐ Good ☐ Neutral ☐ Poor ☐ Very poor
31. ES1 Please describe any other maintenance issues related to the illuminated, active in-pavement marker system at this location.

Costs

32. ES1 What were the initial costs of the illuminated, active in-pavement marker system at this location, including hardware and installation?
33. ES1 What are the ongoing annual costs of the illuminated, active in-pavement marker system at this location, including operation and maintenance?

Benefits

34. ES1 In your opinion, has the illuminated, active in-pavement marker system at this location improved the operation of the facility? ☐ Yes ☐ No
35. ES1 Has the illuminated, active in-pavement marker system at this location resulted in any unexpected operational challenges?
☐ Yes ☐ No
 If yes, please describe?
36. ES1 Have these suspected changes in operations been formally measured and/or documented in an evaluation report? ☐ Yes ☐ No
 If yes, may we get a copy?
37. ES1 In your opinion, has the illuminated, active in-pavement marker system at this location improved the safety of the facility?
☐ Yes ☐ No
38. ES1 Has the illuminated, active in-pavement marker system at this location resulted in any unexpected safety challenges (i.e., sudden braking)? ☐ Yes ☐ No
 If yes, please describe?
39. ES1 Have these suspected changes in safety been formally measured and/or documented in an evaluation report? ☐ Yes ☐ No
 If yes, may we get a copy?
40. ES1 Has improper activation of the illuminated, active in-pavement marker system at this location posed any challenges?

Is there another environmentally sensitive location that you would like to describe?

If yes, respondent is returned to Question 1. ES1 (which is now 1. ES2 for location 2) under Facility Characteristics and asked to complete all 40 questions for the second location. If no, respondent is directed to set of similar questions for new application type.

OTHER

You have indicated that illuminated, active in-pavement marker systems have been used in your <state> <locale>, and the application type was not listed. You will have the opportunity to describe each location in your <state> <locale> equipped with illuminated, active in-pavement marker systems. Considering one location at a time, please provide the following information.

Location #1

Facility Characteristics

1. OTH1 Can you provide a brief description of the application?
2. OTH1 Can you provide a brief description of the location (i.e., roadway, mile-post range, city, etc.)?
3. OTH1 Is the roadway facility constructed of ☐ concrete or ☐ asphalt at the location?
4. OTH1 How many total roadway lanes (including both directions) exist at the location?
5. OTH1 What is the total length of the location in miles?
6. OTH1 What is the average annual daily traffic (AADT) for the roadway at the location?
7. OTH1 What is the posted speed limit for the roadway at the location?

Technology Type and Characteristics

8. OTH1 Who is the manufacturer of the illuminated, active in-pavement marker system at this location?
9. OTH1 What is the size/shape of the individual markers?
10. OTH1 Is the method of illumination ☐ LED or ☐ other?
11. OTH1 What is the illumination output or angle?
12. OTH1 What marker colors are used? ☐ White ☐ Green ☐ Red ☐ Blue ☐ Yellow ☐ Other
13. OTH1 Are the colors ☐ static or ☐ dynamically sequenced?
14. OTH1 Is the illumination ☐ static or ☐ flashing? If flashing, what flash rate is used?
15. OTH1 If multiple rows of pavement markers were used, was the layout aligned (:::) or alternating (.:.)?
16. OTH1 Is the power source ☐ solar, ☐ wired, or ☐ battery only?
17. OTH1 Is the communications method ☐ wireline or ☐ wireless?
18. OTH1 What is the age of the technology?
19. OTH1 Are the markers mounting ☐ in-ground flush with the pavement, ☐ on the surface of the pavement, or ☐ other?

Installation and Construction Methods

20. OTH1 When first installing the illuminated, active in-pavement marker system at this location, did you follow any design standards and specifications (i.e., *MUTCD*), special provisions, standard drawings/details, or supplemental policies and guidance? ☐ Yes ☐ No
If yes, may we get a copy?
21. OTH1 Was the wiring run using ☐ underground conduit, ☐ pavement saw cut, or ☐ other?
22. OTH1 In your opinion, do you think that the installation and construction methods used were adequate to ensure successful system performance?

Operation

23. OTH1 Is the illuminated, active in-pavement marker system at this location operated ☐ on-demand, ☐ during the daytime only, ☐ during the nighttime only, ☐ continuously, or ☐ other?
24. OTH1 What is the method of activation? ☐ Passive detection (e.g., microwave, motion sensors, video detection, light trip beam) ☐ RWIS or speed sensors ☐ Integration with traffic control devices ☐ Other
25. OTH1 Is this location actively enforced? ☐ Yes ☐ No

Maintenance

26. OTH1 Which, if any, type(s) of failure did you experience with the illuminated, active in-pavement marker system at this location? ☐ Individual LED failure ☐ Cracking ☐ Marker came free from pavement ☐ Flicker/loose connection ☐ Power system
27. OTH1 What are the measured failure rates (if available) for the illuminated, active in-pavement marker system at this location?
28. OTH1 Describe the method of notification if a failure is detected?
29. OTH1 In your opinion, how would you rate the durability of the illuminated, active in-pavement marker system at this location? ☐ Very good ☐ Good ☐ Neutral ☐ Poor ☐ Very poor

30. OTH1 In your opinion, how would you rate the adhesion of the illuminated, active in-pavement marker system at this location?
☐ Very good ☐ Good ☐ Neutral ☐ Poor ☐ Very poor
31. OTH1 Please describe any other maintenance issues related to the illuminated, active in-pavement marker system at this location.

Costs

32. OTH1 What were the initial costs of the illuminated, active in-pavement marker system at this location, including hardware and installation?
33. OTH1 What are the ongoing annual costs of the illuminated, active in-pavement marker system at this location, including operation and maintenance?

Benefits

34. OTH1 In your opinion, has the illuminated, active in-pavement marker system at this location improved the operation of the facility? ☐ Yes ☐ No
35. OTH1 Has the illuminated, active in-pavement marker system at this location resulted in any unexpected operational challenges?
☐ Yes ☐ No
 If yes, please describe?
36. OTH1 Have these suspected changes in operations been formally measured and/or documented in an evaluation report?
☐ Yes ☐ No
 If yes, may we get a copy?
37. OTH1 In your opinion, has the illuminated, active in-pavement marker system at this location improved the safety of the facility?
☐ Yes ☐ No
38. OTH1 Has the illuminated, active in-pavement marker system at this location resulted in any unexpected safety challenges (i.e., sudden braking)? ☐ Yes ☐ No
 If yes, please describe?
39. OTH1 Have these suspected changes in safety been formally measured and/or documented in an evaluation report? ☐ Yes ☐ No
 If yes, may we get a copy?
40. OTH1 Has improper activation of the illuminated, active in-pavement marker system at this location posed any challenges?

Is there another location that you would like to describe?

If yes, respondent is returned to Question 1. OTH1 (which is now 1. OTH2 for location 2) under Facility Characteristics and asked to complete all 40 questions for the second location. If no, respondent is directed to set of similar questions for new application type.

May we contact you for additional information regarding your responses to this survey? ☐ Yes ☐ No

Thank you for your time and cooperation in completing this survey. If you have additional information pertaining to specific sites (i.e., pictures or evaluation reports) we would be most interested in obtaining any of these pieces of information. In addition, if you would like to discuss the survey or any of the specific sites in more detail, please feel free to contact Jodi Carson, Anthony Voigt, or Jonathan Tydlacka.

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APPENDIX B

Survey Respondents

Title	Agency	Division	Response
Director of Public Works	City of York, Penn.		No to all
Traffic Operations Engineer	City of Boca Raton, Fla.	Traffic and Special Projects Division	Environmental (turtles); other (ped)
City Traffic Engineer	City of Melbourne, Fla.	Traffic Engineering	No to all
Principal Engineer	Cincinnati, Ohio Department of Transportation and Engineering	Transportation Planning and Urban Design	No to all
Traffic and Transportation Engineer	City of Bloomington, Minn.	Engineering	No to all
Acting Commissioner	City of Toledo, Ohio	Transportation	No to all
State Traffic Engineer	Mississippi DOT	Traffic Engineering Division	No to all
Signing and Marking Engineer	Nebraska Department of Roads	Traffic Engineering	No to all
City Engineer	City of South Bend, Ind.	Department of Public Works	No to all
Traffic Engineer	City of Virginia Beach, Va.	Traffic Engineering	No to all
City Traffic Engineer	City of Long Beach, Calif.	Traffic Engineering	No to all
Chief of Traffic Engineering	Kansas DOT	Operations	Other (ped)
Manager of Traffic Operations	City of Lakeland, Fla.	Public Works	Other (ped)
Traffic Engineer	City of Charleston, W. Va.	Traffic Engineering Dept.	No to all
State Traffic Engineer	Iowa DOT	Highway	No to all
Traffic Engineer	City of Fort Myers, Fla.	Engineering	Stop-bar, multi-turn lanes, merging area
Lake County Traffic Engineer	City of Lake County, Ill.	Division of Transportation	Other (ped)
City of Livonia, MI	City of Livonia, MI	City of Livonia, MI	No to all
Chief Traffic and Lighting Engineer	City of Milwaukee, Minn.	Department of Public Works	No to all
Senior Transportation Engineer	City of Mesa, Ariz.	Transportation Department	No to all
Traffic Eng. Admin	City of Farmington, Ind.	Traffic Engineering	Other (ped)
Traffic Project Development Engineer	South Carolina DOT	Traffic Engineering	Curve
Traffic Engineer	City of Santa Clara, Calif.	Engineering	No to all
Transportation Division Chief	City of Alexandria, Va.	Transportation	Other (ped)
City Engineer & City Traffic Engineer	City of Greenville, S.C.	Engineering	No to all
Traffic Operations Engineer	North Dakota DOT	Planning and Programming Division	No to all
Traffic Operations Engineer	South Dakota DOT	Operations	No to all
City Traffic Engineer	City of Shreveport, La.	Traffic Engineering Division	No to all
City Engineer	City of Council Bluffs, Iowa Public Works	Engineering	No to all
Director of Transportation	City of Winston-Salem, N.C.	DOT	No to all

Transportation Engineer II	City of Durham, N.C.	Transportation	Curve
State Traffic Engineer	Washington State DOT	Maintenance & Operations	Other (ped)
Branch Manager	Colorado DOT	Safety & Traffic Engineering	No to all
City of Little Rock Public Works	City of Little Rock, Ark.	Public Works	No to all
Engineering Department	City of Hoover, Ala.	Engineering Department	No to all
Town Engineer	City of Springfield, Mass. Department of Public Works	Engineering	No to all
Engineering Division Manager	City of Thousand Oaks, Calif.	Public Works	Other (ped)
Senior Professional Engineer	Miami Dade County, Fla. Public Works Department	Traffic Engineering Division	No to all
Civil Engineer	County of Will, Ill.	Highways	No to all
State Traffic Engineer	Texas DOT	Traffic Operations Division	No to all
State Traffic Engineer	Tennessee DOT	Maintenance Division	No to all
Director, Division of Highways	Kenosha County, Wis. Public Works	Highway	No to all
City Traffic Engineer	City of Stockton, Calif.	Public Works Department	Multi-turn lanes, other (ped)
Chief Traffic Engineer	Charlotte, N.C. DOT	Engineering and Operations	No to all
Senior Civil Engineer	City of Vallejo, Calif.	Public Works Department/Traffic Section	No to all
Traffic Operations Engineer	City of Dayton, Ohio	Bureau of Traffic Engineering	No to all
Managing Engineer	Rhode Island DOT	Traffic Design	No to all
Traffic Engineer/Administrator	New Hampshire DOT	Bureau of Traffic	No to all
Director of Traffic Engineering	City of Huntsville, Ala.	Traffic Engineering	No to all
Director of Traffic Engineering	Suffolk County, N.Y. Department of Public Works	Traffic Engineering	No to all
MPO Director	City of Brownsville, Tex.	Transportation	No to all
Traffic Safety Engineer	Missouri DOT	Traffic	No to all
State Traffic Engineer of Design	Wisconsin DOT	Bureau of Highway Operations	Other (ped)
State Traffic Engineer	Hawaii DOT	Highways	Tunnels
State Traffic Engineer	Montana DOT	Safety & Traffic Bureau	No to all
State Traffic Engineer	Alaska DOT		Other (ped)
Director, Traffic Engineering	West Virginia DOT	Highways	No to all
Traffic Operations Engineer	City of Columbus, Ohio—Public Service Department	Transportation	No to all
Engineering Services Director	City of Gaithersburg, Md.	Public Works	No to all
Transportation Engineer	City of Lansing, Mich.	Transportation and Parking Office	No to all
Engineering Department	City of East Hartford, Conn.	Engineering Department	No to all
Assistant City Engineer	City of Fort Wayne, Ind.	Transportation	No to all

APPENDIX C

In-Pavement Lighting System Vendors Contacted for this Synthesis

ITEM Ltd. (LaneLight™)

<http://www.itemltd.com/>

Illinois Solar Products

<http://www.illinoissolarproducts.com/>

SolarMarkers, Co.

<http://www.solarmarkers.com/>

LightGuard Systems

<http://www.crosswalks.com/>

Hotbeam Cool Light

<http://www.hotbeam.com/cool.light/index.cfm>

Sunlights Highway Lighting Products

<http://www.sunlights.us/>

Spot Devices

<http://www.spotdevices.net/>

SmartStud Systems

<http://www.smartstud.com/>

Hil-Tech (LEDLine), Nick Hutchins

<http://www.hil-tech.ca>

Traffic Safety Corporation

<http://www.xwalk.com/>

Astucia

<http://www.astucia.co.uk/>

Intertraffic Systems

<http://www.intertrafficsystems.nl/>

Abbreviations used without definitions in TRB publications:

AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI-NA	Airports Council International-North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	Air Transport Association
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
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
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation