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Investigating the Optimum Performance of Snowplowable Reflective Pavement Markers

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16. Abstract

This project investigated the installation and performance of snowplowable reflective pavement markers (SRPMs) to determine optimum pavement marker solutions and policies for roadways in Illinois. The research evaluated the performance of five traditional cast-iron and two plastic SRPMs on test sections of both asphalt and concrete pavements. Analysis included 1) comparisons of casting design, casting material, and groove design; 2) assessments on how each factor contributed to pavement marker performance; and 3) development of crash modification factors (CMFs) for quantifying any safety improvement from SRPM use. The results of the SRPM performance evaluation and CMF development were used to provide recommended updates to the Illinois Department of Transportation's (IDOT's) departmental policies document TRA-14, which provides guidelines for the use of pavement marking materials (including raised pavement markers) and to IDOT's Raised Reflective Pavement Marker inspection policy, which gives regional engineers instructions on inspection of in-place SRPMs.

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EXECUTIVE SUMMARY

This project investigated the installation and performance of snowplowable reflective pavement markers (SRPMs) to determine optimum pavement marker solutions and policies for roadways in Illinois. The research evaluated the performance of five traditional cast-iron and two plastic SRPMs on test sections of both asphalt and concrete pavements. The five iron markers and one plastic marker were snowplowable raised markers, and the other plastic marker was completely recessed. The analysis included comparisons of how casting design, casting material, and groove design contributed to pavement marker performance. The analysis also included the development of crash modification factors (CMFs) for quantifying any safety improvement from SRPM use. The Illinois Tollway provided the required cost share for this study by contributing two test sections and the crash data for CMF development.

The assessment method for marker performance involved installing six pavement marker test sections throughout the state. One asphalt-surfaced and one concrete-surfaced section were installed in the northern region of the state, and the same two surface-type test sections were installed in the central and southern regions. Six of the seven marker types were installed at all six sites and evaluated annually for three years. One plastic marker came on the market after the study began but was added to the study one year later. This marker was added to the two central sites and evaluated for two years. Annual marker condition assessments evaluated marker housing condition, marker presence (bonded, loose, missing), lens presence, percentage of remaining epoxy, and exposure of leading edge of rails.

The CMF development was separated into two phases. In Phase I, the research team identified sites for CMF development and developed preliminary CMFs using a cross-sectional modeling approach. This approach compared roadway segments with and without the treatment of interest (SRPM presence) to identify safety effectiveness. The Phase II approach of CMF development included the results of the state-of-the-art empirical Bayes before-after analysis. The empirical Bayes approach is currently recognized as a more reliable method for estimating the effectiveness of treatments while accounting for potential biases, such as regression to the mean or changes in traffic volume. Because the Illinois Tollway had the only roadway segments that were without SRPMs for a period of time, the research estimated the safety impacts of SRPMs on Illinois Tollway routes. Illinois Tollway routes, in Phase II, had at least three directional lanes, were access-controlled freeways, and were in urbanized areas likely to have some level of ambient lighting.

The marker performance evaluations showed that the two plastic markers exhibited more rapid deterioration than the iron markers. After three years, nearly 40% of the recessed plastic markers were missing, most of which were on concrete-surfaced roadways. While none of the snowplowable plastic markers were missing after two years, over 40% were missing the lens. The housings were also severely deteriorated—most received a housing condition rating of poor or very poor. Of the iron markers, the two high-profile markers exhibited a slight but consistent and measurably higher degradation than the other iron markers. After three years, all iron markers were present, and most were in good to excellent condition.

The CMF development used data from Illinois Tollway segments that previously did not have SRPMs as well as segments that always had SRPMs installed. The data was used to examine the effects for specific crash types: total, fatal and injury, lane departure, wet pavement lane departure, nighttime lane departure, nighttime wet pavement lane departure, and fatal and injury lane departure. Based on the aggregate results, there were no statistically significant changes in crashes. A disaggregate analysis of the results investigated additional factors associated with the safety performance of SRPMs. While there is some evidence that SRPMs may be more effective (or less effective) under specific conditions and for specific crash types, the disaggregate analysis did not identify any statistically significant differences (i.e., the 95% confidence overlap in all cases for disaggregate analyses). Finally, the project team analyzed individual segments for statistically significant increases or decreases in crash frequency. The results indicated that no sites observed a statistically significant increase in lane departure crashes of any type after the reinstallation of SRPMs. Overall, no crash types were associated with statistically significant changes (i.e., 1.0 is included in the 95% confidence interval) in crash frequency across all segments. However, it should be noted that the sites in this study had at least three directional lanes and were more urban/suburban in nature, likely having ambient light present. **The results in this study would not be appropriate for other facility types**.

The results of the SRPM performance evaluation and CMF development were used to provide recommended updates to the Illinois Department of Transportation's (IDOT's) departmental policies document TRA-14, which provides guidelines for the use of pavement marking materials (including raised pavement markers) and to IDOT's Raised Reflective Pavement Marker inspection policy, which gives regional engineers instructions on inspection of in-place SRPMs.

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CHAPTER 1: OVERVIEW

1.1 BACKGROUND

The purpose of reflective pavement markers is to enhance the nighttime visibility of roadway lane delineation and to increase roadway perception-reaction time. Reflective pavement markers (RPMs) serve an even greater role in roadway safety during wet night conditions. During wet night conditions the visibility of horizontally placed pavement markings can become obscured by water on the pavement, but the elevated, reflective face of a pavement marker can still be seen.

In an effort to determine optimum snowplowable reflective pavement marker (SRPM) solutions and possible improvements in maintenance and construction practices, IDOT initiated a research project through the Illinois Center for Transportation (ICT). In October 2014, ICT awarded project "R27-151: Investigating the Optimum Performance of Snowplowable Reflective Pavement Markers," to Applied Research Associates, Inc. (ARA).

The objective of this project is to investigate the installation and performance of SRPMs to determine optimum pavement marker solutions and policies for roadways in Illinois. The research includes gathering policy information from other states, investigating installation procedures for raised and recessed markers, and evaluating the performance of both marker types on test sections of asphalt and concrete pavements. Analysis included 1) comparisons of how casting design, casting material, and groove design contributed to pavement marker performance and 2) development of crash modification factors (CMFs) for quantifying any safety improvement from SRPM use.

The Illinois Tollway provided the 25% cost share for this study. The Tollway's contributions were two pavement marker test sections in the northern part of the state as well as crash data for the CMF development.

1.2 PAVEMENT MARKER SELECTION

At the beginning of the study, ARA researchers and the ICT Technical Review Panel (TRP) agreed that the study should assess the performance of all currently available snowplowable and recessed pavement markers. Table 1 shows the initial list of markers identified for evaluation on Illinois roadway test sections.

However, several markers were no longer in production in the spring of 2015. After verification with the marker manufacturers, the list was refined to markers that are still in production. Table 2 provides the list of markers in production as of August 2015 and planned for installation in the study's test sections.

Table 1. Initial List of Test Markers (November 2014)

Count	Marker	Manufacturer
1	SM 96	Ennis-Flint
2	SM 96LP	Ennis-Flint
3	SM 101	Ennis-Flint
4	SM 101LP	Ennis-Flint
5	SM 101LPCR	Ennis-Flint
6	H960	Rayolite
7	H960HP	Rayolite
8	H1010	Rayolite
9	H1010HP	Rayolite
10	H1010CR	Rayolite
11	SL100	Rayolite
12	SL150	Rayolite
13	SL300	Rayolite
14	Ironstar Model 664	Rayolite
15	R-100	Marker One

Table 2. Revised List of Test Markers (August 2015)

Count	Marker	Manufacturer
1	SM 101	Ennis-Flint
2	SM 101LP	Ennis-Flint
3	H1010	Rayolite
4	H1010HP	Rayolite
5	SL150	Rayolite
6	R-100	Marker One

The first five markers are traditional cast-iron, grooved-in snowplowable raised pavement markers. The cast design of these markers have a similar "H" shape, with two lead rails and two rear rails for snowplow blades to ride up and over on, and the reflective lens is bonded to the middle section of the "H." The five markers also have four leveling tabs on the outside edges that rest on the pavement and keep the markers at the desired height above the pavement. The rest of the marker is below the pavement surface. An epoxy adhesive is used to completely fill the groove bonding the marker to the pavement, and the front end and trailing end of the rails are slightly below the pavement surface and covered with adhesive. The primary differences between these markers are slight variations in their dimensions and weights. SM 101 and H1010HP are considered high-profile markers because the above-pavement height is slightly higher (approximately 0.16 in. higher) than the other three markers, providing drivers with more visibility of the reflective lens. SM 101LP, H1010, and SL150 are low-profile markers. The lower profile decreases the impact angle with snowplows and therefore decreases a snowplow's impact force on the marker. Figure 1 contains images of the five snowplowable raised pavement markers.

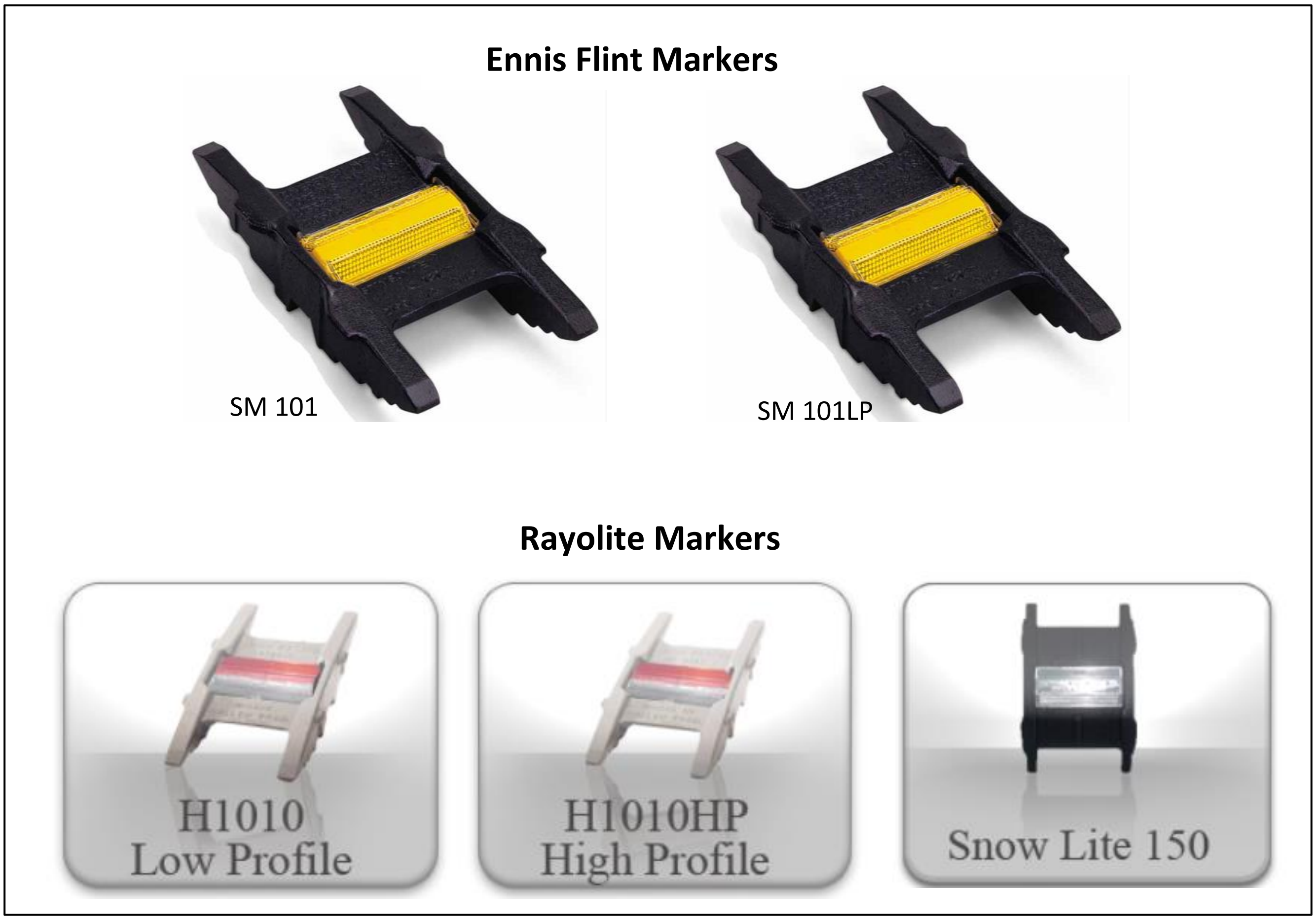


Figure 1. Ennis Flint and Rayolite snowplowable raised pavement markers.

The sixth marker, R-100, is a polycarbonate plastic marker that is completely recessed in a long, shallow groove. The cast design of this marker is a rectangular cradle that holds the reflective lens just below the pavement surface, and there is a leveling tab on each side of the cradle. The length of the groove is approximately 9 ft, and typically two markers are placed in the middle of the groove about 2 ft apart. An epoxy adhesive is used to bond the markers to the pavement but most of the groove remains open (unfilled) so the reflective lens can be seen. Figure 2 contains a photo of an R-100 and a drawing depicting the groove dimensions.

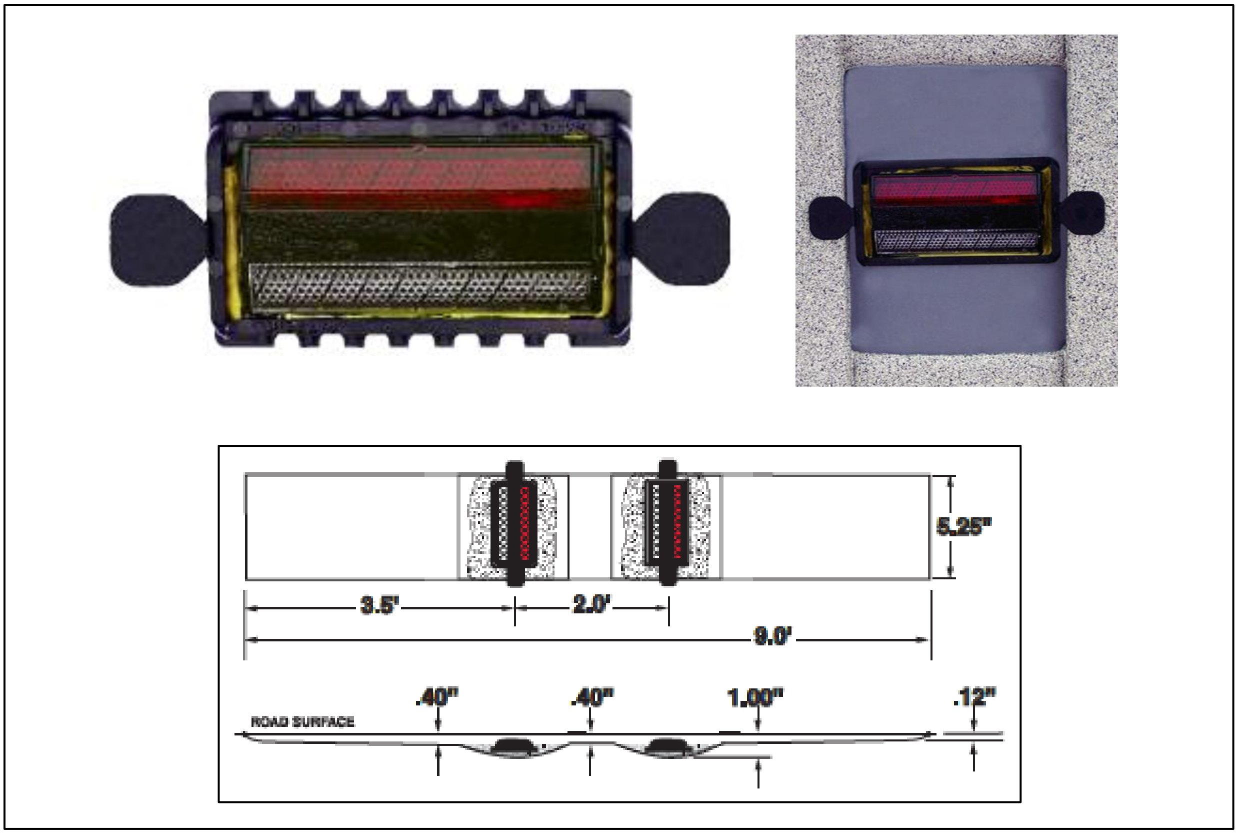


Figure 2. R-100 recessed pavement marker and groove dimensions.

By 2016, all six markers were installed in six test sections. Details about the test sections are provided in Section 1.3. At the time this study began, Trinity Industries began development of a new marker called the Guide Lite. The Guide Lite, shown in Figure 3, is made of lightweight, high-impact grade polymeric material cast in an "H" shape similar to the traditional snowplowable markers. It also has a section of hardened steel embedded through the center of the rails. Similar to traditional cast-iron markers, Guide Lite is placed in a groove and bonded to the pavement with an epoxy adhesive.

Figure 3. Guide Lite snowplowable raised pavement marker.

Due to the timing of its development, Guide Lite was not installed with the other markers in 2016, but it was installed in two of the six test sections in 2017. Table 3 is the final list of test markers evaluated for this study.

Table 3. Final List of Test Markers

Count	Marker	Manufacturer
1	SM 101	Ennis-Flint
2	SM 101LP	Ennis-Flint
3	H1010	Rayolite
4	H1010HP	Rayolite
5	SL150	Rayolite
6	R-100	Marker One
7	Guide Lite	Trinity

Table 4 is a summary of the seven test markers' dimensions and weights. The R-100 and Guide Lite markers weigh considerably less than the cast-iron markers. The intended purpose of making markers from a hard plastic is to lower momentum in the event they are dislodged from the pavement and thrown at a vehicle window.

Table 4. Test Marker Dimensions and Weights

Marker	Length (in)	Width (in)	Height (in)	Above Grade Profile Height (in)	Weight with Reflector (lbs)
SM 101	10	5.5	1.92	0.41	5.5
SM 101LP	10	5.5	1.76	0.25	4.9
H1010	10	5.5	1.75	0.25	4.5
H1010HP	10	5.5	1.91	0.41	5.8
SL150	9.25	5.25	1.5	0.25	4.1
R-100	3	5	0.7	-0.12	0.25
Guide Lite	9.37	5.75	1.87	0.26	1.4

Manufacturer specifications, which contain more product details, are provided in Appendix A.

1.3 TEST SITE SELECTION

At the beginning of the study, ARA researchers and the TRP agreed that the study should assess the performance of test markers on both asphalt- and concrete-surfaced roadways. Also, because of the considerable difference in snowfall from the northern to the southern end of the state, they decided there should be test sites in the northern, central, and southern regions. The markers in the northern part of the state would experience the most snowplow hits, and the markers in the southern test sites would experience the fewest snowplow hits. The locations of the six test sections are as follows:

1. Asphalt surface—Northern region
2. Concrete surface—Northern region
3. Asphalt surface—Central region
4. Concrete surface—Central region
5. Asphalt surface—Southern region
6. Concrete surface—Southern region

As part of the Illinois Tollway's cost share for the study, the two northern sites were selected from Tollway routes. The remaining four sites were on IDOT routes. The original test site plan was to place at least 20 of each marker type on new construction projects as opposed to pavement marker maintenance contracts. New pavement was desired so that the pavement condition would not affect the performance of the markers. The test sites were to be installed in the first summer or fall of the study (2015). However, due to complications with modifying existing construction contracts, the test markers were placed on existing good-condition pavements through maintenance contracts. The criteria for selecting good-condition pavements were based on pavement surface age and IDOT's Condition Rating Survey (CRS) value. CRS is based on a scale of zero to nine. The criteria were as follows:

- CRS = Excellent (7.5–9.0)
- Pavement Surface Age
    - Portland Cement Concrete (PCC) ≤ 10 years
    - Hot-Mix Asphalt (HMA) ≤ 5 years

For approximately eight years leading up to the study, the Illinois Tollway had a moratorium on the use of pavement markers. However, the Tollway had recently changed their policy and was in the process of adding markers to pavements constructed during the moratorium. For this reason, the timing worked well for the Tollway to add test markers to a contract for the newer asphalt-surfaced pavement on the northern end of I-90 in 2015. So, the northern asphalt-surfaced test section was installed in 2015. The remaining five sites were placed in 2016, and the Guide Lite markers were added to the two central sites in 2017. At the four IDOT sites the existing markers were left in place to avoid damaging the pavement, and the reflective lenses were removed. At the sites, markers were spaced between every other pavement marking skip dash, so new markers were installed between skips without markers. Table 5 lists the route and section of each test site, and Figure 4 is a map of the sites.

Table 5. Location of Pavement Marker Test Sites

Test Site	Location
Northern HMA	I-90: EB Milepost (MP) 10 to 11.5
Northern PCC	I-88: WB MP 123.75 to 125
Central HMA	I-155: SB MP 27 to 24.6
Central PCC	IL-8: EB Summit Dr. to Sta 259+00, WB Sta 259+00 to Sta 192+00
Southern HMA	I-57: NB and SB MP 194 to 195
Southern PCC	I-70: EB and WB MP 151 to 152.5

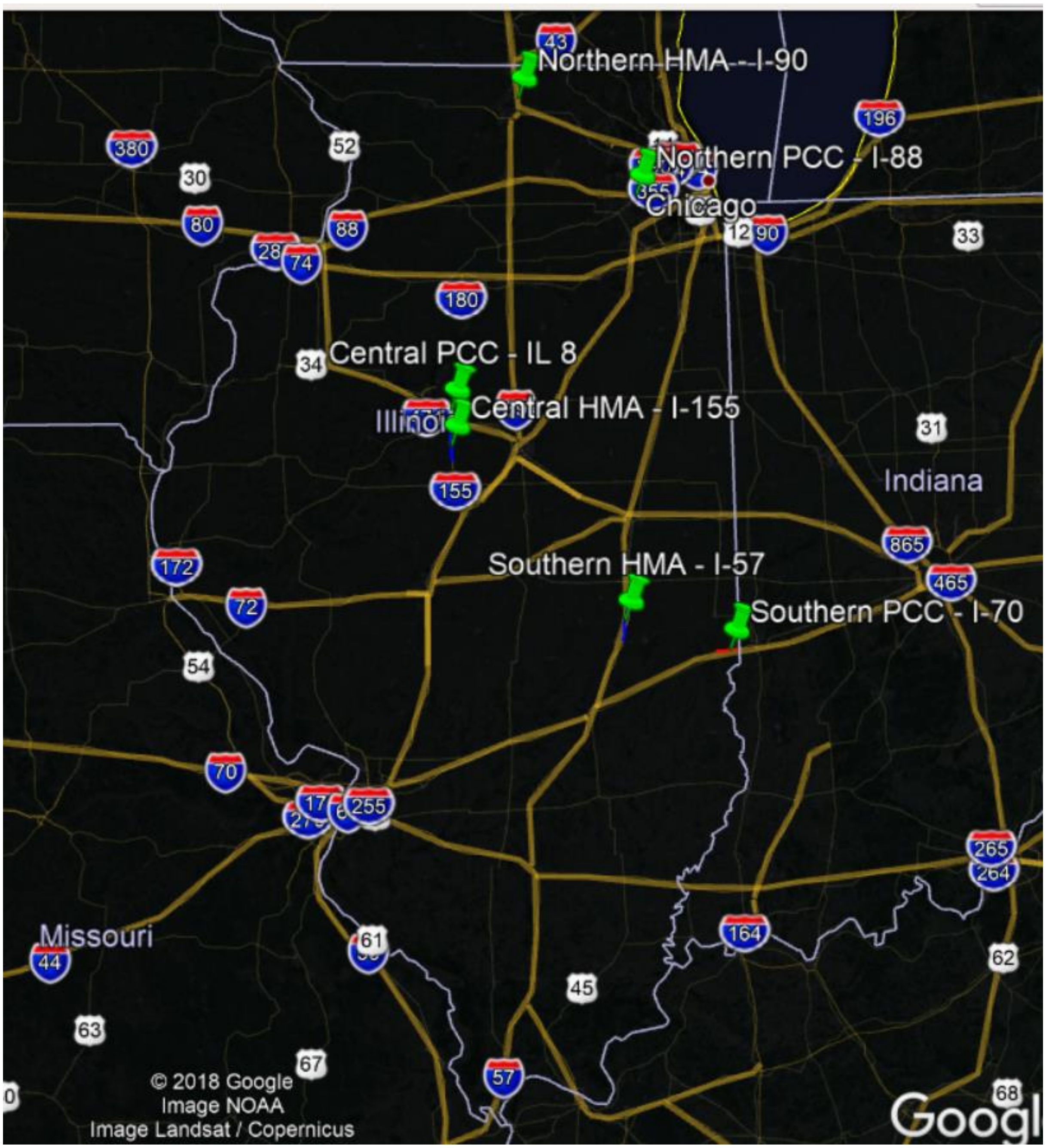


Figure 4. Map of pavement marker test sites.

1.4 PERFORMANCE ASSESSMENT METHODS

1.4.1 Test Marker Installation Assessment

To help ensure that marker performance was not affected by improper installation, a member of the research team was present at each installation to provide quality assurance. For each test site installation, the research team measured and recorded the following details:

- Pavement surface temperature and ambient air temperature.
- Depth of groove cut.
- Whether groove surface was dry and clean prior to placing epoxy.
- Whether leveling tabs rested on the pavement prior to placing epoxy.
- Marker distance from pavement edge or joint.
- Epoxy hardness after one hour (whether screwdriver can be pushed into the epoxy).

The ARA researcher also took a photo of every marker following installation to create a photo log as a baseline reference for annual performance assessments.

1.4.2 Annual Marker Performance Assessment

The annual performance assessment metrics proposed by the researchers and approved by the TRP were as follows:

- Whether the marker is loose or securely bonded to the pavement (Yes/No)
- Pavement condition surrounding the pavement marker
    - Good: No distresses touching marker, nor any within 2″ of marker
    - Fair:
        - One or more minor cracks (< 1/2″ width) touching marker
        - And/or 1 to 2 severe cracks (> 1/2″ width) touching marker
    - Poor:
        - Three or more severe cracks (> 1/2″ width) touching marker
        - Or any spall touching marker
- Quartile percentage of missing epoxy (annual photo compared to installation photo)
- Whether marker rails (particularly leading edges) are exposed or elevated (Yes/No)
- Whether reflectors are still attached to housings (Yes/No)
- Housing Condition Rating using the National Transportation Product Evaluation Program (NTPEP) Scale
    - 5 (Excellent): Completely intact, "Like New," good adhesion
    - 4 (Good): Minor scrapes/scratches visible on close examination
    - 3 (Fair): Some cuts but none larger than 10mm
    - 2 (Poor): Some cuts larger than 10mm
    - 1 (Very Poor): Showing significant wear, no longer protecting lens
    - 0 (Failed): Missing or damaged beyond use

If the marker was missing, then the researcher recorded the apparent reason (e.g. epoxy debonded, pavement failure, etc.).

During each annual assessment, the research team also recorded a nighttime video driving through the test section. The purpose of the videos was to have a recorded annual history of the markers' visibility. A GoPro camera was mounted to the hood of a vehicle, and a video was recorded as the vehicle drove through the test site at 55 mph. Orange traffic cones were placed on the roadway shoulder at the beginning and end of each section so that anyone viewing the video would know the boundaries of the test section. The recording was repeated if oncoming traffic appeared. The final videos had no oncoming headlights in view so that the viewer only sees test markers made visible by the survey vehicle's headlights. Videos were not recorded on the two Illinois Tollway test sites because of much higher traffic volume. Oncoming vehicles are always likely to be present during the night and placing traffic cones on the shoulder would not be safe.

1.5 CRASH MODIFICATION FACTOR DEVELOPMENT METHOD

1.5.1 Approach

To develop a CMF or set of CMFs for quantifying the safety effect from RPM use in Illinois, ARA teamed with Vanasse Hangen Brustlin, Inc. (VHB). A CMF is a multiplicative factor used to compute the expected number of crashes after implementing a given countermeasure at a specific site. A CMF is a point estimate, but a single point estimate may or may not be appropriate. Instead, it may be more appropriate to represent the safety effect as a crash modification function (CMFunction), allowing the value of the CMF to change for different scenarios (e.g., changes in traffic volume or area type). This study examined the development of point estimates of CMFs based on an analysis of the aggregate data. This study also explored more disaggregate analyses to determine the need for a CMFunction or, perhaps, a set of point estimates to reflect differential effects of RPMs under different conditions.

CMF development was separated into two phases. In Phase I, the research team focused on identifying sites for CMF development and developing preliminary CMFs using a cross-sectional modeling approach. This approach compared roadway segments with and without the treatment of interest (in this case SRPM presence) to identify the safety effectiveness. The Phase II approach of the CMF development includes the results of the state-of-the-art empirical Bayes before-after analysis. The empirical Bayes approach is currently recognized as a more reliable method for estimating the effectiveness of treatments while accounting for potential biases, such as regression to the mean or changes in traffic volume. Because the Illinois Tollway had the only roadway segments that were without SRPMs for a period of time, this research estimated the safety impacts of SRPMs on Illinois Tollway routes. Illinois Tollway routes, in Phase II, had at least three directional lanes, were access-controlled freeways, and were in urbanized areas likely to have some level of ambient lighting.

The objective was to estimate the safety effectiveness of this strategy as measured by crash frequency. Target crash types included the following:

- Total crashes (all types and severities combined).
- Injury crashes (K, A, B, and C injuries on KABCO scale).
- Lane departure crashes (all severities combined).
- Lane departure wet pavement crashes (all severities combined).
- Lane departure night crashes (all severities combined).
- Lane departure nighttime wet pavement crashes (all severities combined).
- Lane departure injury crashes (K, A, B, and C injuries on KABCO scale).

A further objective was to address questions of interest such as:

- Do effects vary by traffic volume (i.e., AADT)?
- Do effects vary by number of lanes?
- Do effects vary by horizontal geometry (e.g., horizontal curves)?
- Are there seasonal differences in safety effects?
- Are the effects short-lived?

Phase I evaluation did not consider the safety effectiveness by horizontal and cross-sectional geometry. Using the empirical Bayes before-after methodology in Phase II, the research team conducted further disaggregate analysis of results to determine where SRPMs are more or less effective.

Special requirements were placed on the data collection and analysis tasks to meet the objectives, including the need to:

- Select a large enough sample size to detect, with statistical significance, possible small changes in safety for some crash types.
- Identify appropriate untreated reference sites.
- Properly account for changes in safety due to changes in traffic volume and other nontreatment factors.
- Pool data from multiple facilities to improve reliability of the results and facilitate broader applicability of the products of the research.

1.5.2 Phase I Methodology

Phase I included a cross-sectional study designed to develop the initial CMFs. Cross-sectional studies estimate the safety effect as the ratio of the average crash frequency for two groups, one with the feature of interest and the other without the feature of interest. In this case, the feature of interest is the presence of SRPMs. For this method to work, the two groups should be similar in all regards except for the feature of interest. In practice, this is difficult to accomplish, and multivariable regression models are used to estimate the safety effects of one feature while controlling for other characteristics that vary among sites.

Multivariable regression was used to develop a statistical relationship between the dependent variable and a set of predictor variables. In this case, crash frequency was the dependent variable of interest and several predictor variables were considered, including traffic volume and other roadway characteristics (e.g., presence of interchange). Coefficients were estimated for predictor variables during the modeling process. The coefficients represent the expected change in the dependent variable (crash frequency) due to a unit change in the predictor variable, all else equal.

The current state of the practice for developing cross-sectional crash prediction models is to assume a log-linear relationship between crash frequency and site characteristics. Generalized linear modeling (GLM) techniques were applied to develop the crash prediction model, and a log-linear relationship was specified using a negative binomial error structure. The negative binomial error structure is now recognized as more appropriate for crash counts than the normal distribution assumed in conventional regression modeling. The negative binomial error structure also has advantages over the Poisson distribution used in early crash modeling, because it allows for over-dispersion, which is often present in crash data. Final model specifications were determined using exploratory data analysis (as outlined in Hauer [2015]).

There are several potential sources of bias in the development of cross-sectional crash prediction models. The biases are described below with an explanation of why they were dismissed or how they were addressed:

- *Selection of appropriate functional form*: Functional form relates to both the overall form of the model and the form of each independent variable. The current state of the practice was used for the overall form of the model (i.e., log-linear relationship), and exploratory data analysis techniques were used to identify an appropriate form for each predictor variable.
- *Correlation among independent variables*: Correlation refers to the degree of association among variables. A high degree of correlation among the predictor variables makes it difficult to determine a reliable estimate of the effects of specific predictor variables. The correlation matrix was examined to determine the extent of correlation among independent variables and used to prioritize variables for inclusion.
- *Low sample mean and sample size*: Sample size is generally not an issue with respect to total crashes but may be a potential concern for other crash types (e.g., nighttime, wet pavement, lane departure). This is a specific concern when indicator variables are included in the model. Each binary indicator is composed of two bins: one for sites with the feature of interest and one for sites without the feature. Further subdivisions are created with each indicator variable added to the model. This limits the number of observations when several factors are considered together.
- *Over-fitting of prediction models*: Over-fitting is related to the law of diminishing returns. At some point, it is not worth adding more independent variables to the model because they do not significantly improve the model fit. Over-fitting also increases the opportunity to introduce correlation in the model and the opportunity for small sample issues when considering indicator variables. Several combinations of predictor variables were considered, and relative goodness-of-fit (GOF) measures were employed to penalize models with more estimated parameters.
- *Omitted variable bias*: Cross-sectional models estimate parameters (coefficients) based on the variables included in the model specification. The coefficient for each predictor variable is the impact of that factor given the other factors included in the model. If an important predictor is not included in the model, then that predictor’s effect may be captured by other variables in the model. It is important that all safety-related factors be included in the model specification for interpreting the coefficient for SRPM presence. The project team obtained data from the Illinois Tollway and through additional data collection using Google Earth. For example, the project team collected approximate mileposts of horizontal curves, confirmed number of lanes, confirmed construction presence, and identified breaks between base and interchange segments.

Multivariable models were developed by creating base models with traffic volume and segment length, exploring the need for other predictor variables in the base models, and selecting the final model. Having developed the base models for each crash type (traffic volume only), additional variables were considered using variable introduction exploratory data analysis (VIEDA), as outlined by Hauer (2015). VIEDA was used to identify whether the ratio of observed crashes to fitted crashes exhibited a regular relationship with the variable considered for addition to the model. If so, it was used to identify the proper function for the new variable.

Once a variable was included in the model, the estimated parameters and associated standard errors were examined to determine the following:

- Is the direction of effect (i.e., expected decrease or increase in crashes) in accord with expectations based on previous research?
- Does the magnitude of the effect seem reasonable?
- Are the parameters of the model estimated with statistical significance?
- Does the estimated over-dispersion parameter improve significantly?

The final step was to consider correlations among predictor variables included in the model specifications. Correlated predictor variables were prioritized for inclusion in the final models.

1.5.3 Phase II Methodology

The Phase II study employed the empirical Bayes before-after study design to develop final CMFs. The cross-sectional methodology employed in Phase I provided an indication of the effectiveness of SRPMs but suffers from potential biases due to the number of covariates included in crash prediction models. CMFs estimated in Phase I were a function of only a few covariates collected, and confounding factors across facilities and sections with and without SRPMs can impact the estimates of the CMFs (i.e., omitted variable bias). The Phase II analysis focused on the before-after safety effectiveness while accounting for potential regression to the mean and changes in traffic volumes using the study design methodology outlined in this section.

The general methodology for Phase II is the empirical Bayes before-after study design. This method is based on the observational before-after study design, but benefits from significant advances, which culminated in a landmark book by Hauer (1997). That book, which was used as a resource for this project, also provided guidance on study design elements such as sample size, selection criteria for treatment and reference groups, and pooling data from diverse sources. These are all crucial elements to successfully conduct a safety effectiveness study.

The methodologies documented by Hauer (1997) range from simple before-after comparisons to the more powerful empirical Bayes before-after methodology. The project team implemented the latter approach to overcome the difficulties associated with conventional before-after comparisons. Specifically, the proposed analysis:

- Properly accounts for regression-to-the-mean.
- Overcomes the difficulties of using crash rates in normalizing for traffic volume differences between the before and after periods.
- Reduces the level of uncertainty in the estimates of safety effect.

- Provides a foundation for developing guidelines for estimating the likely safety consequences of contemplated installations.

The approach is comprised of three basic steps.

Step 1: Predict what safety would have been in the “after” period had the status-quo been maintained.

Step 2: Estimate what the actual safety was in the “after” period.

Step 3: Compare the two.

The empirical Bayes before-after procedure requires the calibration of SPFs relating crashes of different types and severities to traffic flow and other relevant factors *for locations without the treatment*, with appropriate adjustments for temporal effects. The SPF is not only used to account for regression-to-the-mean, but also to account for traffic volume changes. Reference sites were used to account for time-related trends.

CHAPTER 2: DATA COLLECTION AND ANALYSIS

2.1 PAVEMENT MARKER PERFORMANCE

2.1.1 Test Marker Installation

To help ensure that the test markers were installed according to specifications, a research team member was present at every test section installation. The first step for installing an SRPM is to cut the groove with the appropriate blade arrangement. Figure 5 is a photo of a grinder head with larger diameter outside blades for cutting the groove for the six marker types with rails. Figure 6 shows a completed cut.

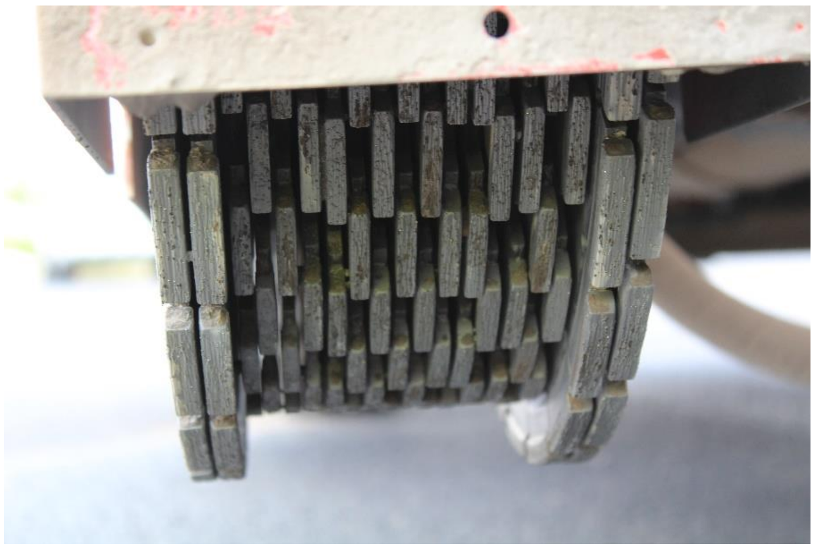


Figure 5. Grinder blade arrangement for SRPMs with rails.

Figure 6. Completed cut for SRPMs with rails.

The R-100 marker does not have rails and therefore requires a grinder head with all blades of equal diameter, as shown in Figure 7. Figure 8 is an example of the completed “banana” cut with two R-100 markers installed.

Figure 7. Grinder blade arrangement for R-100 markers.

Figure 8. Completed “banana” cut with two R-100 markers.

The next step is to check that the marker fits in the groove and the leveling tabs rest on the pavement surface, as shown in Figure 9. Figure 10 shows epoxy adhesive being poured into the groove and then more epoxy being poured after the marker is in the cut. The first pour filled the cut to within approximately 3/8 in. of the pavement surface, and the second pour is common practice to help seal all the edges of the marker.

Figure 9. Marker placed in dry cut (no adhesive) to verify leveling tabs rest on the pavement.

Figure 10. Epoxy adhesive being poured before and after the marker is placed in the cut.

The photos taken by the ARA researcher after installation served as a baseline reference for future comparisons to assess marker conditions. Figure 11 is an example of an installation photo of an H1010 on the I-70 test section.

Figure 11. Example installation photo of an H1010 marker on I-70.

The researchers also made an observation during the installation of the Guide Lite markers. After the epoxy adhesive was poured around the marker, small bubbles appeared in the epoxy, as shown in Figure 12. The marker floats in the adhesive due to its low density. The researchers also noted that if weight is placed on top of the marker before the epoxy is set (e.g. carefully stepping on the center of the marker), then the marker will be pushed down and more air bubbles appear. Annual assessments should show if this slight elevation difference affects the marker's resistance to snowplowing.

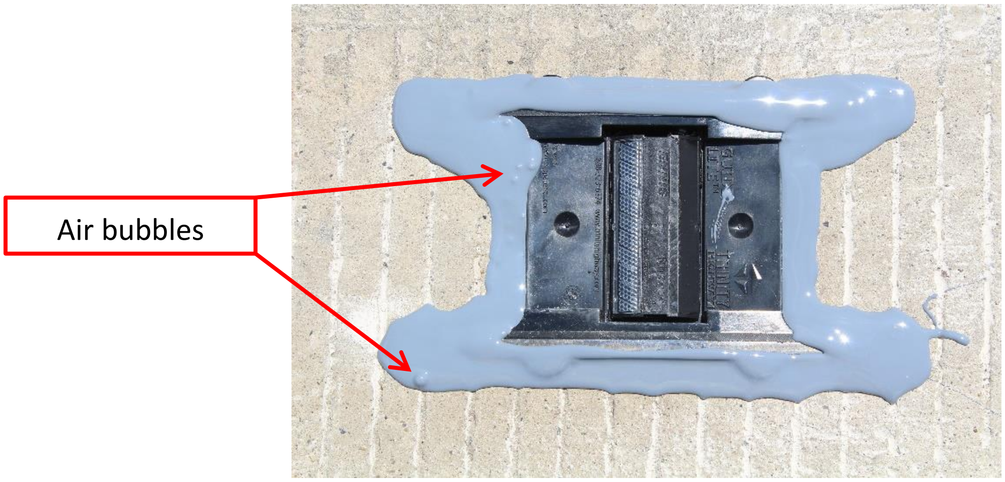


Figure 12. Air bubbles appeared in adhesive after installation of Guide Lite markers.

At the completion of all test section installations, each site had 16 or more of each marker type. The original test plan was to have 20 or more of each marker, and most sites had 20 to 40 of each marker.

2.1.2 Test Marker Annual Assessments

Annual assessments were completed in 2017, 2018, and 2019. This section reports the results of those field assessments. Figure 13 provides a summary of the pavement condition surrounding the markers at each test location after each year. The data is reported by the percentage of markers at each location. After one year, none of the sites were in poor condition, but much of the I-90 and I-57 sites were in fair condition. After the second year, a few marker locations at the I-155 and I-70 sites had pavement in poor condition surrounding them. Although the graphs appear to show an improvement in pavement condition at I-155 between Year 2 and Year 3, this is actually a result of Year 1 and 2 containing the additional Guide Lite markers. All poor-condition pavement at the I-155 site in Year 2 is surrounding the Guide Lite markers, and there is not a Year 3 evaluation of those markers because they were installed one year later than the other markers. By Year 2 the pavement condition surrounding all but two of the I-155 Guide Lite markers was in fair or poor condition. However, at the IL-8 site, just one Guide Lite marker location was in fair condition, and the other 19 were in good condition. Therefore, an assessment of the Guide Lite marker's performance in good-condition pavement can still be made. By the final evaluation year, the pavement surrounding a majority of the pavement markers was in good to fair condition and did not appear to affect the markers' performance. The condition rating scale is described in Section 1.4.2.

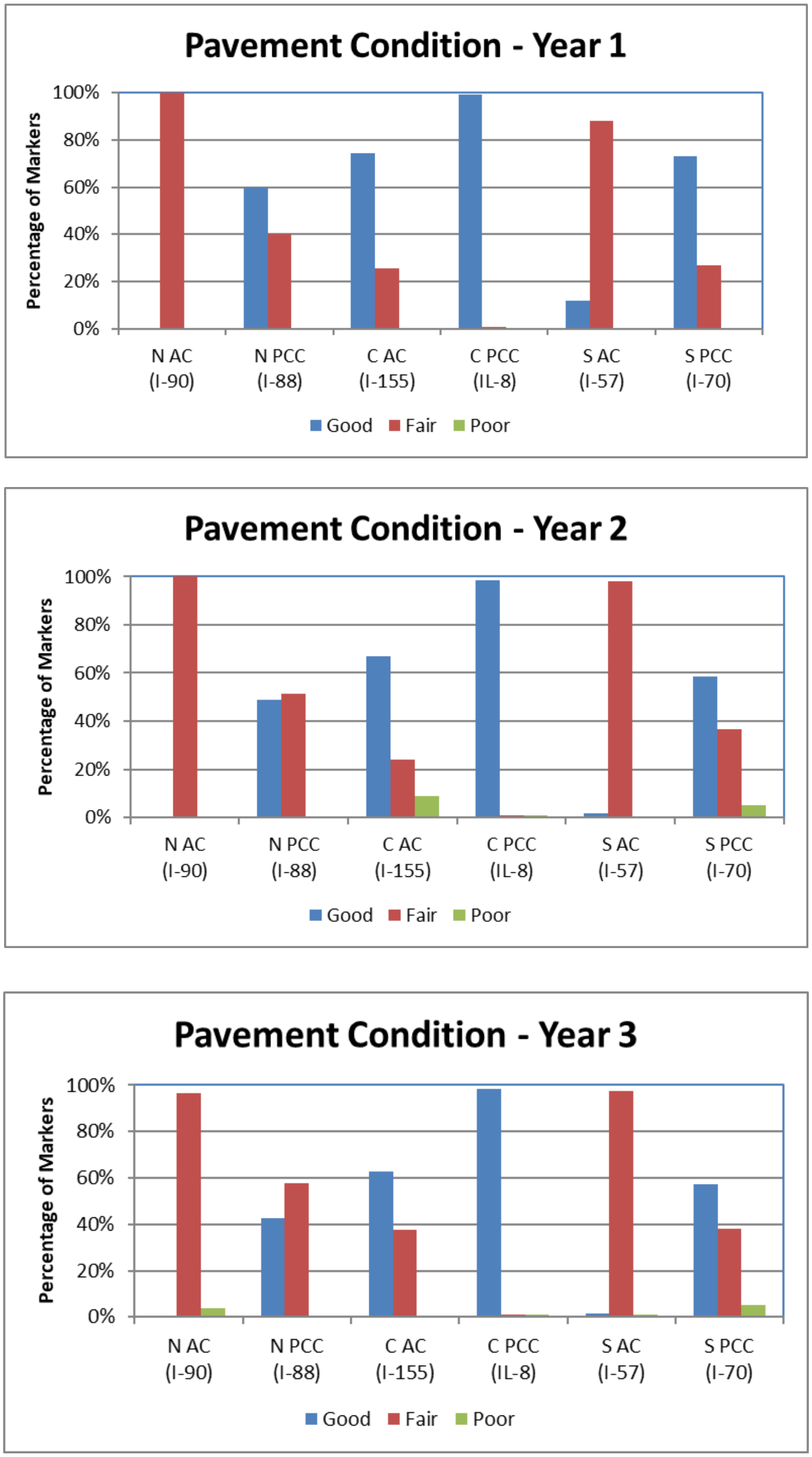


Figure 13. Pavement condition surrounding test markers at each location after each year.

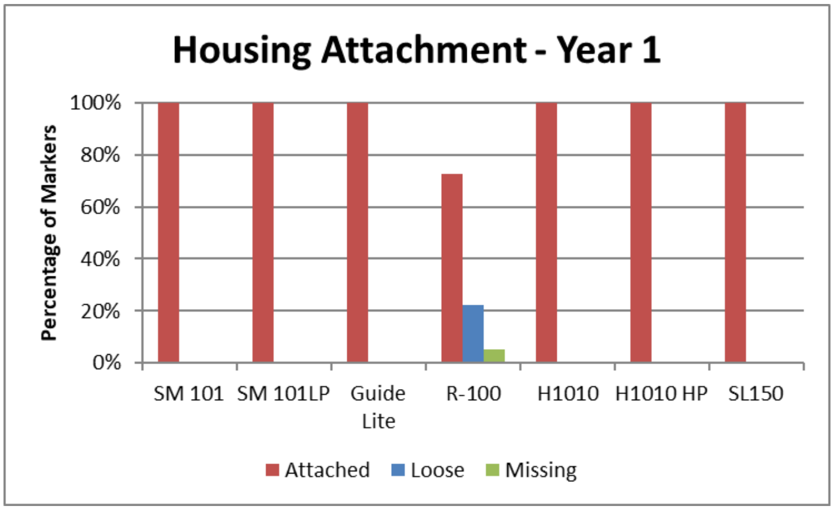
Note: I-155 pavement condition did not improve in Year 3. Years 1 and 2 include the additional Guide Lite markers, and therefore, have a larger and different sample set than in Year 3.

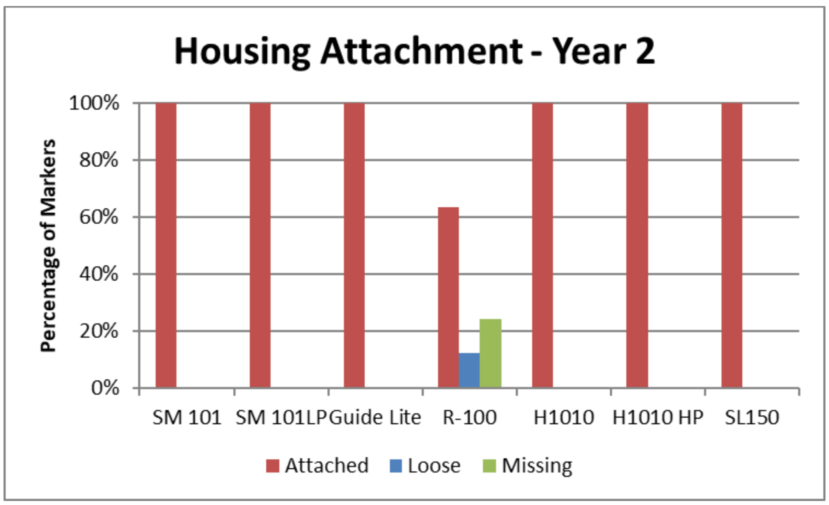
The next twelve figures report the condition of the markers. Because the Guide Lite marker was installed one winter after the other markers, the “Year 1” and “Year 2” assessments include the Guide Lite markers but the “Year 3” assessments do not. Figure 14 displays the percentage of marker housings that are attached, loose, or missing after each year’s winter. R-100 was the only marker that was loose or missing after both Year 1 and Year 2. By the end of Year 3, approximately half of the R-100 markers were loose or missing.

Figure 15 presents the percentage of R-100 markers missing after three years at each test site. The missing R-100 markers are almost entirely from concrete-surfaced sites. After three years, nearly all (18 of 20) R-100 markers on the IL-8 site were missing. Both the marker and the epoxy were gone for nearly all missing R-100. A few markers, like the one shown in Figure 16, were found at the side of the road with the epoxy still bonded to them. As listed in Table 4, R-100 weighs 0.25 lb, and the marker in Figure 16 weighs 0.40 lb, slightly heavier than the marker by itself but still not as dangerous as a projectile as heavier markers.

Figure 17 is a photo of the empty “banana cut” where an R-100 used to be. As seen in the photo, water is now “ponding” in these cuts. Water ponding on the pavement surface that freezes can cause pavement deterioration issues. Figure 18 is a photo of the location where an R-100 is now missing from an asphalt-surfaced site. The entire marker, all of the epoxy, and some of the asphalt pavement overlay are gone. The epoxy used for the R-100 markers was the same epoxy as used for all other markers at the test site.

Although many of the Guide Lite markers were severely damaged after Year 2, all of them still remained attached to the pavement. After Year 3, there was one SM101 on I-70 (southern PCC site) and one H1010 on IL-8 (central PCC site) that appeared to be a little loose. However, after three winters, all 783 traditional cast-iron markers were still bonded to the pavement surface.





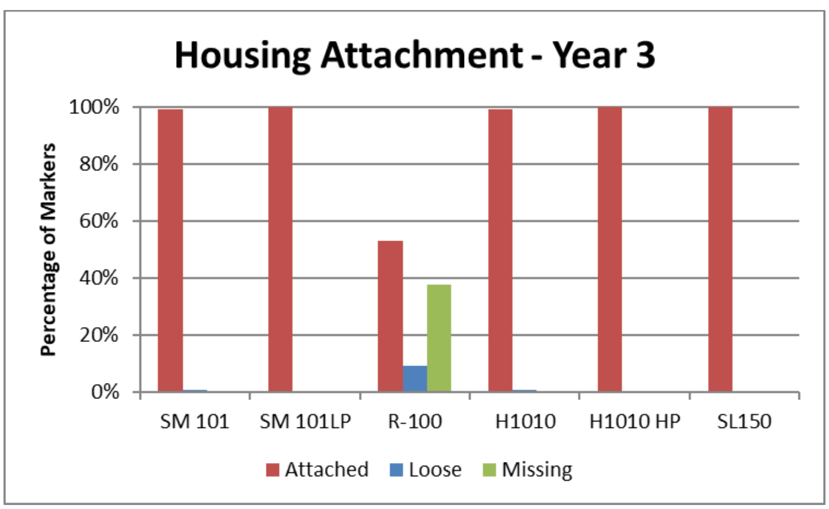


Figure 14. Marker housing attachment condition after each year.

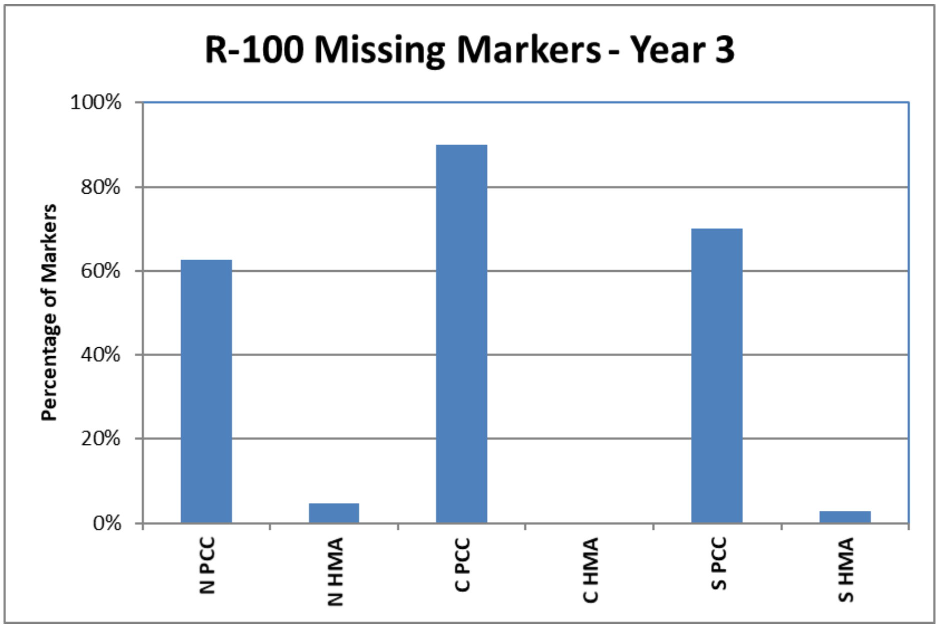


Figure 15. Percentage of missing R-100 markers by test site location after three years.

Figure 16. Dislodged R-100 with epoxy still bonded to it.

Figure 17. Missing R-100 on IL-8 (central PCC site).

Figure 18. Missing R-100 on I-90 (northern HMA site).

Figure 19 reports the percentage of markers with missing lenses after each year. The reflective lens was only counted as missing if the housing was still present. Therefore, the percentage of missing markers is also reported here. After one year, all but the Guide Lite and SL150 had at least one marker with a missing lens. R-100 had the highest number of missing lenses. After two years, every marker type had at least one lens missing, but the Guide Lite had the highest percentage of missing lenses, with over 40% missing. After three years, H1010HP had the highest percentage of missing lenses, with 10% missing, of the traditional markers. Of this 10%, the majority of missing lenses were from the central and northern test sites. The higher loss of lenses may be attributable to the higher-profile design of the marker; however, SM 101 (a high-profile marker) had a lower percentage (2%) of missing lenses than SM 101LP (a low-profile counterpart), with 5% of lenses missing.

Figure 20 is an example of a Guide Lite on I-155 (central HMA site) with a missing lens after two years. The figure includes the installation and Year 1 photos to show the progressive condition. The Year 2 photo also shows damage to the marker itself. Of the markers with three years of service, R-100 has the highest percentage of missing lenses and missing markers, but H1010HP has the highest percentage of missing only lenses, with 10% missing.

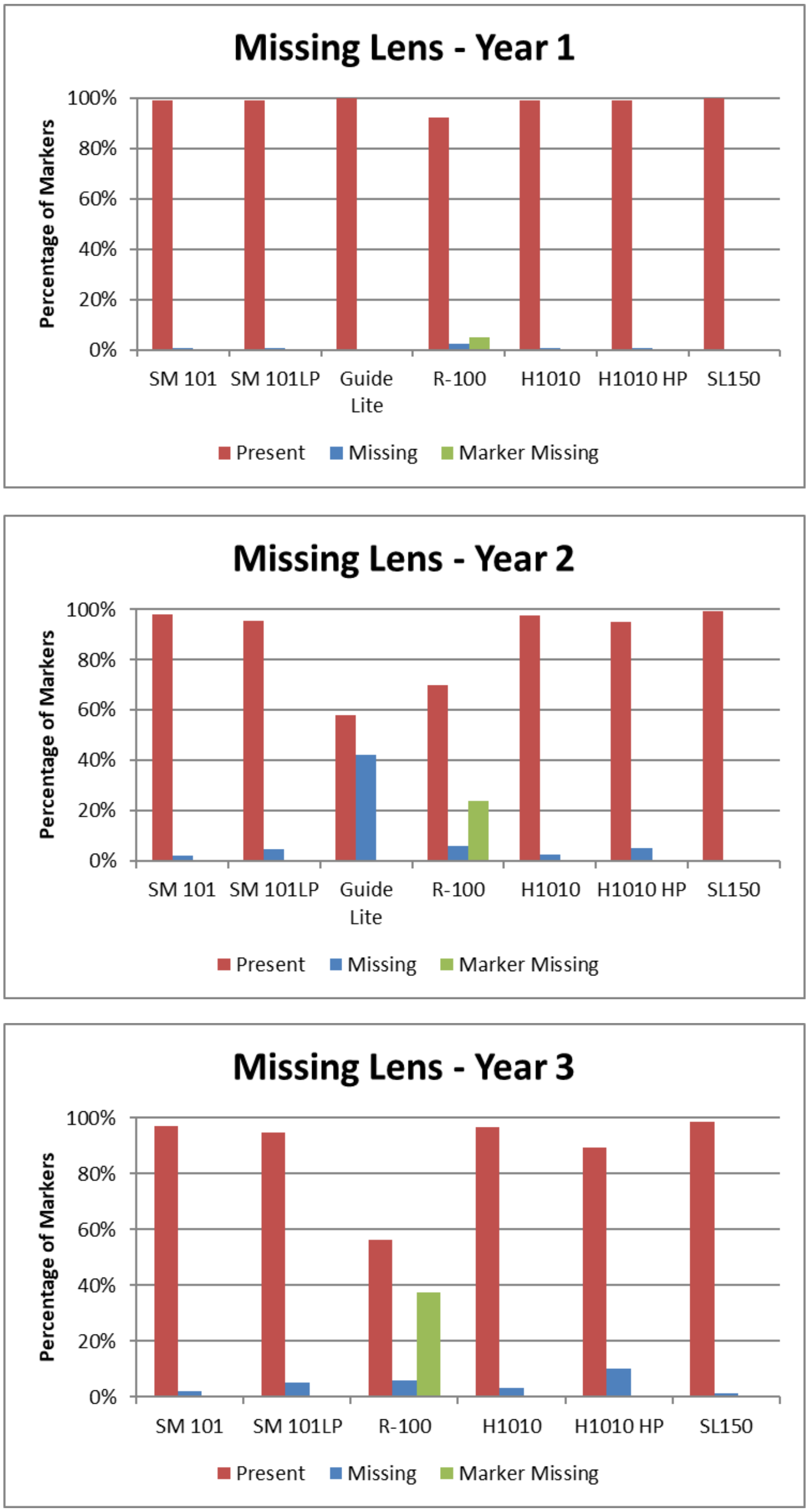


Figure 19. Percentage of markers with and without reflective lenses after each year.

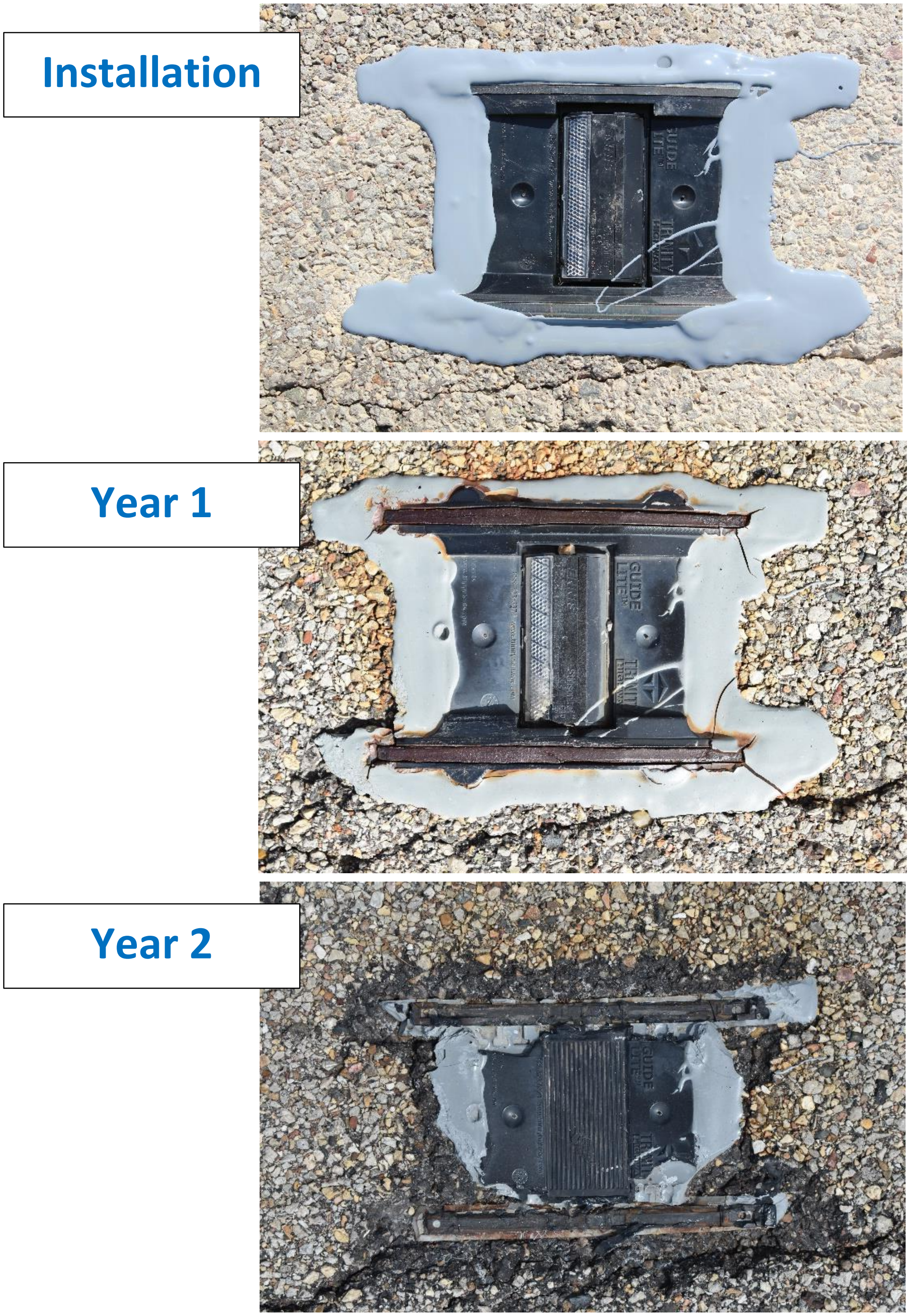


Figure 20. Guide Lite with no lens after two years of service on I-155 (central HMA site).

Figure 21 shows that the missing lenses do not appear to be strongly associated with a particular type of pavement surface. However, there is a higher percentage of missing lenses in the central and northern regions of the state than there is in the southern region.

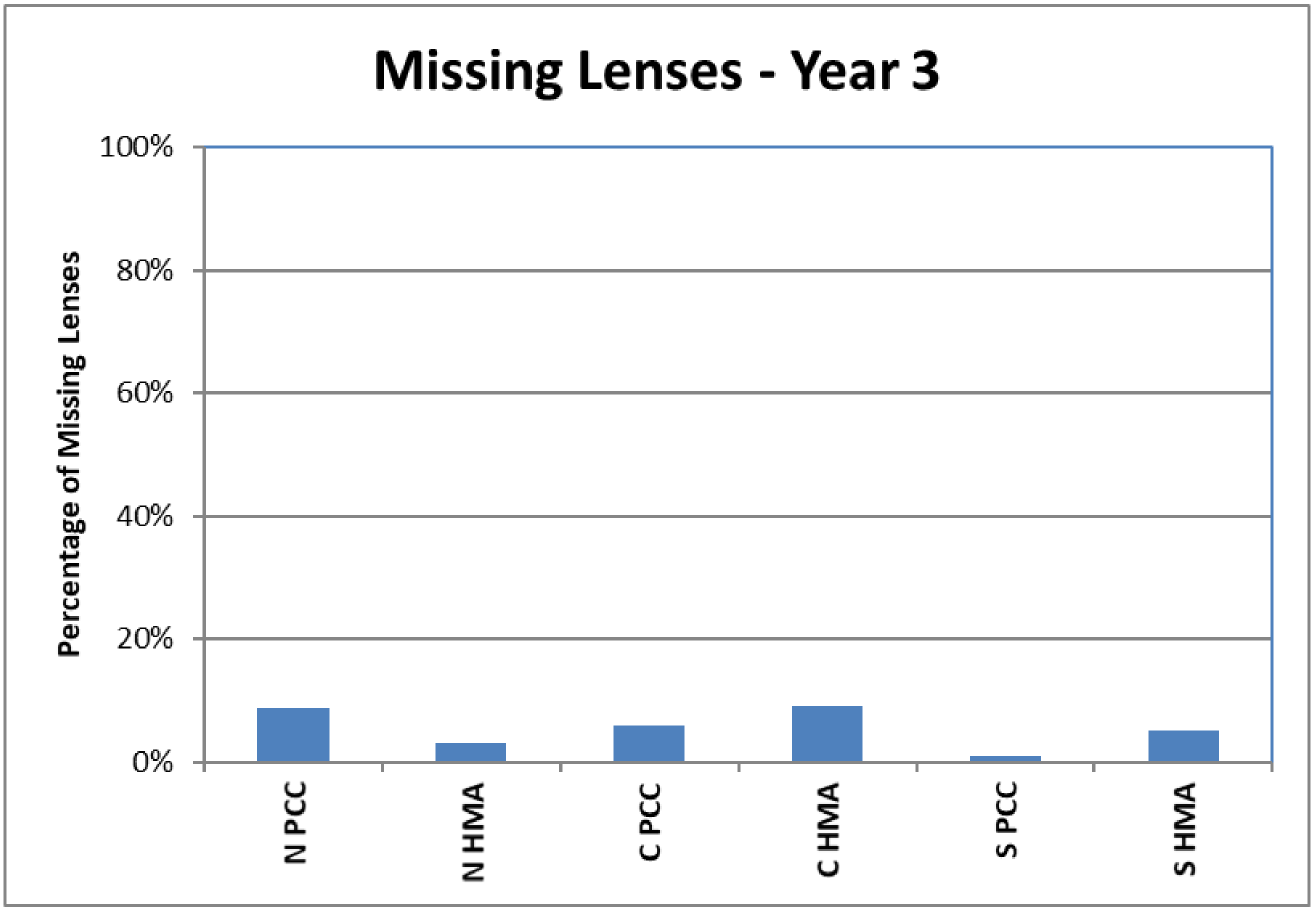


Figure 21. Percentage of missing lenses by test site location after three years.

Figure 22 reports the percentage of markers with the leading rails exposed after each year. Keeping the leading edge covered with adhesive and below the pavement surface will help keep water from infiltrating the groove and snowplows from shearing or removing the marker. Because R-100 does not have rails, it is not included in these figures. As shown, the five SRPMs with rails installed in 2016 are performing well. However, nine of the 57 Guide Lite markers had exposed rails after the first year, and nearly 90% had exposed rails after the second year. This is likely due to the marker floating up in the epoxy at installation. However, the leading edge of every Guide Lite was still below the pavement surface. Figure 23 is an example of a Guide Lite marker on I-155 that has a leading edge exposed after one year of service. Some damage to the steel rail can also be seen after one year.

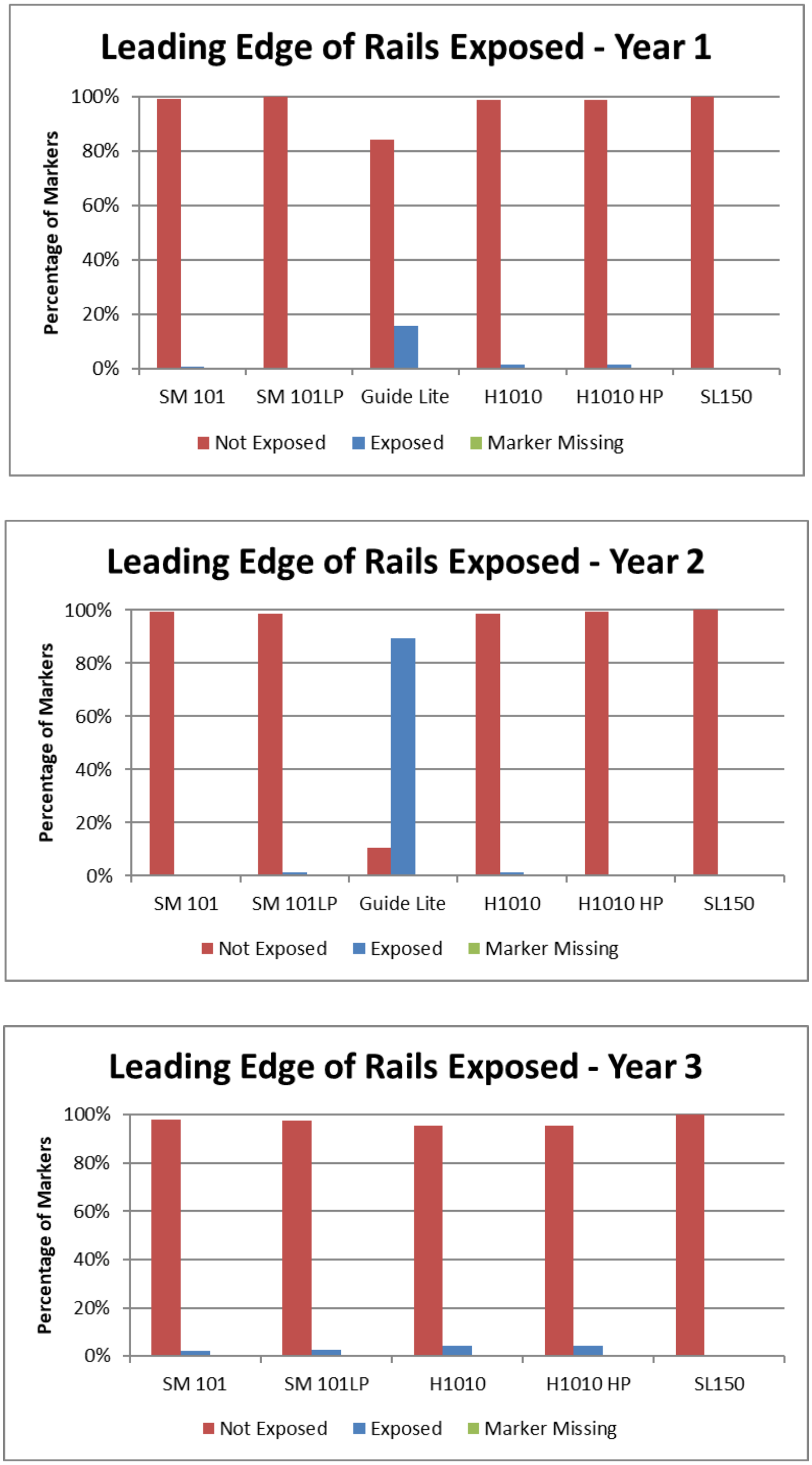


Figure 22. Percentage of markers with leading edge of rails exposed after each year.

Figure 23. Example of Guide Lite with leading edge of rail exposed after one year.

To assess the performance of the epoxy adhesive remaining bonded to the marker and pavement, a visual comparison was made of every marker's installation photo to its final annual inspection photo. The percentage of missing epoxy was recorded in one of five categories:

1. 0% missing
2. 1–25% missing
3. 26–50% missing
4. 51–75% missing
5. 76–100% missing

These percentages are based on the top view of the markers, as seen in the photos, and do not represent the total amount of epoxy because a portion of the epoxy is beneath the marker. Figure 24 presents the results of the missing epoxy assessment for the six marker types with three annual inspections, and Figure 25 presents the results of the Guide Lite markers after the two-year inspection. The majority of the five traditional markers had only 25% or less epoxy missing. The R-100 markers were in all five of the missing epoxy categories. Some had no missing epoxy and some had 100% of the epoxy missing, including the epoxy beneath the marker as previously shown in Figure 17 and Figure 18. After just two years, none of the Guide Lite markers had 100% of the epoxy remaining. Most of the Guide Lite markers had 26% to 100% of the visible (top view) epoxy missing. However, despite the epoxy missing on the surface, the epoxy beneath the marker was performing well since all Guide Lite markers were still present and bonded to the pavement.

The epoxy used for installing the Guide Lite markers was P3 Infrastructure's Duradhesive. The epoxy used for the I-88 (northern PCC) test site is unknown, and the epoxy used for all other markers was Epoplex's MA50. The epoxies were selected by the contractors installing the pavement markers. Since the two known epoxy types were used with different markers, no comparisons can be made between their performance. A comparison of the epoxy types would require them to be used with the same marker, on the same pavement surface, and in the same environment. Therefore, without MA50 and Duradhesive both being used with the Guide Lite marker, it cannot be inferred whether the greater epoxy loss was due to the type of epoxy. It is possible that the Duradhesive may simply have had a stronger bond to the marker than the pavement and was removed with the marker as pieces of the marker were broken off.

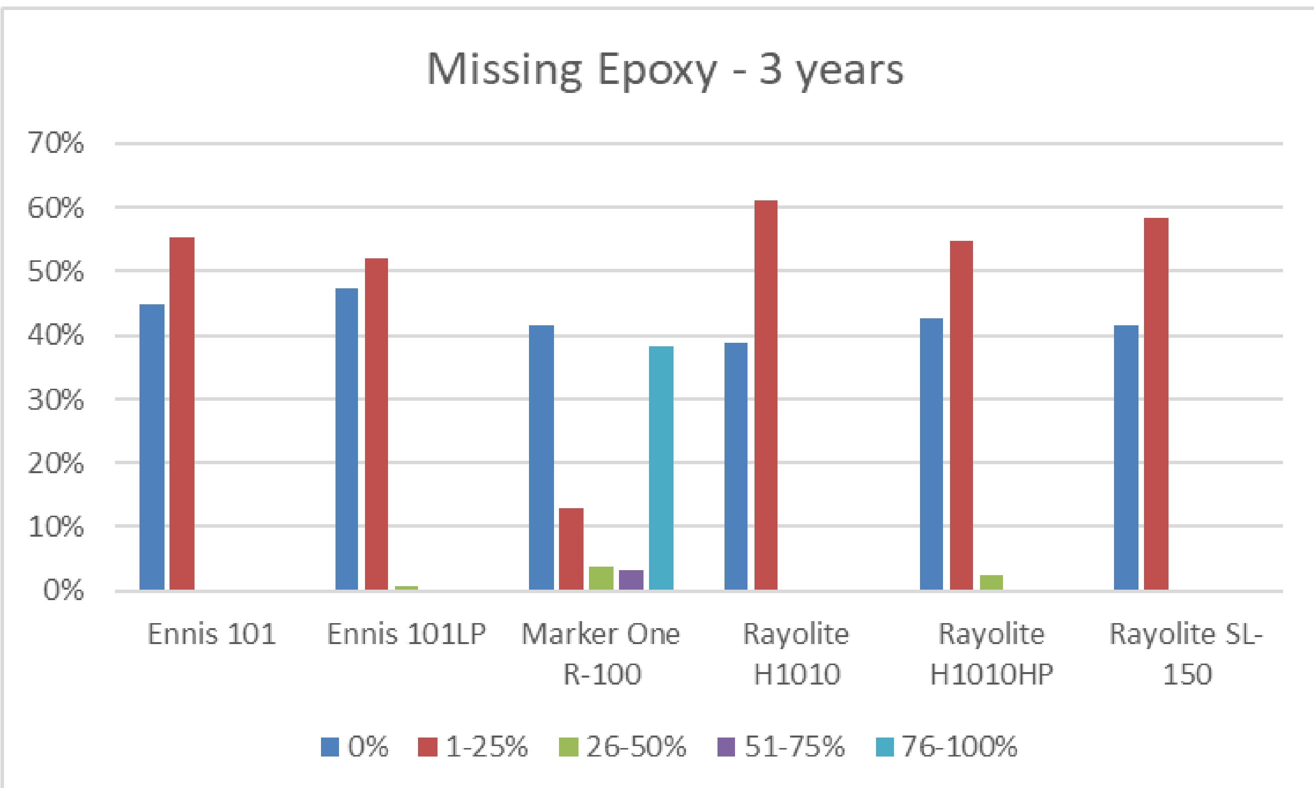


Figure 24. Percentage of missing epoxy from top view of six SRPMs after three years.

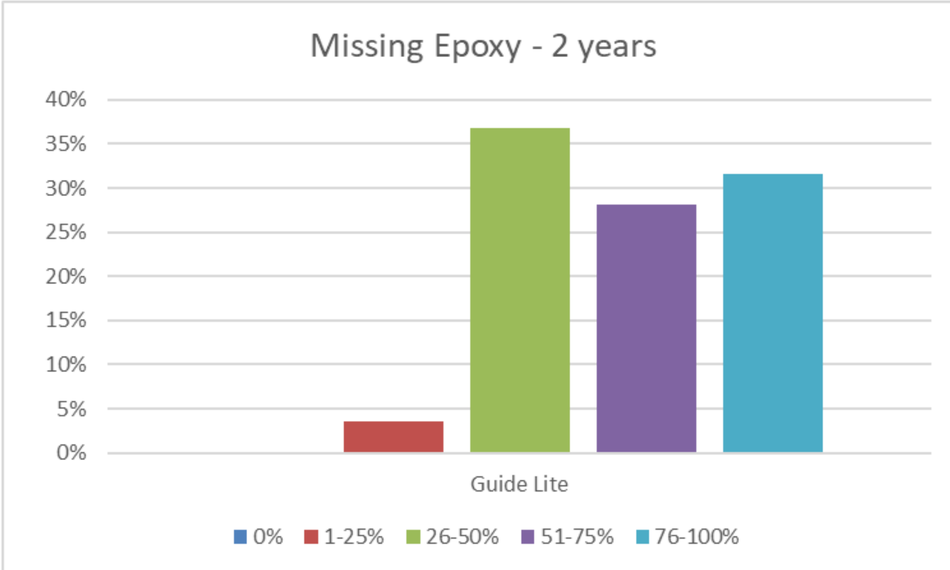
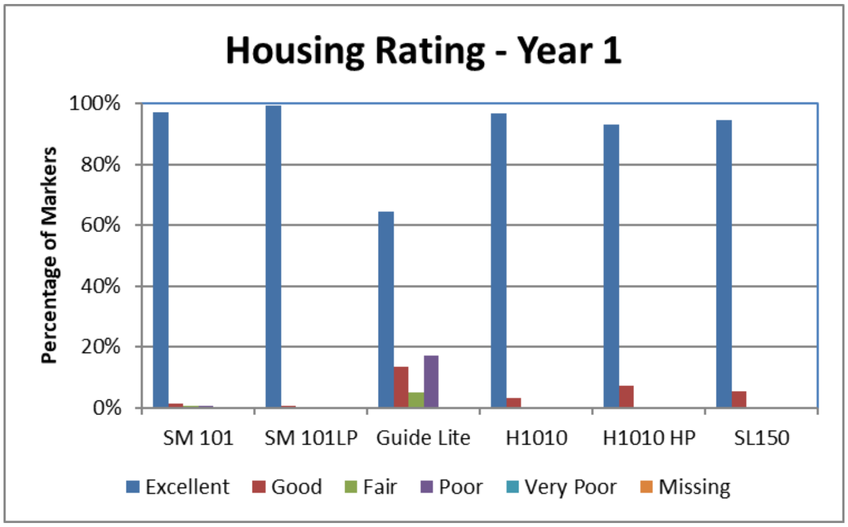
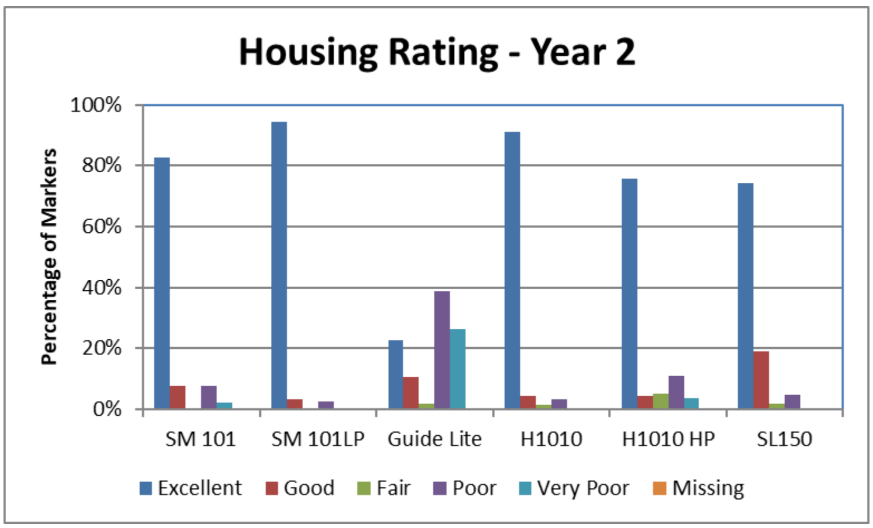


Figure 25. Percentage of missing epoxy from top view of Guide Lite markers after two years.

Figure 26 provides each year's results of the overall marker housing condition based on the NTPEP rating scale, as described in Section 1.4.2. Because the NTPEP scale is based on traditional SRPM housing, this assessment does not include R-100. After one winter, the Guide Lite experienced the most damage. The traditional cast-iron markers exhibited more damage after Year 2, but a majority of the markers were still in excellent condition. The Guide Lite marker housing was in the worst condition, with over 60% of the markers in poor or very poor condition. After Year 2, the two high-profile markers, SM 101 and H1010 HP, were the first of the traditional markers to have a few markers (2% and 4%, respectively) in very poor condition. After the third winter, these two high-profile markers were still the only traditional markers to have a few in very poor condition (2% and 8%, respectively). The higher profile means that the markers are in greater contact with snowplows, which explains the higher rate of damage. After the third winter, H1010 HP had the lowest overall housing condition ratings, with 25% in fair to very poor condition. SM 101 had 17% in fair to very poor condition, and 17% of SL150 were in fair to poor condition. SM 101LP had the highest overall housing condition rating, with 94% in good to excellent condition, and H1010 had the second-highest rating, with 89% in good to excellent condition. The lower profile marker design affects the longevity of the marker condition.

Figure 27 is an example of the deterioration of a Guide Lite marker on I-155 (central HMA site) after two years of service. The marker exhibits severe damage, and the damage shown is representative of the other markers in poor to very poor condition. The rail component of the markers sustained the most damage. The plastic rails and the steel inserts are often either cracked or broken. As previously mentioned, the pavement condition surrounding the I-155 Guide Lite markers was mostly in fair or poor condition, but the IL-8 Guide Lite marker locations were almost entirely in good condition. However, 85% of the IL-8 Guide Lite marker housings were in poor to very poor condition, and 54% of the I-155 Guide Lite markers were in poor to very poor condition. Therefore, the pavement condition did not contribute to the Guide Lite markers' performance.





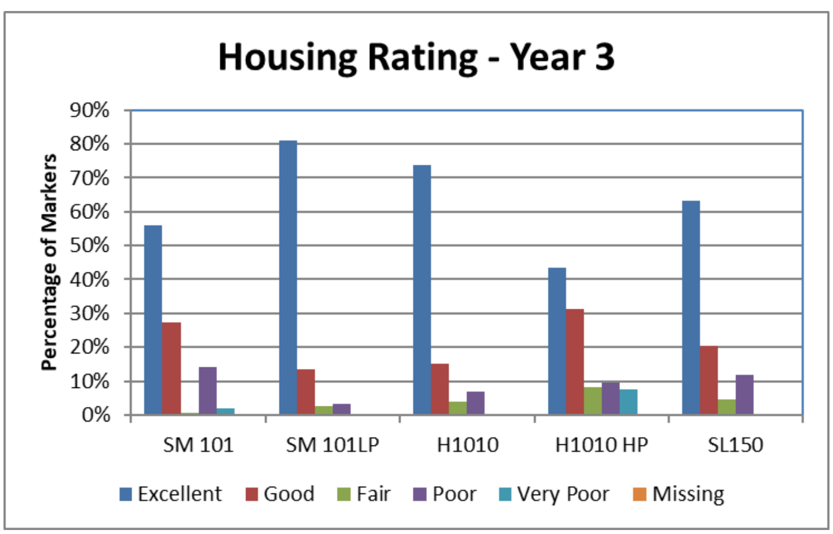


Figure 26. SRPM housing condition rating after each year.

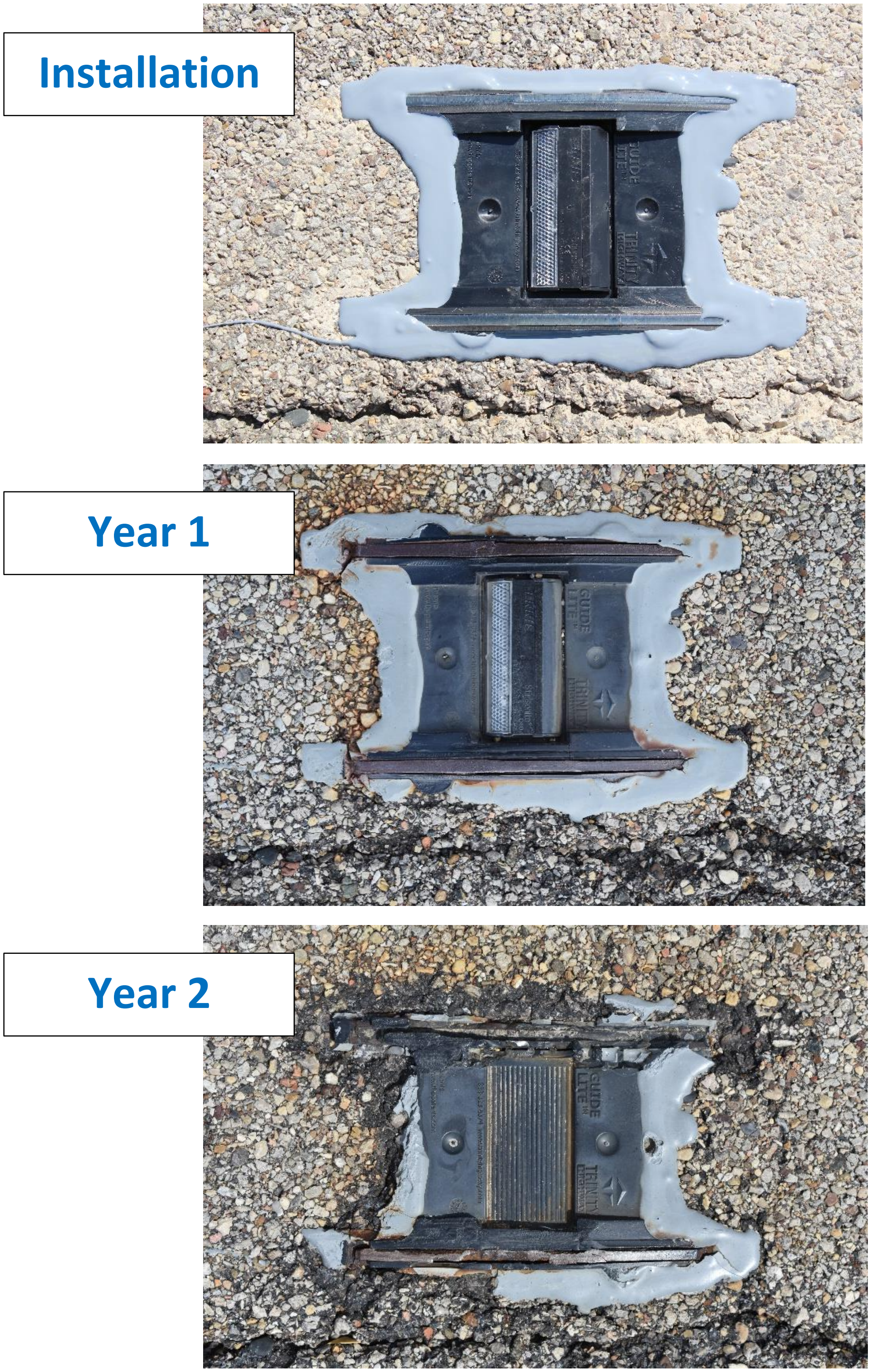


Figure 27. Guide Lite marker in very poor condition after two years of service on I-155.

2.2 CRASH MODIFICATION FACTOR DEVELOPMENT

2.2.1 Literature Review

Bahar et al. (2004) examined the safety effects of snowplowable permanent raised pavement markers (PRPMs) in six states along two-lane roadways, four-lane expressways, and four-lane freeways using an empirical Bayes before-after safety evaluation methodology. Safety performance functions were developed for total, fatal and injury, nighttime, nighttime fatal and injury, daytime, daytime fatal and injury, wet weather, dry weather, and guidance related crashes. The disaggregate analyses showed that:

- Nonselective implementation of PRPMs on two-lane roadways does not have a significant association with total or nighttime crashes.
- For locations where PRPMs were implemented based on selective policies (e.g., poor crash history), significant positive effects were found in some instances (decreases in total, nighttime, wet weather, and wet weather nighttime crashes). Additionally, PRPMs that were installed based on nighttime crashes were found to be associated with a significant increase in crashes for AADTs between 5,000 and 15,000 with a degree of curvature greater than 3.5.
- Nonselective implementation of PRPMs on four-lane freeways showed no safety effect for total or nighttime crashes. Significant reductions were found for wet weather crashes at non-interchange locations, and results showed that PRPMs were effective in reducing nighttime crashes where the AADT exceeds 20,000.
- The safety effect of PRPMs was not explored for four-lane expressways due to data constraints.

Smiley et al. (2004) found that retroreflective raised pavement markers (RRPMs) can be used as a treatment for locations with a history of unusual crash frequencies. They found a decrease in total crashes, nighttime crashes, and wet weather crashes when the RRPMs were installed at locations with high numbers of wet weather nighttime crashes. The benefit of RRPMs was not as clear at locations selected based on total crashes or without any selection criteria. Total, dry weather, and wet weather crashes increased in frequency after the application of RRPMs, showing that selective implementation may prove effective and nonselective implementation ineffective.

Wright et al. (1982) estimated a 22% reduction in nighttime crashes compared with daytime crashes. Sites installed in 1976 and 1977 had reductions of 33% and 32%, respectively. Sites installed in 1978 observed a 53% increase in nighttime crashes. Single-vehicle crashes were estimated to have been reduced by 12% more than other nighttime crash types. These reductions were found to be independent of average daily traffic (ADT) and curvature (although all curves were 6 degrees or greater).

Kugle et al. (1984) collected two-year before-and-after installation for PRPMs installed on two, three, four, five, and six lane roadways from 1977 to 1979 in Texas. The evaluation methods provided results indicating a 15% to 31% increase in nighttime crashes and an insignificant 1% to 1.4%

decrease in wet weather crashes. The authors noted that about 10% of the sites showed very large increases in total crashes, which may have unfairly skewed the overall results.

Mak et al. (1987) reevaluated Kugle's data, screening those sides that underwent major modifications other than PRPM installation, using a statistical procedure based on the cross-product ratio. The results showed that four locations experienced a significant decrease in nighttime crashes relative to daytime crashes, nine showed significant increases, and 74 showed no significant change.

Griffin (1990) reevaluated the Mak sites by calculating a weighed log odds ratio. The expected change in nighttime crashes was estimated to have a significant 16.8% increase.

New York State Department of Transportation (DOT) (1989) analyzed the effect of PRPMs on unlit suburban and rural roadways with proportionally high numbers of nighttime and nighttime wet weather crashes using a simple before-after methodology. The DOT found a 7% decrease in total crashes, 26% decrease in nighttime crashes, 33% decrease in nighttime wet weather-related crashes, 23% reduction in all guidance-related crashes, and a 39% reduction in nighttime guidance-related crashes. A second analysis of 60 long sections of highway found an 8.6% reduction in nighttime crashes, 7.5% reduction in total crashes, and a 7.4% increase in nighttime wet weather crashes. They concluded that PRPMs should be installed only at locations with high frequencies of wet weather, nighttime, and guidance-related crashes.

Orth-Rodgers and Associates, Inc. (1998) used the odds-ratio to evaluate the effects of raised and recessed pavement markers on nighttime crashes on rural interstate highway locations in Pennsylvania. Results indicated a 12.3% increase in nighttime crashes, a 1.2% decrease for locations with raised pavement markers, and a 20.1% increase for locations with recessed pavement markers. Nighttime wet condition crashes showed increases from 30 to 47%, and nighttime wet road sideswipe and fixed-object crashes increased 56.2%. However, the odds ratio methodology required the researchers to drop sites with zero crashes in any period. Since the after period was shorter than the before period, a bias is created toward the underestimation of effects if a zero crash after period is due to the PRPM installation.

Das et al. (2013) examined the safety impact of RPMs along with pavement striping on Louisiana freeways using annual condition inspection ratings. This study included nine years of data for each site, where each site experienced several cycles of good to poor ratings for RPMs or striping. The authors found that RPMs have a significant effect in reducing crashes, particularly nighttime crashes, at all annual average daily traffic (AADT) levels. The analysis results also indicated that RPMs do not have any safety benefits on urban freeways. The analysis was conducted as a t-test for equality of means for crash rates between segments with good RPM ratings and poor RPM ratings.

Pendleton (1996) used classical and empirical Bayes before and after methods to evaluate the effect of PRPM nighttime crashes on undivided and divided arterials in Michigan. He found an increase in nighttime crashes for undivided roadways and a decrease in nighttime crashes for divided roadways. Daytime crashes as comparison sites yielded larger reductions (or smaller increases) in crashes than when nighttime crashes at untreated sites were used as a comparison group. However, no results were significant.

Bahar et al. (2006) performed a time-series safety analysis on pavement markings and markers on multilane freeways, multilane highways, and two-lane highways in California. National Testing Product Evaluation Program data were used to develop retroreflectivity models as a function of age, color, material type or marker type, climate region, and amount of snow removal. The authors found that the difference in safety for markings or markers between time periods with high retroreflectivity and low retroreflectivity is approximately zero. The authors surmised that it is important that markings are present and visible but level of retroreflectivity is less important.

2.2.2 Phase I Analysis

The initial data reconnaissance included conversations with the Illinois Department of Transportation (IDOT) and the Illinois Tollway. IDOT indicated that SRPMs have been used on most roadways for many years and original installation dates do not exist. Since SRPMs are used so frequently, IDOT indicated that it would be difficult to obtain an applicable set of reference sites. The installation sites used for in-service performance evaluation for this research had SRPMs in the before period and could not be used for a before-after analysis. Additionally, IDOT noted that they apply SRPMs as a blanket treatment on roadways except for some rural, two-lane highways with AADT less than 2,500, with a policy dating back to 1987. Due to the inability to find a condition pre-existing SRPM installation or a candidate set of reference sites for cross-sectional analysis, the project team did not further explore IDOT roadways.

The Illinois Tollway placed a moratorium on installing SRPMs on its roadways for a brief period, creating a scenario where several sections of the tollway had SRPMs, had them removed, and then had them reinstalled. The following corridors were noted to have no SRPMs for the years provided:

- Interstate 90; MP 2.5 to 17.5 from 2009–2015.
- Interstate 94; MP 0.0 to 25.0 from 2009–2014.
- Interstate 294; MP 0.0 to 17.5 from 2009–2015.
- Interstate 355; MP 0.0 to 12.5 from 2007–2013.

The project team determined that these sections could be used to develop a CMF for the presence of SRPMs. Initially, the project intended to use these sites for a before-after-after analysis, where the before period included SRPMs, the first after period had no SRPMs (i.e., CMF for removal of SRPMs), and the second after period had SRPMs reinstalled (i.e., CMF for installation of SRPMs). However, in compiling the data for analysis, the project team determined that the removal of SRPMs coincided with reconstruction activities that included the addition of a through lane in each travel direction for all corridors. As such, Phase I utilized a cross-sectional analysis method to compare sites with and without SRPMs. The cross-sectional analysis provided initial estimates of the effectiveness of SRPMs but included some biases that can be further accounted for using before-after studies.

For example, for cross-sectional studies, the safety effect is estimated by taking the ratio of the average crash frequency for two groups, one with the feature of interest and the other without the feature of interest. In this case, the feature of interest is the presence of SRPMs. For this method to work, the two groups should be similar in all regards except for the feature of interest. In practice, this is difficult to accomplish, and modeling results tend to capture differences between treated and untreated sites in the estimate of effectiveness. Therefore, the Phase II analysis included a statistically more reliable approach (a before-after empirical Bayes approach). Further details on the Phase I analysis are provided in the Interim Report.

2.2.3 Phase II Analysis

This section provides the results of the Phase II analysis, which included a before-after empirical Bayes approach to developing CMFs. This section provides an overview of the methodology used, data collection, development of safety performance functions, aggregate analysis, and disaggregate analysis.

2.2.3.1 Methodology

The empirical Bayes methodology for observational before-after studies was used for the Phase II evaluation. This methodology is considered rigorous in that it accounts for regression to the mean and changes in traffic volume using a reference group of similar sites. In the process, safety performance functions (SPFs) are used to address the following:

- Overcoming the difficulties of using crash rates in normalizing for volume differences between the before and after periods.
- Accounting for time trends.
- Reducing the level of uncertainty in the estimates of safety effect.

In the empirical Bayes approach, the change in safety (Δ) for a given crash type at a site is given in the following:

$$\Delta Safety = \lambda - \pi$$

where:

> λ = expected number of crashes that would have occurred in the after period without the strategy.
>
> π = number of reported crashes in the after period.

In estimating λ, the effects of regression to the mean and changes in traffic volume were explicitly accounted for using SPFs, relating crashes of different types to traffic flow and other relevant factors based on reference sites. Annual SPF multipliers were calibrated to account for temporal effects on safety (e.g., variation in weather, demography, and crash reporting).

In the empirical Bayes procedure, the SPF is used to first estimate the number of crashes that would be expected in each year of the before period at locations with traffic volumes and other characteristics similar to the one analyzed (i.e., reference sites). The sum of these annual SPF estimates (*P*) is then combined with the count of crashes (*x*) in the before period at an installation site to obtain an estimate of the expected number of crashes (*m*) before installation, as shown as:

$$m = w(P) + (1 - w)(x),$$

where *w* is estimated from the mean and variance of the SPF estimate, shown as:

$$w = \frac{1}{1+kP},$$

where *k* is the constant for a given model and is estimated from the SPF calibration process with the use of a maximum likelihood procedure. In that process, a negative binomial distributed error structure is assumed with *k* being the overdispersion parameter of this distribution.

A factor (C) is then applied to *m* to account for the length of the after period and differences in traffic volumes between the before and after periods, shown as:

$$\lambda = Cm$$

where C is the sum of the annual SPF predictions for the after period divided by *P*, the sum of these predictions for the before period. The result, after applying this factor, is an estimate of λ. The procedure also produces an estimate of the variance of λ.

The estimate of λ is then summed over all installation sites in a group of interest (to obtain λ_{sum}) and compared with the count of crashes observed during the after period in that group (π_{sum}). The variance of λ is also summed over all sites in the strategy group.

The Index of Effectiveness (θ) is estimated as:

$$\theta = \frac{\pi_{sum} / \lambda_{sum}}{1 + \left(Var(\lambda_{sum}) / \lambda_{sum}^2 \right)},$$

The standard deviation of θ is given as:

$$StDev(\theta) = \sqrt{\frac{\theta^2 \left(\frac{Var(\pi_{sum})}{\pi_{sum}^2} + \frac{Var(\lambda_{sum})}{\lambda_{sum}^2} \right)}{\left(1 + \frac{Var(\lambda_{sum})}{\lambda_{sum}^2} \right)^2}},$$

The percent change in crashes is calculated as 100(1–θ); thus, a value of θ = 0.7 with a standard deviation of 0.12 indicates a 30% reduction in crashes with a standard deviation of 12%.

2.2.3.2 Data Collection

As described in the review of Phase I, the Illinois Tollway provided information on when segments of the Tollway did not have SRPMs installed. Also, as indicated above, the removal and subsequent reinstallation of SRPMs did not coincide with a direct analysis of safety performance (i.e., a measurable effect on crash frequency). SRPMs were removed because of major construction work and complete reconstruction of the alignment, including the addition of a directional lane on these segments. SRPMs were removed during the reconstruction of the roadway and were not replaced due to the moratorium. SRPMs were not removed in other locations due to the moratorium. SRPMs were reinstalled on the segments between 2013 and 2015. The following sections provide insights on the data collected for segments with SRPMs reinstalled (i.e., treatment sites) and for reference sites.

2.2.3.2.1 Installation Data

The Tollway provided information on the sections without SRPMs by milepost with removal and reinstallation years. The data were provided as the following:

- Interstate 90, MP 2.5 to 17.5: removal in 2009, reinstallation in 2015.
- Interstate 94, MP 0.0 to 25.0: removal in 2009, reinstallation in 2014.
- Interstate 294, MP 0.0 to 17.5: removal in 2009, reinstallation in 2015.
- Interstate 355, MP 0.0 to 12.5: removal in 2007, reinstallation in 2013.

The project team removed the first and last year of each period from analysis due to construction activities and the removal or addition of SRPMs within that year. Additionally, the lanes on Interstate 355 were not open to traffic until 2008; therefore, the project team removed 2007 and 2008 from the analysis for all segments. Further, 2007 and 2008 were removed for all sites to limit the before period to five years. Having more than five years of consecutive data increases the odds that other unobserved effects could impact the safety effectiveness evaluation of the treatment of interest (in this case SRPMs).

2.2.3.2.2 Roadway Data

The Illinois Tollway provided as-built drawings covering most of the Tollway's network. However, multiple drawings covered the same span of the network while some sections did not have as-built drawings. For this reason, the project team was not able to establish all horizontal curve features for the study segments. The Tollway also provided 2003 to 2015 mainline surveys, including line maps. From this information, the project team was able to establish the number of lanes on each directional segment by year. The project team supplemented this data with a review on Google Earth to verify the number of lanes (using the historical feature) and to verify when total reconstructions were taking place on the network. Using the KMZ files provided by the Illinois Tollway, the project team also segmented the Illinois Tollway into basic freeway segments and interchange segments. Interchange segments were defined from the beginning of an exit taper to the end of the farthest entrance taper for one interchange. If no taper existed, then the project team used the midpoint of an auxiliary lane to define the end of the segment. Basic freeway segments were defined as those outside of interchange segments.

For each treatment and reference segment, the project team collected the following data attributes:

- Segment beginning milepost, ending milepost, and segment length.
- Route and direction.
- Number of horizontal curves.
- Total length of horizontal curves in the segment.
- Proportion of segment that was horizontal curve.
- Segment type (interchange or base).

- Number of lanes.
- Presence of construction within a given year.

The Illinois Tollway network was divided into directional segments to better quantify the effects of interchange influence, as ramps were often not symmetric with the centerline of the roadway. Additionally, volume data was provided directionally, allowing for a directional analysis of safety performance. Each directional segment across all facilities had at least three travel lanes per direction and were generally suburban in nature, having some ambient light at nighttime. However, the data collection process could not capture the magnitude of ambient light.

2.2.3.2.3 Traffic Data

The Illinois Tollway (2019) provided the 2007 through 2017 annual *Traffic Data Report for the Illinois Tollway System*. This report provided detailed information on freeway segment volumes, ramp volumes, and toll plaza volumes. This allowed the project team to calculate detailed AADT data by segment, accounting for lower traffic volumes between exit ramps and entrance ramps. AADT data were provided for each year. Additionally, the annual report provided an overview of types and locations of construction activities present on the Tollway. The project team used this data to validate the findings from the historical feature of Google Earth.

2.2.3.2.4 Crash Data

The Illinois Tollway provided 2007 through 2017 crash data for the Tollway sections, covering both the treatment and reference sites. The crash data provided details on crash location, crash direction, lighting condition, pavement condition, and crash type. From these details, the project team developed counts of the total number of crashes by type and severity for each directional segment (by route, direction, and milepost). The crash types developed included the following:

- Total crashes.
- Fatal and injury (FI) crashes.
- Lane departure (LD) crashes.
- Lane departure wet pavement (LD W) crashes.
- Lane departure nighttime (LD N) crashes.
- Lane departure wet pavement nighttime (LD WN) crashes.
- Lane departure fatal and injury crashes (LD FI) crashes.

The definitions of each crash type are provided in the Data Characteristics and Summary section.

2.2.3.2.5 Reference Sites

The project team identified adjacent segments (when possible) to serve as a reference group. Typically, the reference group would consist of nearby sites that could have been treated, but were not, for the entire period. In this way, the reference sites help to account for potential regression to the mean bias and to account for unobserved factors over time (e.g., weather conditions that may have influenced annual crash trends for the region). In this case, regression to the mean bias is not suspected since the treatment sites were not selected for improvement due to crash history.

Therefore, the project team used the before period data from treatment sites to develop SPFs. The purpose of the SPFs for this analysis was to account for changes in traffic volume at treatment sites. The reference group was established to account for unobserved effects each year during the study period. Reference group data were collected from 2009 through 2017 for this purpose.

The project team used a test of suitability to ensure the time-based effects of the reference group were similar to the treatment sites. The test of suitability compares the annual trends of the before period data from the treatment sites to the data from the same time period for comparison sites. Due to the presence of construction activities during the study period, sites were excluded from the analysis if construction activities took place during that time year. Therefore, the project team compared crash rates (i.e., crashes/mile) from year to year in the test of suitability. Total crashes, fatal and injury crashes, and lane departure crashes were the focus for the test of suitability because of sample sizes and expected development of SPFs.

Figure 28 provides a graphical representation of total crash rate per year for treatment and reference sites (from 2009 to 2014). The graphics for fatal and injury and lane departure crashes are quite similar to total crashes. From Figure 28, it appears as though the reference sites adequately mimic the trends in the treatment sites prior to installation. Further, the test of suitability provides a reliable, scientifically rigorous method for determining if the reference sites are sufficient. The test of suitability computes odds-ratios from year to year for treatment and reference sites and determines if the odds ratios are significantly different from 1.0. If 1.0 is within the 95% confidence interval, then the null hypothesis cannot be rejected. (The null hypothesis is that the two groups have the same trends.) Based on the test of suitability, the 95% confidence interval for total crashes was 0.77 to 1.33 for total crashes (with a mean of 1.05), 0.54 to 1.60 for fatal and injury crashes (with a mean of 1.07), and 0.57 to 1.47 for lane departure crashes (with a mean of 1.02). Therefore, there is sufficient evidence to suggest that the reference group is suitable for identifying annual factors for the treatment group.

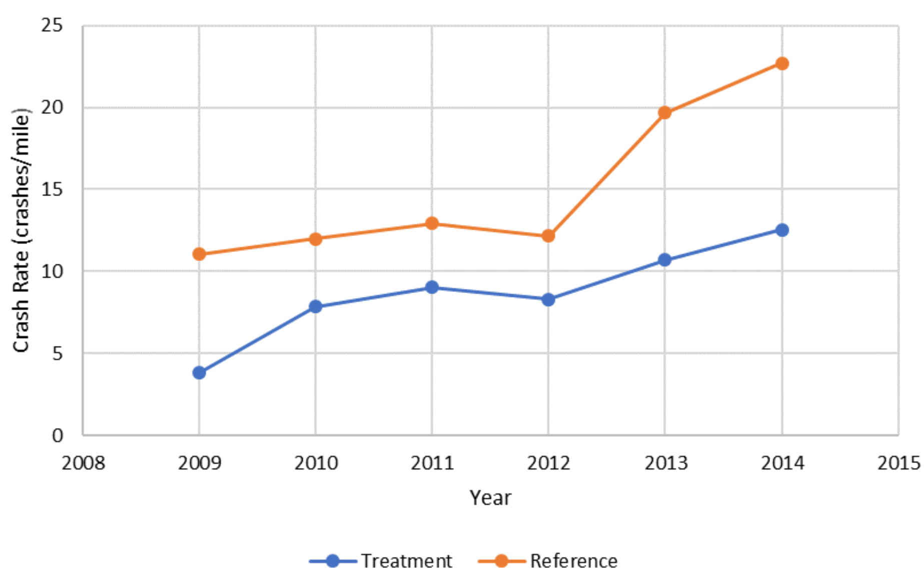


Figure 28. Annual crash rates for treatment and reference groups.

2.2.3.2.6 Data Characteristics and Summary

Table 6 defines the crash types used across facilities.

Table 6. Definitions of Crash Types

Total	Fatal and Injury	Lane Departure	Nighttime	Wet Pavement
Identified as all crashes, without exclusion	Coded as 2—Reported, not evident; 5—Non-incapacitating injury; 9—Incapacitating injury; 10—Fatal	Coded as 5—Overturned; 6—Fixed object; 12—Sideswipe same direction; 13—Sideswipe opposite direction; 14—Head-on	Coded as 2—Dawn; 3—Dusk; 4—Darkness; 5—Darkness, lighted road	Roadway surface coded as 2—Wet

Table 7 provides summary information for the data collected for the installation sites. Segments with construction were excluded from analysis for the year of construction activities. The information in Table 7 should not be used to make simple before-after comparisons of crashes per site year, since it does not account for factors, other than the strategy, that may cause a change in safety between the before and after periods. Such comparisons are properly done with the empirical Bayes (EB) analysis as presented in Section 2.2.3.4 Aggregate Analysis. Table 8 provides summary information for the reference site data.

Table 7. Data Summary for Installation Sites

Interstate	294	90	94	355	Total
Segment years before	104	90	171	80	445
Segment years after	21	24	130	80	255
Mile years before	141.1	139.8	185.2	83.6	549.7
Mile years after	28.3	35.0	138.5	83.6	285.4
Total crashes before*	14.9	3.9	10.7	4.3	9.1
Total crashes after*	23.1	3.8	13.7	6.9	11.4
FI crashes before*	2.7	0.8	1.9	0.8	1.6
FI crashes after*	4.7	0.9	2.3	1.0	2.0
LD crashes before*	9.3	2.3	5.5	2.5	5.2
LD crashes after*	13.8	2.5	6.8	3.8	6.1
LD W crashes before*	1.6	0.4	0.8	0.5	0.8
LD W crashes after*	2.0	0.7	0.9	0.9	1.0
LD N crashes before*	3.8	0.9	1.8	1.1	2.0
LD N crashes after*	5.9	1.0	2.7	1.3	2.4
LD WN crashes before*	0.7	0.2	0.3	0.2	0.4
LD WN crashes after*	1.2	0.3	0.4	0.3	0.5
LD FI crashes before*	1.8	0.5	1.1	0.5	1.0
LD FI crashes after*	2.9	0.7	1.4	0.6	1.2
AADT before	Avg: 61,872 Min: 39,300 Max: 78,770	Avg: 24,094 Min: 20,550 Max: 28,850	Avg: 49,258 Min: 26,990 Max: 78,680	Avg: 26,485 Min: 16,770 Max: 35,280	Avg: 43,146 Min: 16,770 Max: 78,770
AADT after	Avg: 73,553 Min: 53,110 Max: 88,470	Avg: 28,000 Min: 23,560 Max: 33,750	Avg: 56,028 Min: 31,340 Max: 88,180	Avg: 30,787 Min: 18,930 Max: 41,140	Avg: 46,248 Min: 18,930 Max: 88,470

Interstate	294	90	94	355	Total
Interchange mileage	7.75	8.75	14.65	10.70	41.85
Base segment mileage	20.55	19.20	33.30	10.20	83.25
Proportion curve	0.31	0.13	0.22	0.35	0.25

*Crash rates are presented as crashes/mile/year; FI = fatal and injury; LD = lane departure; LD W = wet pavement lane departure; LD N = nighttime lane departure; LD WN = nighttime wet pavement lane departure

Table 8. Data Summary for Reference Sites

Interstate	294	90	94	355	Total
Segment years	319	184	N/A	143	646
Mile years	400.6	464.0	N/A	143.4	1007.9
Total crashes*	22.0	5.7	N/A	18.4	14.0
FI crashes*	3.4	0.9	N/A	2.4	2.1
LD crashes*	10.3	2.8	N/A	6.2	6.3
LD W crashes*	1.9	0.5	N/A	0.9	1.1
LD N crashes*	3.5	1.2	N/A	1.9	2.2
LD WN crashes*	0.8	0.3	N/A	0.3	0.5
LD FI crashes*	1.7	0.5	N/A	1.0	1.0
AADT	Avg: 72,240 Min: 43,450 Max: 97,730	Avg: 24,207 Min: 15,480 Max: 47,530	N/A	Avg: 59,933 Min: 46,860 Max: 76,370	Avg: 55,835 Min: 15,480 Max: 97,730
Interchange mileage	108.1	49.2	N/A	66.6	234.1
Base segment mileage	292.5	414.8	N/A	76.8	774.9
Proportion curve	0.31	0.14	N/A	0.48	0.30

*Crash rates are presented as crashes/mile/year; FI = fatal and injury; LD = lane departure; LD W = wet pavement lane departure; LD N = nighttime lane departure; LD WN = nighttime wet pavement lane departure

2.2.3.3 Development of Safety Performance Functions

This section presents the SPFs developed for each crash type and severity, which are subsequently used in the empirical Bayes methodology. Generalized linear modeling was used to estimate model coefficients, assuming a negative binomial error distribution, which is consistent with the research in developing these models. In specifying a negative binomial error structure, the dispersion parameter, *k*, was estimated iteratively from the model and the data. For a given data set, smaller values of *k* indicate relatively better models.

Since there was a blanket moratorium for segments without SRPMs (and all other sites had SRPMs the entire time), regression to the mean bias should not be present. (i.e., sites were not selected for treatment due to crash history.) Therefore, the pretreatment period was used to develop SPFs to account for changes in traffic volume from the before period to the after period. Additionally, reference sites were used to account for other unobserved factors that contribute to safety performance (e.g., annual weather patterns).

The form of the SPFs for all crash types is given as:

$$\frac{\frac{crashes}{mi}}{year} = L^b \times AADT^c \times e^{(a+d\times int\_seg)}$$

where:

L = Segment length (miles).
AADT = Directional annual average daily traffic volume for freeway segment.
int_seg = Segment is located within an interchange.
a – d = Regression parameters estimated as part of the modeling process.

Additionally, the following parameter is provided for each SPF: *k* is the overdispersion parameter of the model.

Table 9 provides SPFs estimated from pretreatment data for freeway segments. Further, for wet pavement lane departure, nighttime lane departure, nighttime wet pavement lane departure, and fatal and injury lane departure crashes, sample sizes were too small to estimate separate SPFs. Therefore, for these crash types, the total crashes' SPF was used, along with the proportion of crashes for each crash type, which are as follows:

- Wet pavement lane departure crashes = 9.32%.
- Nighttime lane departure crashes = 21.6%.
- Nighttime wet pavement lane departure crashes = 3.90%.
- Fatal and injury lane departure crashes = 11.5%.

Further, the project team developed Cumulative Residual plots, or CURE plots, to compare the cumulative residuals to a 95% confidence interval across all segments. The CURE plots identify if the SPFs adequately predict crash frequency across the range of a unique characteristic (in this case AADT). The CURE plots showed that the SPFs provided an adequate estimate of predicted crash frequency compared to observed crash frequency. The CURE plots are provided in Appendix B.

The reference site data were also used to develop annual factors to account for unobserved trends over time. Table 10 provides the annual factors used in the safety effectiveness evaluation. Note that the sample size for wet pavement lane departure, nighttime lane departure, nighttime wet pavement lane departure, and fatal and injury lane departure crashes did not allow for separate factors to be estimated. Therefore, the annual factors for total crashes were applied for those crash types for consistent use with the total crashes' SPF.

Table 9. Pretreatment Freeway Segment SPFs

Crash Type	Parameter Estimates (Standard Error)				
	a	***b***	***c***	***d***	***k***
Total	-12.23 (0.65)	0.95 (0.05)	1.33 (0.06)	0.72 (0.06)	0.16
FI	-12.85 (1.00)	0.97 (0.07)	1.24 (0.09)	0.42 (0.09)	0.07
LD	-12.34 (0.73)	0.95 (0.05)	1.29 (0.07)	0.51 (0.07)	0.15

Table 10. Annual Adjustment Factors Based on Reference Sites

Year	2009	2010	2011	2012	2013	2014	2015	2016	2017
Total	0.892	0.904	0.903	0.949	0.952	1.072	1.093	1.106	1.135
FI	0.815	0.966	0.923	0.971	0.903	0.967	1.069	0.996	0.961
LD	1.029	1.002	0.881	0.870	0.985	1.108	0.986	1.005	0.952
LD W	0.892	0.904	0.903	0.949	0.952	1.072	1.093	1.106	1.135
LD N	0.892	0.904	0.903	0.949	0.952	1.072	1.093	1.106	1.135
LD WN	0.892	0.904	0.903	0.949	0.952	1.072	1.093	1.106	1.135
LD FI	0.892	0.904	0.903	0.949	0.952	1.072	1.093	1.106	1.135

2.2.3.4 Aggregate Analysis

Table 11 provides the estimates of expected crashes in the after period without installation, the observed crashes in the after period, and the estimated CMF and its standard error for all crash types considered. The results of a simple before-after analysis are provided in the final column for comparative purposes. The simple before-after analysis indicates statistically significant increases for installing SRPMs across all crash types and severities based on a 95% confidence interval. Accounting only for the increase in traffic volumes (AADT), the results indicate statistically significant increases in total crashes (14%), lane departure crashes (8%), and nighttime lane departure crashes (18%) at the 95% confidence interval. Reference sites (i.e., nearby sites that had SRPMs for the entire period) were used to account for time trends. Interstate 94 had no reference sites, and several of the Interstate 90 reference sites were removed due to a change in the number of lanes during the study period. Reference sites included Interstate 90, Interstate 294, and Interstate 355. Accounting for time trends, the results of the EB analysis in Table 11 indicate no statistically significant changes (at the 95% confidence interval) in crash frequency after the installation of SRPMs. The results of the EB analysis should be used since this methodology is the most statistically rigorous and, therefore, the most reliable.

Table 11. Aggregate CMFs for SRPMs by Crash Type

Crash Type	Empirical Bayes estimate of crashes expected in the after period without strategy	Count of crashes observed in the after period	Estimate of CMF	Standard Error of CMF	Naïve Before/ After CMF
Total	3,386.9	3,266	0.96	0.02	**1.39** (0.03)
KABC	540.5	568	1.05	0.06	**1.33** (0.08)
LD	1,661.7	1,736	1.04	0.03	**1.33** (0.04)
LD W	301.9	280	0.92	0.08	**1.34** (0.11)
LD N	689.0	685	0.99	0.05	**1.46** (0.08)
LD WN	126.2	129	1.01	0.13	**1.58** (0.20)
LD KABC	382.1	353	0.92	0.07	**1.32** (0.10)

Note: Statistically significant results at the 95% confidence interval are indicated in boldface.

2.2.3.5 Disaggregate Analysis

The disaggregate analysis sought to identify those conditions under which the strategy may be most effective. Since lane departure, wet pavement lane departure, nighttime lane departure, nighttime wet pavement lane departure, and fatal and injury lane departure crashes are the focus of SRPMs, these crash types are the focus of the disaggregate analysis. Several variables were identified as being of interest and available: Illinois Tollway facility, segment type, number of lanes, AADT, segment length, total curve length, and year after installation. Note that in each case, a lower and upper 95% confidence interval value is provided to indicate statistically significant results.

Table 12 provides the disaggregate results by Illinois Tollway facility. The purpose of this analysis was to determine if the results were consistent across the facilities, or if changes in crashes at one or more facilities were driving the results. Table 12 also provides the lower and upper 95% confidence intervals for each crash type by facility. There were no significant differences across facilities in any crash type based on the 95% confidence interval. However, the results indicated a statistically significant increase in lane departure crashes on Interstate 294 and a statistically significant decrease in wet pavement lane departure crashes on Interstate 94, both based on a 95% confidence interval.

Table 13 provides the disaggregate results by segment type. The purpose of this analysis was to determine if SRPMs have differential safety effects on base segments and interchange segments. The results in Table 13 indicate no statistically significant difference in effectiveness between segment types. However, the mean CMF estimates were generally smaller for interchange segments than base segments; however, the 95% confidence intervals overlapped for all crash types. The results in Table 13 also indicate a statistically significant reduction in fatal and injury lane departure crashes on interchange segments with the installation of SRPMs based on a 95% confidence interval.

Table 12. CMF Estimate of Safety Effects of SRPMs by Facility

Facility	LD	LD W	LD N	LD WN	LD FI
Lower 95	0.66	0.64	0.50	0.34	0.59
Interstate 90	0.86	1.26	0.81	1.26	1.09
Upper 95	1.07	1.88	1.13	2.19	1.60
Lower 95	0.92	**0.57**	0.86	0.56	0.71
Interstate 94	1.01	**0.75**	1.01	0.86	0.88
Upper 95	1.10	**0.92**	1.16	1.15	1.05
Lower 95	**1.00**	0.66	0.91	0.83	0.85
Interstate 294	**1.13**	0.93	1.11	1.37	1.13
Upper 95	**1.26**	1.20	1.30	1.91	1.41
Lower 95	0.92	0.80	0.62	0.37	0.45
Interstate 355	1.11	1.28	0.86	0.94	0.74
Upper 95	1.30	1.76	1.09	1.51	1.03

Note: Statistically significant results at the 95% confidence level are indicated in boldface.

Table 13. CMF Estimate of Safety Effects of SRPMs by Segment Type

Segment Type	LD	LD W	LD N	LD WN	LD FI
Lower 95	0.98	0.80	0.92	0.79	0.85
Base	1.07	1.01	1.06	1.15	1.04
Upper 95	1.16	1.22	1.21	1.52	1.23
Lower 95	0.91	0.60	0.76	0.53	**0.58**
Interchange	1.01	0.81	0.90	0.84	**0.76**
Upper 95	1.11	1.01	1.05	1.15	**0.93**

Note: Statistically significant results at the 95% confidence level are indicated in boldface.

Table 14 provides the disaggregate results by number of lanes. The purpose of this analysis was to determine if SRPMs have differential safety effects on freeway segments with three directional lanes versus those with four or more lanes. The results in Table 14 indicate no statistically significant difference for any crash type between segments with three directional lanes and those with four or more directional lanes. Additionally, the results in Table 14 indicate a statistically significant decrease in wet pavement lane departure crashes on segments with four or more lanes based on a 95% confidence interval.

Table 14. CMF Estimate of Safety Effects of SRPMs by Number of Lanes

Number of Lanes	LD	LD W	LD N	LD WN	LD FI
Lower 95	0.90	0.88	0.65	0.52	0.57
Three Lanes	1.05	1.29	0.85	1.04	0.84
Upper 95	1.19	1.69	1.04	1.71	1.10
Lower 95	0.97	**0.65**	0.92	0.72	0.79
Four+ Lanes	1.04	**0.80**	1.04	0.99	0.94
Upper 95	1.12	**0.95**	1.16	1.27	1.09

Note: Statistically significant results at the 95% confidence level are indicated in boldface.

Table 15 provides the disaggregate results by AADT category. The purpose of this analysis was to determine if SRPMs have differential safety effects on freeway segments by level of traffic volume. Note that the cross-sectional analysis in Phase I indicated SRPMs may be more effective at higher traffic volumes. The results in Table 15 indicate no statistically significant difference in the safety effects of SRPMs by AADT level based on a 95% confidence interval. Additionally, the results indicate no statistically significant change in any crash type for any level of AADT. For lane departure, wet pavement lane departure, and fatal and injury lane departure crashes, there is some evidence (based on the trend of mean CMF estimates) that SRPMs are more effective for higher traffic volumes. Conversely, there is some evidence that SRPMs are more effective for nighttime crashes on sections with lower volumes. This would be intuitive since the markers help to delineate lanes, which is more important when there are fewer adjacent vehicles assisting with lane-keeping.

Table 16 provides the disaggregate results by segment length. The purpose of this analysis was to determine if SRPMs have differential effects on longer segments (as compared to shorter segments). Longer segments tend to be less urbanized and may have less ambient light, therefore making the SRPMs more effective. The results in Table 16 indicate no statistically significant difference between longer and shorter segments for any crash type based on a 95% confidence interval. However, the results indicate a statistically significant decrease in fatal and injury lane departure crashes for shorter segments. This is consistent with the finding for interchange segments.

Table 15. CMF Estimate of Safety Effects of SRPMs by AADT Category

AADT	LD	LD W	LD N	LD WN	LD FI
Lower 95	0.90	0.73	0.67	0.40	0.69
< 30 K	1.07	1.13	0.89	0.87	1.02
Upper 95	1.23	1.54	1.10	1.34	1.36
Lower 95	0.90	0.63	0.77	0.39	0.62
30 K–50 K	1.04	0.94	0.99	0.88	0.90
Upper 95	1.18	1.26	1.21	1.38	1.17
Lower 95	0.95	0.66	0.89	0.76	0.72
50+ K	1.04	0.83	1.03	1.09	0.89
Upper 95	1.12	1.01	1.16	1.41	1.05

Table 16. CMF Estimate of Safety Effects of SRPMs by Segment Length

Length	LD	LD W	LD N	LD WN	LD FI
Lower 95	0.93	0.60	0.79	0.52	**0.52**
< 1 mile	1.06	0.85	0.98	0.92	**0.73**
Upper 95	1.18	1.10	1.17	1.32	**0.93**
Lower 95	0.96	0.77	0.87	0.75	0.83
1+ mile	1.04	0.95	1.00	1.05	1.00
Upper 95	1.12	1.14	1.12	1.35	1.17

Table 17 provides the disaggregate results by in-segment horizontal curve length. The purpose of this analysis was to determine if SRPMs have differential effects on segments with more curve mileage than segments with shorter curve mileage. SRPMs are anticipated to provide more benefit on horizontal curves by helping to delineate their presence for nighttime wet pavement conditions. The results in Table 17 indicate no statistically significant difference between segments with shorter curve mileage versus those with longer curve mileage based on a 95% confidence interval. Additionally, the results indicate no statistically significant change in any crash type for segments with shorter or longer curve mileage.

Table 18 provides the disaggregate results by year after installation. The purpose of this analysis was to determine if SRPMs sustain the same level of effectiveness or become less effective over time. The results in Table 18 indicate no statistically significant difference over time for each crash type based on a 95% confidence interval. Additionally, there is no notable trend across crash types of SRPMs becoming more or less effective. However, there was a statistically significant increase in lane departure crashes after the first year based on a 95% confidence interval.

Table 17. CMF Estimate of Safety Effects of SRPMs by Horizontal Curve Length

Curve Length	LD	LD W	LD N	LD WN	LD FI
Lower 95	0.95	0.71	0.92	0.52	0.66
< 0.25 mi	1.06	0.95	1.09	0.82	0.85
Upper 95	1.16	1.20	1.26	1.13	1.04
Lower 95	0.95	0.89	0.93	0.80	0.79
0.25+ mi	1.03	1.12	1.08	1.16	0.98
Upper 95	1.12	1.34	1.22	1.53	1.16

Table 18. CMF Estimate of Safety Effects of SRPMs by Year after Installation

Years After	LD	LD W	LD N	LD WN	LD FI
Lower 95	**1.01**	0.71	0.94	0.77	0.83
1st Year	**1.09**	0.89	1.07	1.08	1.00
Upper 95	**1.17**	1.06	1.20	1.38	1.16
Lower 95	0.90	0.62	0.78	0.48	0.66
2nd Year	1.00	0.84	0.94	0.81	0.85
Upper 95	1.11	1.06	1.10	1.13	1.04
Lower 95	0.84	0.65	0.71	0.58	0.63
3rd Year	0.95	0.89	0.87	0.97	0.83
Upper 95	1.06	1.12	1.03	1.35	1.03

Furthermore, the project team conducted supplemental analyses based on before-after EB changes in crashes on individual segments. The project team evaluated each segment to determine if there was a significant change in crash frequency (from before to after SRPM installation) for each crash type. The sites (and directional mileage) saw significant changes (based on a 95% confidence interval) in crashes by type after reinstalling SRPMs, respectively:

- LD Crashes: 0 sites increase, 10 sites (10.4 mi) decrease.
    - I 94 WB: MP 9.2 to 9.7.
    - I 94 EB: MP 11.25 to 11.55.
    - I 90 WB: MP 15.15 to 15.7.

- I 94 WB: MP 0.85 to 0.95.
- I 90 WB: MP 12.85 to 15.15.
- I 94 WB: MP 14.15 to 15.95.
- I 94 EB: MP 22.6 to 23.85.
- I 94 EB: MP 0.3 to 0.7.
- I 94 EB: MP 14.2 to 16.0.
- I 294 WB: MP 11.6 to 13.0

- LD Wet Pavement Crashes: 0 sites increase, 20 sites (21.85 mi) decrease.
    - I 355 NB: MP 6.45 to 7.95.
    - I 355 SB: MP 7.8 to 1.45.
    - I 355 SB: MP 8.5 to 9.45.
    - I 94 WB: MP 0.95 to 2.75.
    - I 355 NB: MP 8.55 to 9.45.
    - I 94 WB: MP 19.3 to 21.45.
    - I 294 SB: MP 11.6 to 13.0.
    - I 94 WB: MP 21.45 to 22.6.
    - I 94 EB: MP 1.7 to 2.85.
    - I 94 WB: MP 15.95 to 16.15.
    - I 90 WB: MP 15.15 to 15.7.
    - I 94 WB: MP 14.15 to 15.95.
    - I 94 EB: MP 0.3 to 0.7.
    - I 94 EB: MP 0.7 to 1.7.
    - I 94 WB: MP 4.65 to 5.1.
    - I 355 NB: MP 2.55 to 3.95.
    - I 94 EB: MP 13.3 to 14.2.
    - I 94 EB: MP 9.9 to 11.25.
    - I 94 WB: MP 0.85 to 0.95.
    - I 94 EB: MP 22.6 to 23.85.

- LD Nighttime Crashes: 0 sites increase, 13 sites (14.4 mi) decrease.
    - I 355 SB: MP 7.8 to 8.5.
    - I 355 NB: MP 6.45 to 7.95.
    - I 94 EB: MP 11.25 to 11.55.
    - I 94 EB: MP 0.3 to 0.7.
    - I 94 EB: MP 0 to 0.3.
    - I 294 NB: MP 0 to 0.5.
    - I 94 EB: MP 22.6 to 23.85.
    - I 94 EB: MP 14.2 to 16.0.
    - I 355 NB: MP 5.4 to 6.45.
    - I 94 WB: MP 22.6 to 24.0.
    - I 94 WB: MP 0.85 to 0.95.
    - I 90 EB: MP 4.2 to 8.2.

- I 355 SB: MP 1.45 to 2.5.

- LD Nighttime, Wet Pavement Crashes: 0 sites increase, 11 sites (16.2 mi) decrease.
    - I 94 WB: MP 19.3 to 21.45.
    - I 94 EB: MP 5.1 to 8.0.
    - I 355 SB: MP 8.5 to 9.45.
    - I 94 WB: MP 14.15 to 15.95.
    - I 94 WB: MP 0.95 to 2.75.
    - I 94 WB: MP 0.85 to 0.95.
    - I 94 WB: MP 16.15 to 17.8.
    - I 355 SB: MP 0.8 to 1.45.
    - I 355 NB: MP 5.4 to 6.45.
    - I 94 EB: MP 0.3 to 0.7.
    - I 94 WB: MP 5.1 to 7.8.

- LD Fatal and Injury Crashes: 0 sites increase, 17 sites (15.7 mi) decrease.
    - I 355 NB: MP 4.5 to 5.4.
    - I 94 EB: MP 8 to 8.95.
    - I 355 SB: MP 8.5 to 9.45.
    - I 94 WB: MP 15.95 to 16.15.
    - I 355 NB: MP 5.4 to 6.45.
    - I 355 SB: MP 7.8 to 8.5.
    - I 94 WB: MP 22.6 to 24.0.
    - I 94 EB: MP 0 to 0.3.
    - I 355 NB: MP 2.55 to 3.55.
    - I 94 WB: MP 18.4 to 19.3.
    - I 355 SB: MP 6.35 to 7.8.
    - I 94 WB: MP 9.85 to 11.15.
    - I 94 EB: MP 17.8 to 18.4.
    - I 355 SB: MP 6.35 to 7.8.
    - I 94 WB: MP 7.8 to 9.2.
    - I 94 EB: MP 17.8 to 18.4.
    - I 355 NB: MP 6.45 to 7.95.

The results indicate that no sites observed a statistically significant increase in lane departure crashes of any type after the installation of SRPMs. However, multiple sites did observe a significant decrease in lane departure crashes after the installation of SRPMs. While this indicates a trend toward decreased crashes by type, the overall CMFs estimated across sites by type in the aggregate and disaggregate analyses indicate little to no overall effect when considering sites together. Sites observing significant decreases tend to have few crashes; while sites with no changes tended to be a mix of low, medium, and high crash counts.

CHAPTER 3: SUMMARY AND CONCLUSIONS

3.1 PAVEMENT MARKER PERFORMANCE

The first objective of this research was to investigate the performance of SRPMs to determine optimum pavement marker solutions and policies for roadways in Illinois. The project team evaluated seven SRPMs that were available at the beginning of the study. Table 19 is a list of the marker names and manufacturers. Small sections (16 to 40 markers) of each of the first six marker types were installed at six test sites across the state in 2016. The test sites consisted of both an asphalt- and a concrete-surfaced roadway in the northern, central, and southern regions of the state. The Guide Lite marker came on the market shortly after the study began, but two sections were added to the study in 2017. One section was added to the central asphalt-surfaced site and the other was added to the central concrete-surfaced site.

Table 19. Final List of Test Markers

Count	Marker	Manufacturer
1	SM 101	Ennis-Flint
2	SM 101LP	Ennis-Flint
3	H1010	Rayolite
4	H1010HP	Rayolite
5	SL150	Rayolite
6	R-100	Marker One
7	Guide Lite	Trinity

Marker performance assessments were conducted annually at each test site. The performance metrics used for this study are described in Section 1.4.2 of this report and summarized here.

3.1.1 Pavement Condition

The pavement condition surrounding each marker was monitored to ascertain whether the pavement condition affected the markers' performance. By the final evaluation year, the pavement surrounding a majority of the pavement markers was in good to fair condition and did not appear to affect the markers' performance.

3.1.2 Marker Bonded, Loose, or Missing

When considering a marker's ability to remain bonded to the pavement surface, R-100 performed the poorest by far. By the end of Year 3, approximately half of the R-100 markers were loose or missing. The missing R-100 markers were almost entirely from the concrete-surfaced sites. Although many of the Guide Lite markers were severely damaged after Year 2, all of them remained attached to the pavement. After Year 3, one SM101 on I-70 (southern PCC site) and one H1010 on IL-8 (central PCC site) appeared to be a little loose. However, after three winters, all 783 traditional cast-iron markers were still bonded to the pavement surface.

3.1.3 Missing Lenses

After two years, every marker type had at least one lens missing, but the Guide Lite had the highest percentage of missing lenses, with over 40% missing. Of the markers with three years of service, R-100 had the highest percentage of missing lenses and missing markers, but H1010HP had the highest percentage of missing only lenses, with 10% missing. Of this 10%, the majority of missing lenses were from the central and northern test sites. Missing lenses do not appear to be strongly associated with a particular type of pavement surface, but there is a higher percentage of missing lenses in the central and northern regions of the state than there is in the southern region.

3.1.4 Leading Edge of Rails Exposed

The five traditional SRPMs with rails performed well. After three winters, these markers had low percentages of the rails exposed where epoxy had covered them. However, nine of the 57 Guide Lite markers had exposed rails after the first year and nearly 90% had exposed rails after the second year. This is likely due to the marker floating up in the epoxy at installation.

3.1.5 Missing Epoxy

The majority of the five traditional markers had only 25% or less of the visible (top view) epoxy missing. The R-100 markers were in all five of the missing epoxy categories. Some had no missing epoxy and some had 100% of the epoxy missing. After just two years, none of the Guide Lite markers had 100% of the epoxy remaining. Most of the Guide Lite markers had 26% to 100% of the visible epoxy missing. However, despite all of the epoxy missing on the surface, the epoxy beneath the marker was performing well, since all Guide Lite markers were still present and bonded to the pavement.

3.1.6 Marker Housing Condition Rating

Of the H-shaped markers, the Guide Lite marker housing condition was in far worse condition after two years than the other markers were after three years. After two years, over 60% of the Guide Lite markers were in poor or very poor condition. The two high-profile markers, SM 101 and H1010 HP, performed the poorest of the five traditional cast-iron SRPMs. After the third winter, these two markers were the only traditional markers to have a few markers in very poor condition (2% and 8%, respectively). The higher profile means the markers are in greater contact with snowplows, which explains the higher rate of damage. By the end of the study the lower profile markers, SM 101LP and H1010, had performed the best. SM 101LP had the highest overall housing condition rating, with 94% in good to excellent condition, and H1010 had the second highest rating with 89% in good to excellent condition. The lower profile marker design affects the longevity of the marker housing condition.

3.2 CRASH MODIFICATION FACTOR

The second objective of this research was to perform a rigorous before-after evaluation of the safety effectiveness, as measured by crash frequency, of SRPMs applied on Illinois Tollway segments in northeast Illinois. The study used data from Illinois Tollway segments that previously did not have SRPMs as well as segments that have always had SRPMs installed. The data was used to examine the effects for specific crash types, including total, fatal and injury, lane departure, wet pavement lane departure, nighttime lane departure, nighttime wet pavement lane departure, and fatal and injury lane departure. Based on the aggregate results in Table 20, there were no statistically significant changes in crashes. Since installation locations were not selected based on nighttime crash history, the results are consistent with the most reliable study to date (Bahar et al. 2004), where the authors found no statistically significant changes on four-lane freeway segments with nonselective installation.

However, it should be noted that the sites in this study all had at least three directional lanes and were more urban/suburban in nature, likely having ambient light present. **The results in this study would not be appropriate for other facility types**.

Table 20. Aggregate CMFs for SRPMs by Crash Type

Crash Type	Empirical Bayes estimate of crashes expected in the after period without strategy	Count of crashes observed in the after period	Estimate of CMF	S.E. of CMF
Total	3,386.9	3,266	0.96	0.02
KABC	540.5	568	1.05	0.06
LD	1,661.7	1,736	1.04	0.03
LD W	301.9	280	0.92	0.08
LD N	689.0	685	0.99	0.05
LD WN	126.2	129	1.01	0.13
LD KABC	382.1	353	0.92	0.07

A disaggregate analysis of the results investigated additional factors associated with the safety performance of SRPMs. The results suggested that SRPMs may be more effective on interchange segments than base freeway segments for all crash types (see Table 13); however, this difference was not statistically significant at the 95% confidence level for any crash type. Further, for lane departure, wet pavement lane departure, and fatal and injury lane departure crashes, there is evidence that SRPMs are more effective for higher traffic volumes (see Table 15). Conversely, there is evidence that SRPMs are more effective for nighttime crashes on sections with lower volumes (see Table 15). However, these differences are not statistically significant at the 95% confidence level. This would be intuitive since the markers help to delineate lanes, which is more important when there are fewer adjacent vehicles assisting with lane-keeping. While there is some evidence that SRPMs may be more effective (or less effective) under specific conditions and for specific crash types, the disaggregate analysis did not identify any statistically significant differences (i.e., the 95% confidence overlap in all cases for disaggregate analyses). Finally, the project team analyzed individual segments for statistically significant increases or decreases in crash frequency. The results indicate that no sites observed a statistically significant increase in lane departure crashes of any type after the reinstallation of SRPMs. However, multiple sites did observe a significant decrease in lane departure crashes after the reinstallation of SRPMs. This suggests some evidence of safety improvement because of the installation of SRPMs. Overall, as shown in Table 20, no crash types were associated with statistically significant changes (i.e., 1.0 is included in the 95% confidence interval) in crash frequency across all segments.

CHAPTER 4: RECOMMENDATIONS

The Illinois Department of Transportation (IDOT) has two documents that provide guidance on the use of SRPMs and the field inspection of in-place SRPMs. IDOT departmental policies document TRA-14 provides guidelines for the use of pavement marking materials (including raised pavement markers) on state highways, and IDOT's Raised Reflective Pavement Marker inspection policy gives regional engineers instructions on inspection of in-place SRPMs. The results of this study are applied to give recommendations on updates to both of these policies. Additionally, to help ensure SRPMs provide the expected service from the time of installation, an installation inspection guide is included in Appendix C.

4.1 TRA-14 GUIDELINES FOR THE USE OF PAVEMENT MARKING MATERIALS

Currently, the TRA-14 guidance recommends using pavement markers in sections that are unlighted or lighted only to the extent that the markers are still effective. The findings from the crash analysis research concur that SRPMs placed in suburban freeway sections (with the potential for ambient light) are not effective. This guidance should be strengthened to call more attention to the potential for situations where markers may be ineffective. Clarifying text may include sections with roadway lighting, interchange lighting, or within urban/suburban areas.

Furthermore, the results of this study are applicable only to freeway sections with six or more lanes (combined directions). No other factors were found to be significantly associated with SRPM effectiveness. Therefore, no recommendations can be given to further identify situations where they should or should not be used (e.g., AADT thresholds, horizontal curves, number of lanes, etc.).

Based on the findings of the pavement marker performance evaluation, recommendations on the use of the specific pavement marker types can be made. Due to the high loss of lenses and the significant marker housing failures after just two years, use of the Guide Lite markers on IDOT and Illinois Tollway routes is not recommended. Due to the large number of R-100 markers that debonded from the concrete-surfaced roadways, the use of R-100 markers is not recommended on that pavement type. R-100 could be used on asphalt-surfaced roadways but consideration should be given to the potential for water retained within the open 9-ft cut in the pavement surface. All five of the traditional cast-iron SRPMs performed well and could continue to be used.

4.2 RAISED REFLECTIVE PAVEMENT MARKER INSPECTION POLICY

The initial inspection and frequency of follow-up inspections for reflective lenses and marker housing for traditional cast-iron pavement markers installed on new or good condition pavements can be estimated from the results of the study and from input from the Technical Review Panel members.

As shown in Table 21, the reflective lenses of a pavement marker section should be inspected for damaged or missing lenses three years after installation, and then every year following the initial inspection. Table 21 also presents the timing of the initial inspection and follow-up inspection of the marker housings. Because the traditional cast-iron markings in the study were all still bonded to the pavement and the majority of the housing conditions were all still pretty high, the initial inspection was projected based on an estimated deterioration rate and on input from TRP members. Due to the lower degradation rate of the low-profile markers, their initial inspection is recommended at five years after installation, and the high-profile markers' is recommended at four years after installation. The frequency of follow-up inspection is annual for both types of markers.

Table 21. Reflective Lens and Marker Housing Inspection Frequency

Pavement Marker Profile	Reflective Lens Inspection		Marker Housing Inspection	
	Initial Inspection After Installation	Frequency After Initial Inspection	Initial Inspection After Installation	Frequency After Initial Inspection
Low	3 Years	Every Year	5 Years	Every Year
High	3 Years	Every Year	4 Years	Every Year

If a section of road begins to exhibit marker housing failures (damaged or missing) before the scheduled inspection, then the inspection cycle should be shortened. In order to accommodate scheduled inspections in different areas of a district, the district offices may perform an initial inspection one year sooner and then the first follow-up inspection may be two years later. The marker lenses and housings should be inspected any time it is determined there may be a problem with the markers or with the pavement condition.

Reflective lens inspections may consist of a drive-through visual survey looking for failed lenses. A reflective lens is considered failed if it is covered by epoxy or other material, is broken, no longer provides adequate reflectivity, or is missing. Ideally, marker housing inspections should be performed "foot on ground" to assess if markers are loose. However, if labor or other resources are limited, then the marker housing inspections should be performed either with a rolling lane closure at a speed low enough to make an adequate visual inspection of each marker or, if available, from roadway videos with sufficient resolution to assess marker condition. A marker housing is considered failed if it is broken, cracked (partially or fully), significantly gouged, or missing (partially or entirely). Broken leveling tabs or minor scratches on the housing do not constitute a failure. If the pavement surrounding the housing is failing or if the housing is not completely installed within the pavement surface, the marker should be removed regardless of its condition.

Following each inspection, preparations should be made to remove and/or replace any damaged or deteriorated reflective lens or marker housing. These SRPM elements should be removed but not immediately replaced if the pavement will be resurfaced in the near future or is in poor condition and cannot support the installation of new SRPMs. These SRPMs should be replaced as part of a pavement resurfacing or treatment. Removal of damaged or deteriorated RPM elements may be accomplished using in-house forces or statewide SRPM maintenance contracts. Damaged or deteriorated SRPM elements should be removed and replaced when the pavement is in good condition and is not planned to be resurfaced in the near future. Removing and replacing SRPM elements should be accomplished using statewide SRPM maintenance contracts.

REFERENCES

Bahar, G., Masliah, M., Erwin, T., Tan, E., & Hauer, E. (2006). *Pavement marking materials and markers: Real-world relationship between retroreflectivity and safety over time*. Washington, DC: Transportation Research Board, National Research Council. https://doi.org/10.17226/23255

Bahar, G., Mollett, C., Persaud, B., Lyon, C., Smiley, A., Smahel, T., & McGee, H. (2004). *Safety evaluation of permanent raised pavement markers*. NCHRP Report 518. Washington, DC: Transportation Research Board. https://doi.org/10.17226/13724

Das, S., Sun, X., He, Y., Wang, F., & Leboeuf, C. (2013). Investigating the safety impact of raised pavement markers on freeways in Louisiana. *International Journal of Engineering Research and Innovation*, 5(2), 74-80. https://www.researchgate.net/publication/258332697_Investigating_the_Safety_Impact_of_Raised_Pavement_Markers_on_Freeways_in_Louisiana

Griffin, L. (1990). *Using the before-and-after design with yoked comparisons to estimate the effectiveness of accident countermeasures implemented at multiple treatment locations*. College Station, TX: Texas Transportation Institute.

Hauer, E. (2015). *The art of regression modeling in road safety*. Cham, Switzerland: Springer International Publishing.

Hauer, E. (1997). *Observational before-after studies in road safety: Estimating the effect of highway and traffic engineering measures on road safety*. London: Emerald Publishing Limited.

Illinois Tollway (2019). Traffic Information. Illinois Virtual Tollway, https://www.illinoisvirutaltollway.com/Traffic/Traffic.aspx.

Kugle, C., Pendleton, O., & Von Tress, M. (1984). *An evaluation of the accident reduction effectiveness of raised pavement marker*s. College Station, TX: Texas Transportation Institute.

Mak, K., Chira-Chavala, T., & Griffin, L. (1987). *Evaluation of the safety effects of raised pavement markers*. College Station, TX: Texas Transportation Institute.

New York State Department of Transportation. (1989). *Highway safety improvement program—Annual evaluation report*. Albany, NY: NYSDOT.

Orth-Rodgers and Associates, Inc. 1998. *Safety and congestion management research and advanced technology applications—Final report (Technical assistance to the RPM task force)*. Research Work Order Number 1. Philadelphia, PA.

Pendleton, O. (1996). *Evaluation of accident analysis methodology*. FHWA-RD-96-039. College Station, TX: Texas Transportation Institute.

Smiley, A., Bahar, G., & Persaud, B.N. (2004). *Human factors and safety impacts of delineation countermeasures on two-lane rural roads*. Presented at the Annual Conference of the Transportation Association of Canada, Quebec City, Quebec, September 19–22.

Wright, P., Zador, P., Park, C., & Karpf, R. (1982). *Effect of pavement markers on nighttime crashes in Georgia*. Washington, DC: Insurance Institute for Highway Safety.

APPENDIX A: PAVEMENT MARKER MANUFACTURER SPECIFICATIONS

STIMSONITE MODEL 101

SPECIFICATION

SPECIFICATION FOR ABRASION RESISTANT, HIGH BRIGHTNESS PRISMATIC RETROREFLECTIVE PAVEMENT MARKER **SM101 – June 2006**

GENERAL DESCRIPTION

The marker shall consist of an iron casting to which is attached a replaceable prismatic retroreflector for reflecting light from a single or opposite directions. Both ends of a bi-directional casting are shaped to deflect a snowplow blade. The bottom of the casting shall incorporate two parallel keels and an arcuately shaped web designed to fit into a grooved surface.

DETAILED SPECIFICATIONS

1. DESIGN AND FABRICATION

A. Dimensions and Construction Details

1) Casting

A. Dimensional Details

Overall dimensions shall be approximately 10.00 in. long by 5.50 in. wide and 1.92 in. high (25.4 cm x 13.97 cm x 4.88 cm). Installed height shall be approximately 0.41 in. (1.041 cm) above the road surface.

B. Material

Nodular iron, conforming to Specification ASTM-A536-84, Grade 80-55-06, hardened to 51-55 RC.

C. Surface

Surface of the keel and web shall be free of scale, dirt, rust, oil, grease or any other contaminant which may reduce its bond to the installation adhesive.

D. Weight

Approximately 5.5 lbs. (2.49 kg).

E. Identification

Casting shall be marked with manufacturer's name and model number of marker.

2) Reflector

Reflector shall consist of either Ennis Traffic Safety Solutions Stimsonite Division Model C40 or 944 lens. Please refer to specifications SMC40 or SM944 respectively for reflector specification.

ENNIS
TRAFFIC SAFETY SOLUTIONS

ENNIS-FLINT
A Traffic Safety Solutions Company

SPECIFICATION FOR HIGH BRIGHTNESS PRISMATIC RETROREFLECTIVE PAVEMENT MARKER

GENERAL DESCRIPTION

The 101LP marker shall consist of an iron casting to which is attached a replaceable prismatic retroreflector for reflecting light from a single or opposite directions. Both ends of a bi-directional casting are shaped to deflect a snowplow blade. The bottom of the casting shall incorporate two parallel keels and an arcuately shaped web designed to fit into a grooved surface. LP indicates the marker has a lower profile above grade to minimize plow truck jarring.

DETAILED SPECIFICATIONS

A. Dimensions and Construction Details

1) Casting

A. Dimensional Details
Overall dimensions shall be approximately 10.00 in. long by 5.50 in. wide and 1.76 in. high (25.4 cm x 13.97 cm x 4.47 cm). Installed height shall be approximately 0.25 in. (0.635 cm) above the road surface.

B. Material
Nodular iron, conforming to Specification ASTM-A536-84, Grade 80-55-06, hardened to 51-55 RC.

C. Surface
Surface of the keel and web shall be free of scale, dirt, rust, oil, grease or any other contaminant which may reduce its bond to the installation adhesive.

D. Weight
Approximately 4.9 lbs. (2.23 kg)

E. Identification
Casting shall be marked with manufacturer's name and model number of marker.

2) Reflector

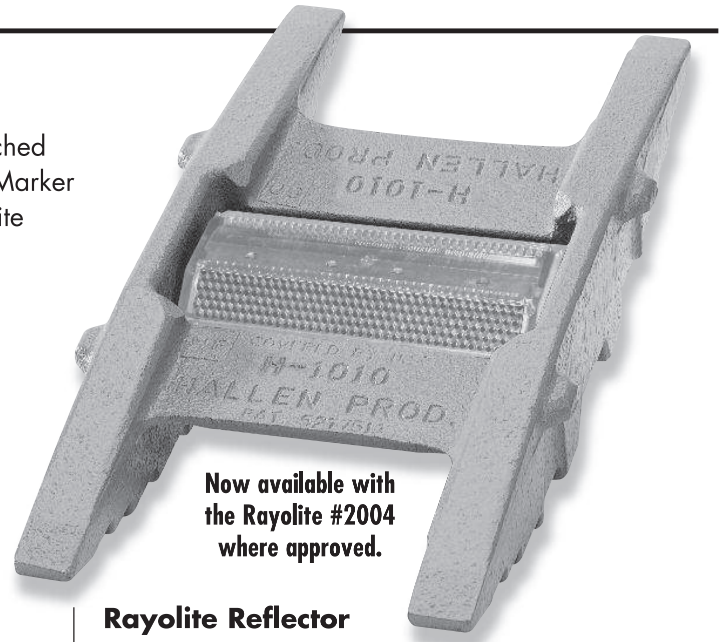
Reflector shall consist of an Ennis-Flint Stimsonite Model C40 lens. Please refer to specification SMC40 for reflector specification.

Specifications
Model H1010 Low Profile – Narrow

Two-Way, All Weather, Snowplowable, Raised Reflective Pavement Marker

4500 N. Sam Houston Parkway W.
Building A, Suite 120
Houston, Texas 77086

Phone: (281) 617-2240
Toll Free: (800) 848-7025
Fax: (281) 583-1506



Now available with the Rayolite #2004 where approved.

Description

Marker consists of Iron casting to which is attached a replaceable Rayolite #2004 Snowplowable Marker Insert for reflecting light from a single or opposite directions. Reflector features:

- Optic grade Methyl Methacrylate
- Abrasion-resistant lens hardcoat

All aspects of reflector installation are factory controlled to insure proper adhesion to casting.

Dimensional Details

Overall Dimensions are approximately:

- 10 inches long
- 4.9 inches wide
- 1.75 inches high
- Installed height is approximately .250 inches above road surface

Material

Nodular Iron, conforming to Specification ASTM A536-84 Hardened to 52-54 Rockwell "C"

Surface

Surfaces of casting shall be free of scale, dirt, rust, oil, grease or any other contaminant which may reduce its bond to the installation adhesive.

Weight

Approximately 4.5 pounds each.

Identification

Casting is marked with manufacturer's name and model number of marker.

Rayolite Reflector Design and Fabrication

Construction Details:

- Molded with optic grade Methyl Methacrylate, filled with adherent thermosetting compound, with filler designed for impact and wear resistance.
- Dimensions are 4 inches long (101.6 mm) by 2 inches wide (50.8 mm) and 0.467 inches high (11.86 mm)
- Face Angle: 32%
- Reflective Area: 2.0 in^2.
- Pad Thickness: .035"

Rayolite Optical Performance

(0.2° observation angle; measured in cd/ftcd)

Entrance Angle	0°	20°
White	3.0	1.2
Amber	1.8	.72
Red	.75	.30

Note

Rayolite Snowplowable Marker #2004 is provided in new Hallen Products castings and can also be applied as replacement markers in most other castings. The #2004 markers are manufactured with an adhesive layer and peel-away liner and can be installed in existing castings using Liquid Nails LN-602 adhesive.

rayolite®

HALLEN PRODUCTS LIMITED

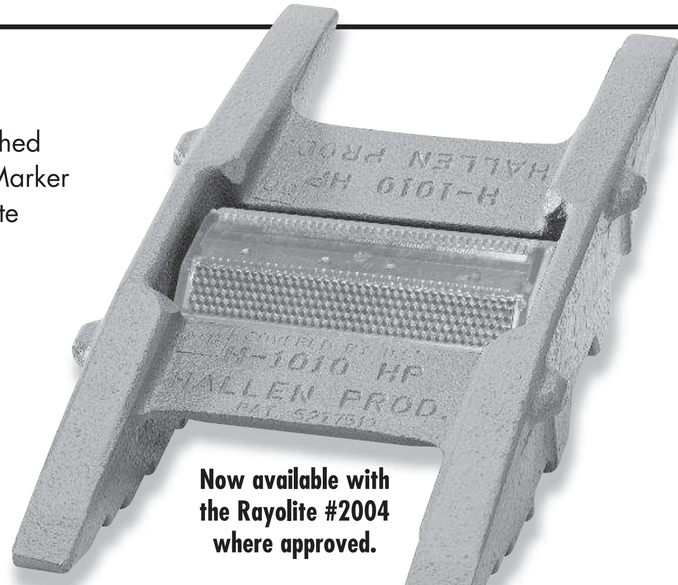
Specifications

Model H1010HP High Profile – Narrow

Two-Way, All Weather, Snowplowable, Raised Reflective Pavement Marker

4500 N. Sam Houston Parkway W.
Building A, Suite 120
Houston, Texas 77086

Phone: (281) 617-2240
Toll Free: (800) 848-7025
Fax: (281) 583-1506



Now available with the Rayolite #2004 where approved.

Description

Marker consists of Iron casting to which is attached a replaceable Rayolite #2004 Snowplowable Marker Insert for reflecting light from a single or opposite directions. Reflector features:

- Optic grade Methyl Methacrylate
- Abrasion-resistant lens hardcoat

All aspects of reflector installation are factory controlled to insure proper adhesion to casting.

Dimensional Details

Overall Dimensions are approximately:

- 10 inches long
- 4.9 inches wide
- 1.90 inches high
- Installed height is approximately .410 inches above road surface

Material

Nodular Iron, conforming to Specification ASTM A536-84 Hardened to 52-54 Rockwell "C"

Surface

Surfaces of casting shall be free of scale, dirt, rust, oil, grease or any other contaminant which may reduce its bond to the installation adhesive.

Weight

Approximately 5.8 pounds each.

Identification

Casting is marked with manufacturer's name and model number of marker.

Rayolite Reflector Design and Fabrication

Construction Details:

- Molded with optic grade Methyl Methacrylate, filled with adherent thermosetting compound, with filler designed for impact and wear resistance.
- Dimensions are 4 inches long (101.6 mm) by 2 inches wide (50.8 mm) and 0.467 inches high (11.86 mm)
- Face Angle: 32%
- Reflective Area: 2.0 in^2.
- Pad Thickness: .035"

Rayolite Optical Performance

(0.2° observation angle; measured in cd/ftcd)

Entrance Angle	0°	20°
White	3.0	1.2
Amber	1.8	.72
Red	.75	.30

Note

Rayolite Snowplowable Marker #2004 is provided in new Hallen Products castings and can also be applied as replacement markers in most other castings. The #2004 markers are manufactured with an adhesive layer and peel-away liner and can be installed in existing castings using Liquid Nails LN-602 adhesive.

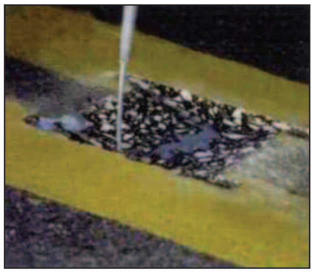
Snow-Lite® 150 Installation and Details

Medium Profile, Two-Way Snowplowable, Raised Pavement Marker

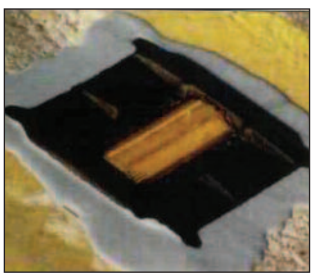
4500 N. Sam Houston Parkway W.
Building A, Suite 120
Houston, Texas 77086

Phone: (281) 617-2240
Toll Free: (800) 848-7025
Fax: (281) 583-1506

1. **CUT:** Saw roadway to a depth of approximately 1.5 inches (3.8 cm)



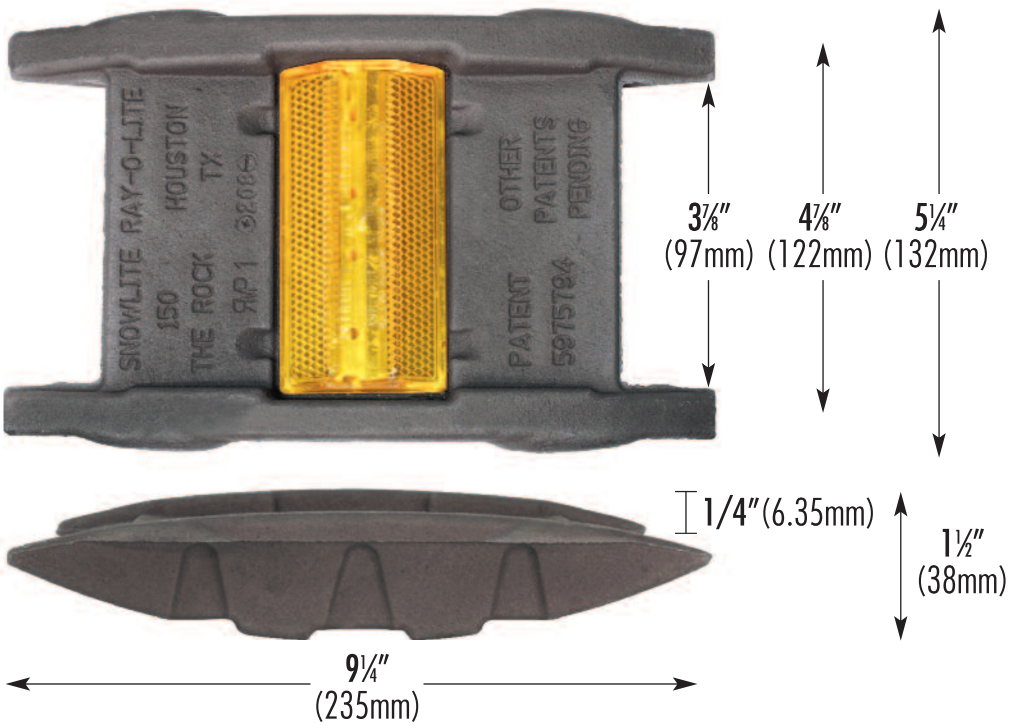
2. **EPOXY:** Next, fill cut-out area with an approved two-part epoxy to approximately one half inch (1.3 cm) from the upper lip.

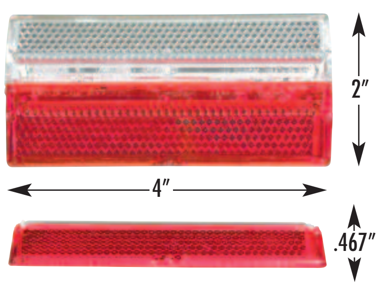


3. **DROP-IN PLACE:** Simply position the marker so that the leveling flares on either side sit flush on the road surface and both ends are covered by the epoxy.

Snow-Lite® 150 and CR150 Snowplowable Reflector Markers

These Snow-Lite® models feature a Medium profile design that incorporates both the reduced impact for the snow plow operator from both directions and an increased reflective visibility over the Low Profile design. Both include a highly reflective insert with our Abrasion Resistant Coating. You may choose either the standard Model 150 or the Model CR150 which includes a center rail for additional protection of the reflective lens.





2004 Long-Life Reflectors

The Model 2004 is a snowplowable type reflective pavement marker designed for slot mounting or as a replacement reflector for most snowplowable castings.

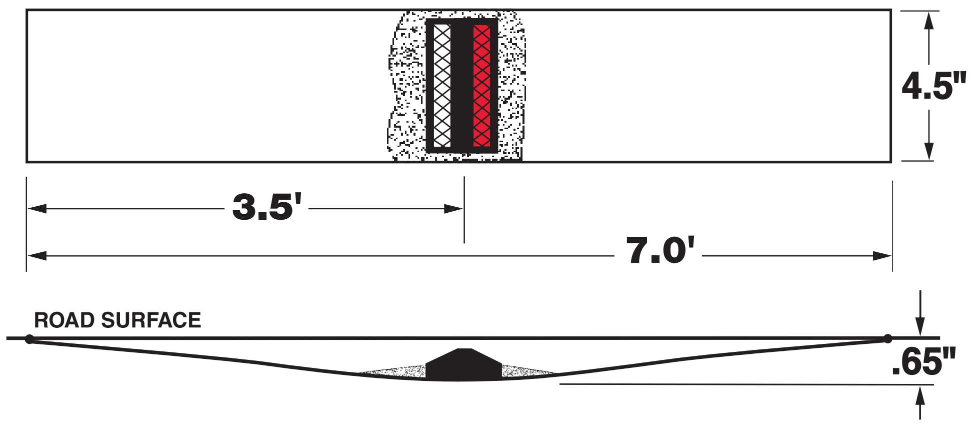
An abrasion resistant coating is chemically bonded to the lens surface to protect it from the grinding action of dirt, sand and contact from traffic volume.

Snowplowable Reflectors

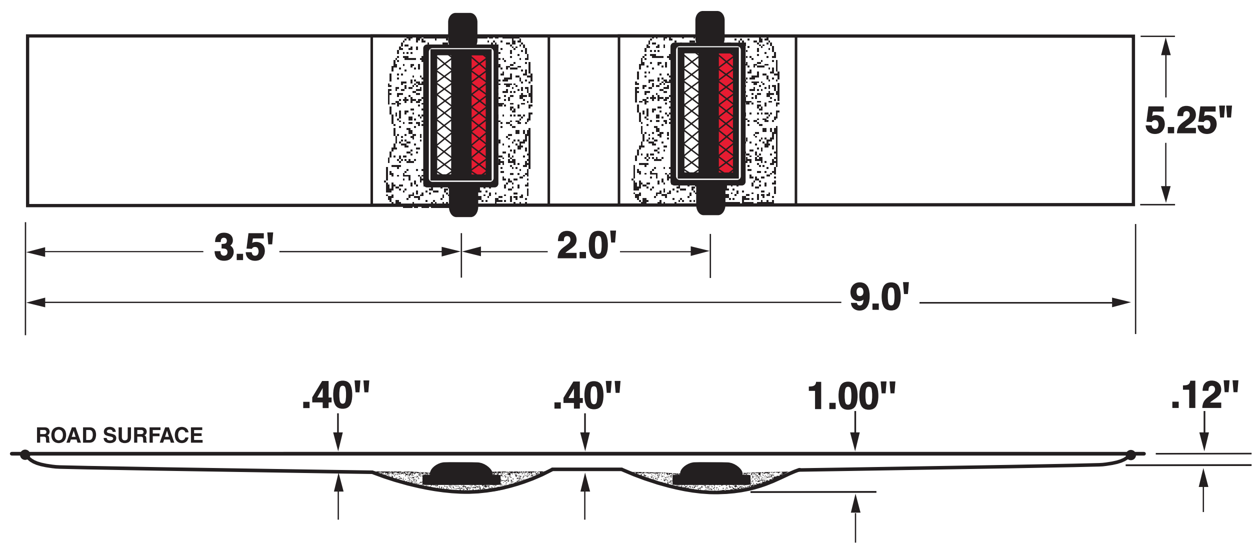
Lens Type		Part Numbers: Insert Only	Part Numbers: Model 150
Type B	2 Way Clear	20042W	SL150R042W
Type C	Clear and Red	2004WR	SL150R042WR
Type D	2 Way Amber	20042A	SL150R042A
Type G	1 Way Clear	20041W	SL150R041W
Type H	1 Way Amber	20041A	SL150R041A
Type K	1 Way Red	20041R	SL150R041R
Type DR	2 Way Red	20042R	SL150R042R
Type X	Amber and Red	2004AR	SL150R04AR
Type Z	Clear and Amber	2004WA	SL150R04WA

RECESS SPECIFICATIONS

TRADITIONAL Recessed Marker



MARKER ONE Recessed Marker



REFLECTIVITY OF R-100 MARKERS

REFLECTIVE INTENSITY IS MEASURED BY THE HEIGHT (IN.) OF REFLECTIVE AREA OBSERVED BY A MOTORIST APPROACHING THE REFLECTORS ON CLEAR DRY PAVEMENT (1)

DISTANCE FROM HEADLIGHTS TO REFLECTOR (FT.)	DISTANCE FROM BEGINNING OF GROOVE TO REFLECTOR (FT.)		
	RAISED MARKERS (2) (NO GROOVE)	TRADITIONAL 3.5	MARKER ONE 3.5/5.5
	1 Reflector	*1 Reflector*	*2 Reflectors*
600	.20	.03	.03 + .07 = .10
500	.20	.06	.06 + .09 = .15
400	.20	.10	.10 + .15 = .25
300	.20	.17	.17 + .18 = .35
200	.20	.25	.25 + .25 = .50

(1) Max. Ht. of Reflective Area (1 Reflector)= .25 in.
(2) Benchmark Reflective Height of Low Profile Design

Specifications for R-100 Housing and Reflector

MATERIAL:	Polycarbonate Plastic
WEIGHT:	Housing 2.00 oz. Reflector 2.00 oz.
HOUSING SIZE:	5.00" x 3.00" x .70" high
SPECIFIC INTENSITY cd/fc OF REFLECTIVITY AT 0.2° OBSERVATION ANGLE	
WHITE:	3.0 at 0° entrance angle 1.2 at 20° entrance angle
YELLOW:	60% of white values
RED:	25% of white values

TRINITY HIGHWAY GUIDE LITE™ SNOW-PLOWABLE RAISED PAVEMENT MARKER (SRPM) GENERAL PRODUCT SPECIFICATION

1) DESCRIPTION

The Guide Lite™ SRPM body is made from a lightweight, yet tough, polymeric material. Embedded in the polymeric body are two hardened steel rub rails. The marker shall have a pocket to receive a replaceable prismatic lens reflector for reflecting vehicle headlights from single or opposing directions. The marker keels are shaped with a ramp to deflect a snowplow blade over the prismatic lens reflector. The symmetrical design allows for the marker to be plowable from opposing directions of travel. In the event that the prismatic reflector is damaged, it can be easily removed in the field and replaced with a new reflector. The shallow design of the keels allows the marker to be used on roads and highways as well as bridge decks. The marker shape and footprint is similar to a standard cast iron marker, so standard slot cutting tools and materials can be used for installation. When road resurfacing is performed, the steel rub rails can be dislodged from the product and the marker body can be left in place, since it will not harm road grinding equipment.

2) DETAILED SPECIFICATIONS

a) MARKER BODY:

i) Dimensions:

Length:	9.37 in
Width:	5.75 in
Height:	1.87 in
Installed Height:	0.26 in above road surface

ii) Material:
The marker body shall be made from a lightweight high-impact grade polymer material.

b) Rub Rails
The rub rails shall be made from hardened, abrasion resistant steel.

c) Reflector

i) The reflector shall be either 3M Series 190 or Ennis Paint, Inc. Stimsonite Division Model C40.

APPENDIX B: CUMULATIVE RESIDUAL (CURE) PLOTS

Figures A29 through A35 provide the CURE plots for the SPFs for total, fatal and injury, lane departure, wet pavement lane departure, nighttime lane departure, nighttime wet pavement lane departure, and fatal and injury lane departure crashes. In all cases, the CURE plots show a relatively good fit of predictions compared to observed values. There are small sections for fatal and injury, lane departure, wet pavement lane departure, nighttime lane departure, and fatal and injury lane departure where the cumulative residuals exceed the 95% confidence interval, but in all cases, this is very brief. Note that the CURE plots for all subsets of lane departure crashes were developed using the total crashes' SPF in combination with a proportion factor for the crash type (as indicated in the text of the report).

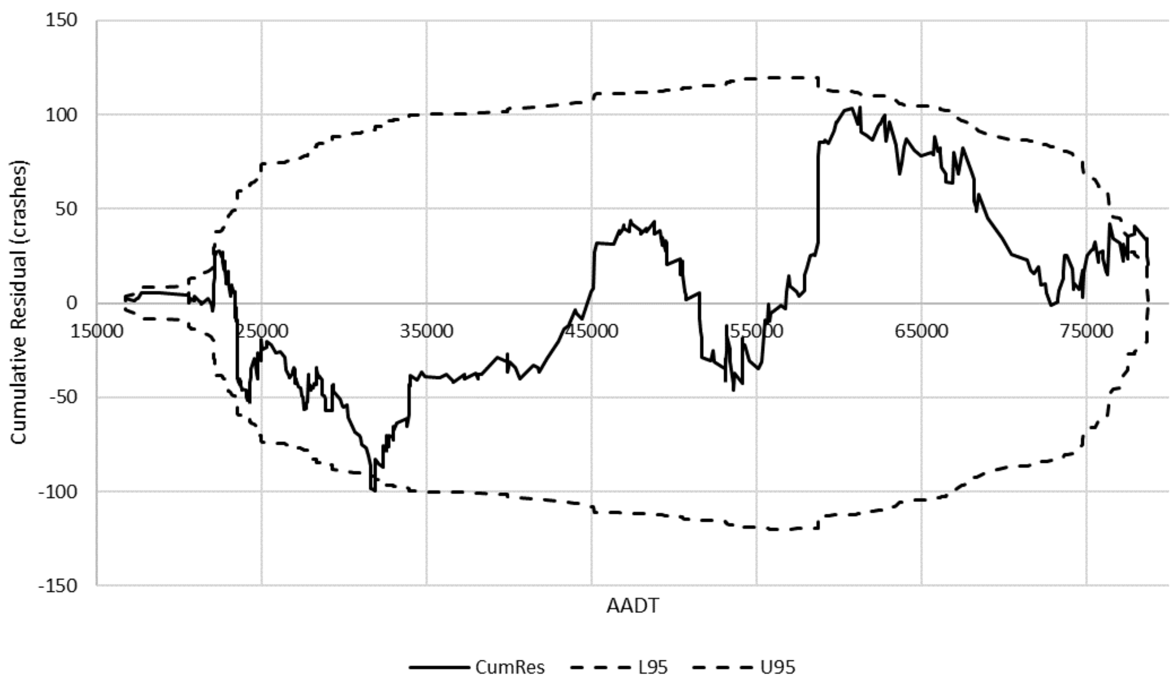


Figure A29. CURE plot for total crashes.

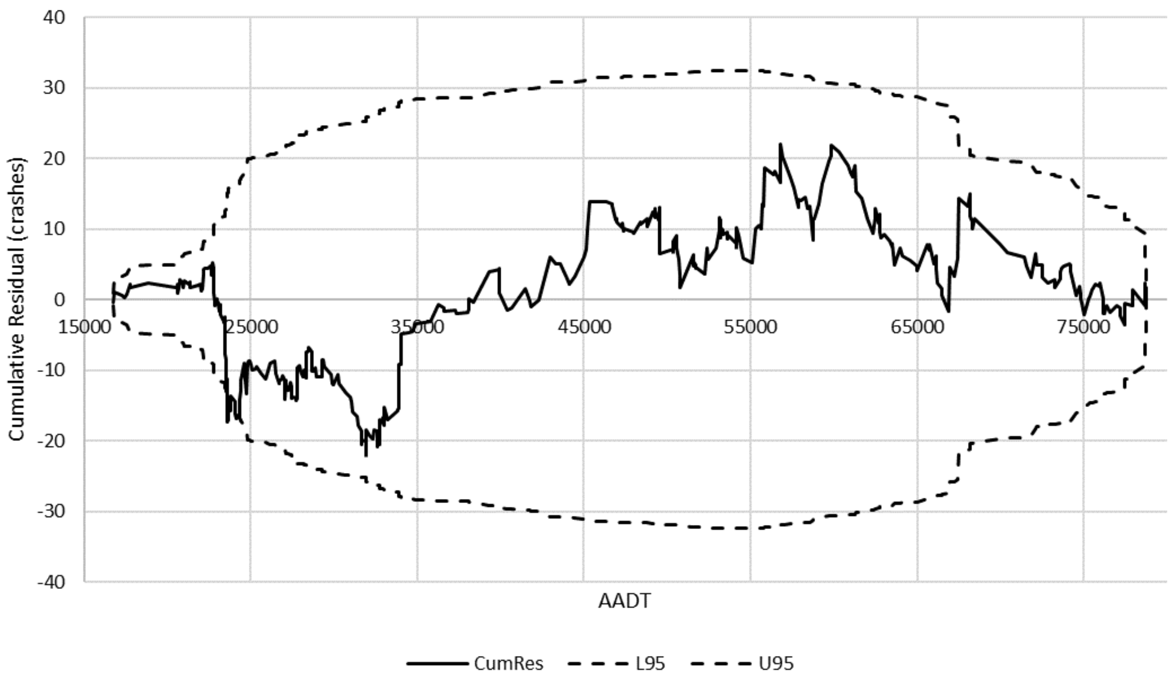


Figure A30. CURE plot for fatal and injury crashes.

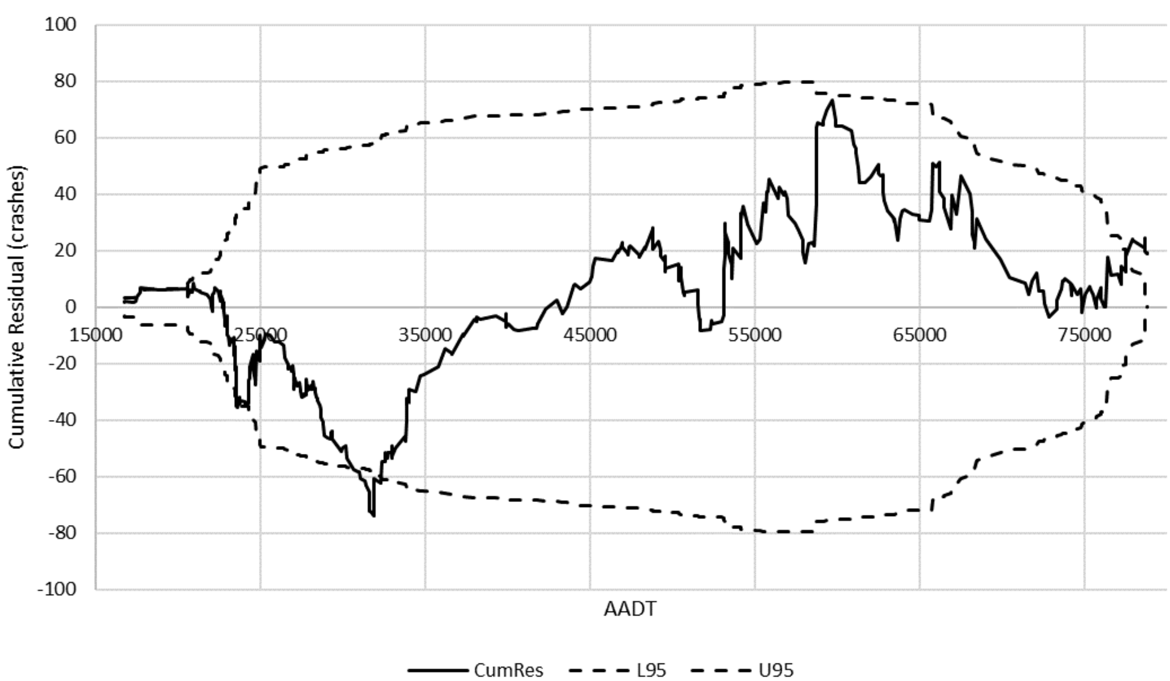


Figure A31. CURE plot for lane departure crashes.

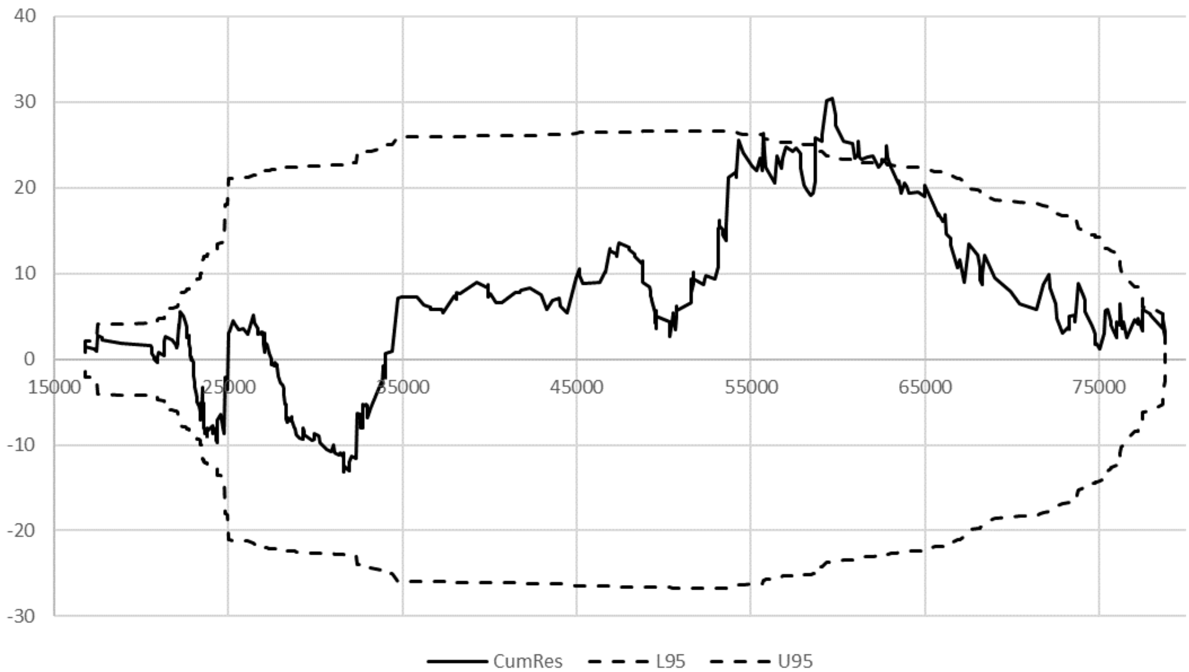


Figure A32. CURE plot for wet pavement lane departure crashes.

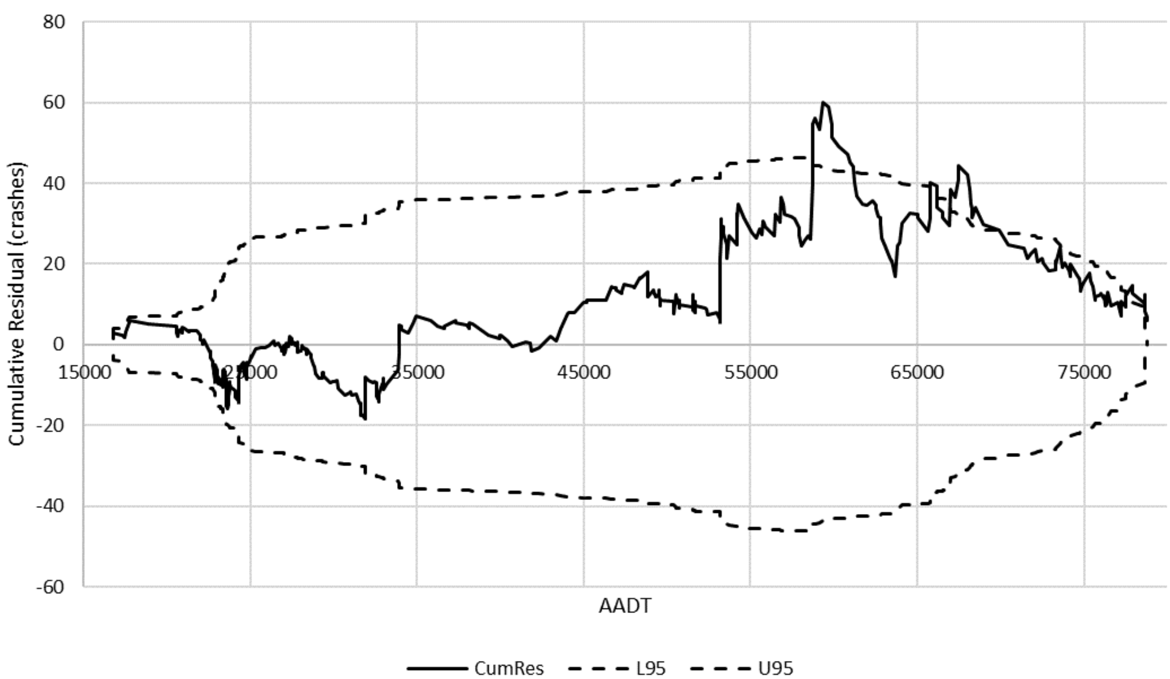


Figure A33. CURE plot for nighttime lane departure crashes.

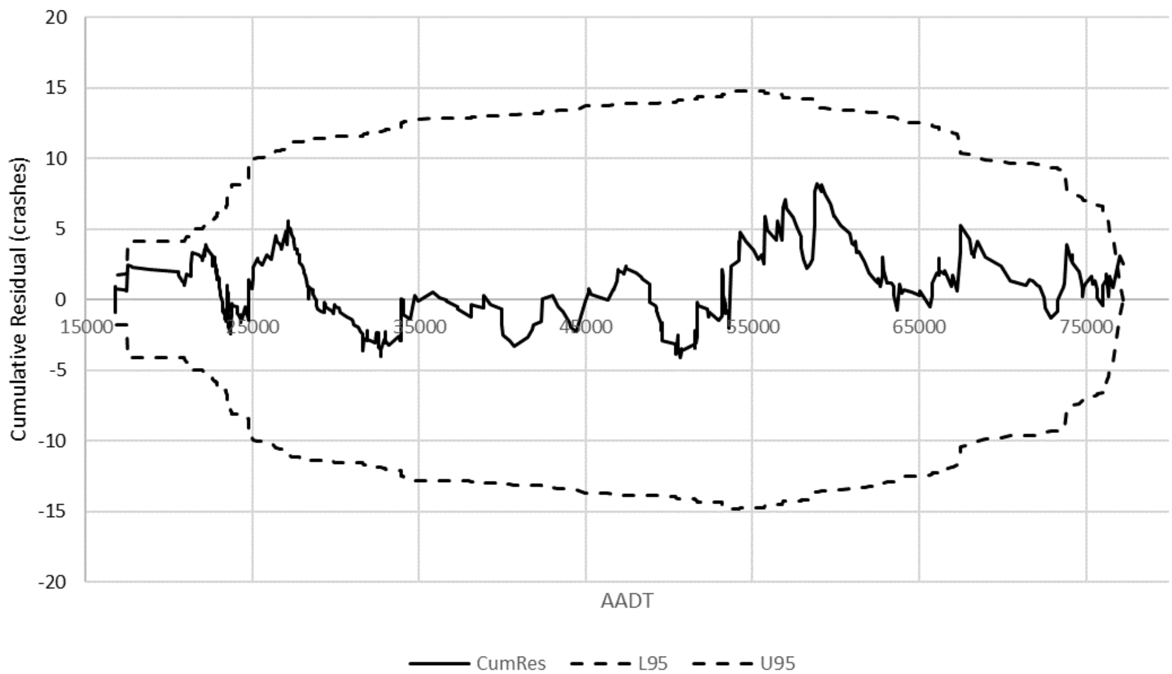


Figure A34. CURE plot for nighttime wet pavement lane departure crashes.

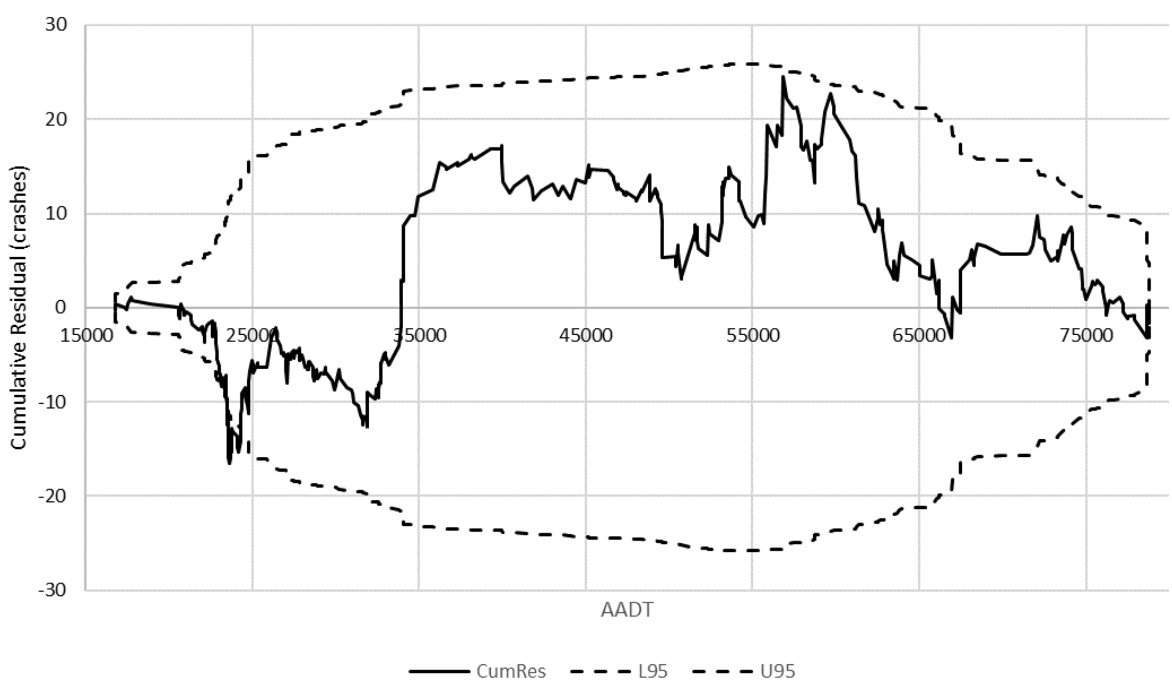


Figure A35. CURE plot for fatal and injury lane departure crashes.

APPENDIX C: SRPM INSTALLATION INSPECTION GUIDE

Illinois Department of Transportation

Snowplowable Reflective Pavement Marker Installation Inspection Guide

During Marker Installation

During marker installation there are 5 main items to inspect:

1. Location
2. Cut dimensions
3. Cut cleanliness
4. Epoxy
5. Marker placement

During Marker Installation

1. Marker **location** must meet the following:

- Reflective face must be perpendicular to the roadway center line.
- Markers must have a minimum 2” offset from any lane striping.
- Markers should NOT be installed in any longitudinal or transverse pavement joints or in cracks in the pavement surface.
- Markers must be at least 2” away from any joint, crack or seam.

During Marker Installation

2. Marker **cut dimensions** must meet the following:

- Pavement should be cut to match the bottom contour of the marker.
- A single plunge cut, using a stack of 18” diameter concrete saw blades bordered by 20” diameter blades, is required.
- A marker should be placed in the cut to verify proper fit:
  - 1/8” side to side clearance.
  - All 4 leveling lugs resting on the pavement.
  - Leading edge of the casting rails must lie below the pavement surface.

During Marker Installation

3. Marker **cut cleanliness** must meet the following:

- The saw cut area must be free of dust, dirt or any material which will adversely affect the bond of the adhesive.
- The saw cut area MUST BE DRY before filling with epoxy.
- It is recommended to clear the saw cut with compressed air and then dry with a hand torch prior to filling with epoxy to ensure a clean, dry cut.

During Marker Installation

4. Marker **epoxy** must meet the following:

- Epoxy components should be combined and thoroughly mixed just prior to anchoring the markers, following the manufacturer’s instructions for mixing.
- Properly mixed, the epoxy turns uniformly gray, without any visible streaks.
- Epoxy should be poured into the outer two grooves and then in the cut between the grooves.
- Epoxy should fill to within 3/8” of the pavement surface. At this level, some adhesive should overflow around the installed casting to seal the sawcut area.

During Marker Installation

5. Marker **placement** must meet the following:

- Markers should be placed by hand into the epoxy filled saw cut.
- All 4 leveling lugs should be resting directly on the pavement.
- Leading edges of the rails should be below the pavement surface.
- Epoxy should not flow onto the reflective lens or the plate in front of it to avoid blocking the lens' visibility.

Incorrect Installations

It is important to identify an incorrect installation and understand what could happen as a result of the error. The following slides provide examples and consequences of incorrect installations.

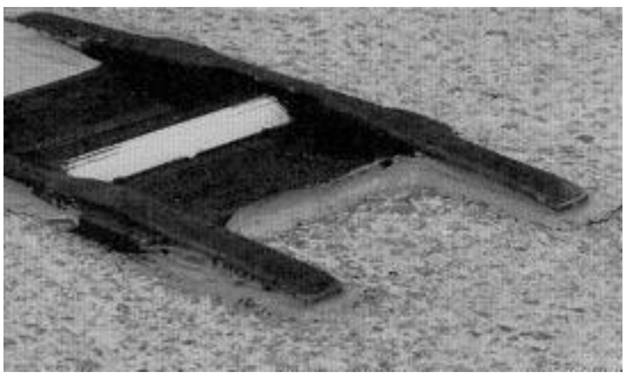
In cases when a bad installation has to be identified, **corrective action must be taken immediately**, including re-installation of the marker in a new saw cut.

Additional inspection of the roadway should be conducted to locate other potential improper installations.

Incorrect Installations

Leading rail tips are above the pavement surface

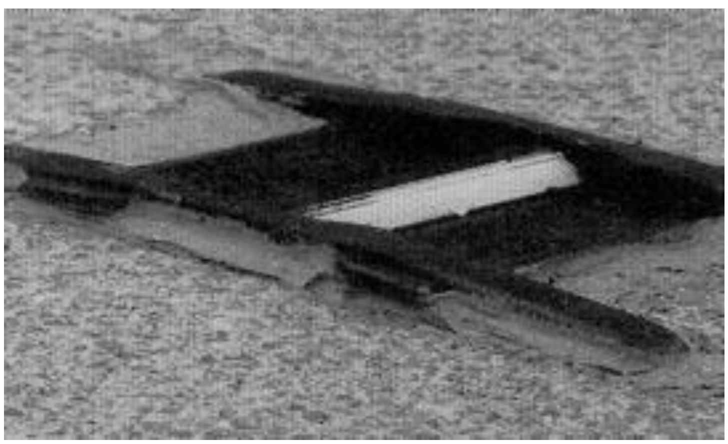
- Plow blade could hit these tips and fracture or dislodge marker



Incorrect Installations

Leveling lugs are not resting on the pavement surface

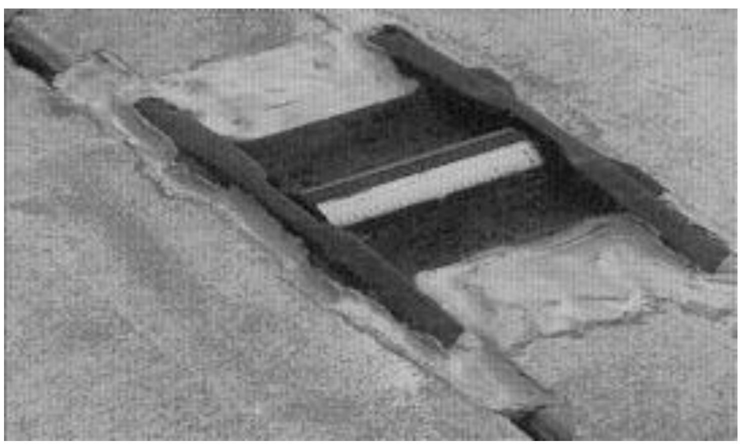
- Can lead to leading tips coming above pavement surface level exposing the marker to a plow blade



Incorrect Installations

Marker is installed in a pavement joint

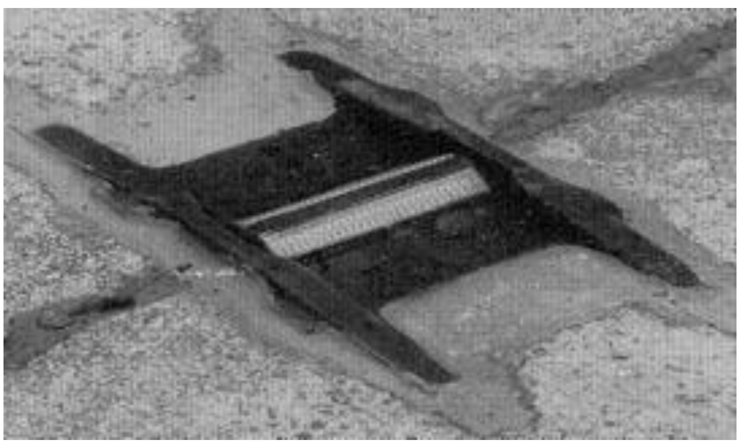
- Results in a weaker bond than installation in a complete saw cut, possibly leading to de-bonding and pavement joint degradation.



Incorrect Installations

Marker is installed in a pavement crack

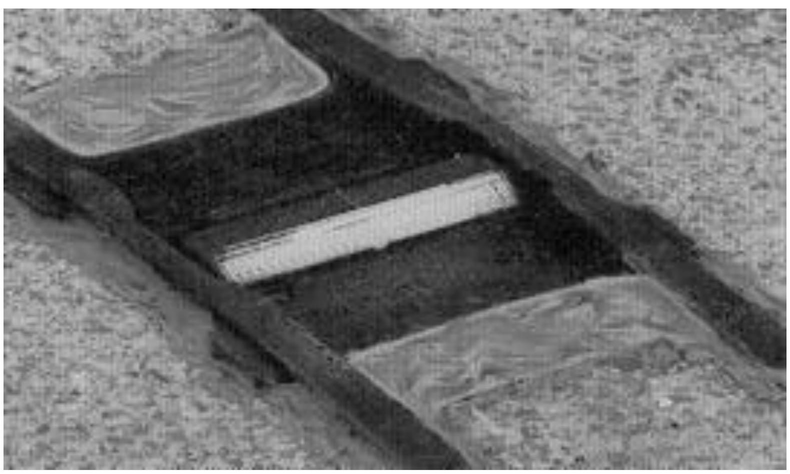
- Results in a weaker bond than installation in a clean saw cut.
- Pavement can buckle, possibly leading to de-bonding.



Incorrect Installations

Streaks in the epoxy reveal improper mixing

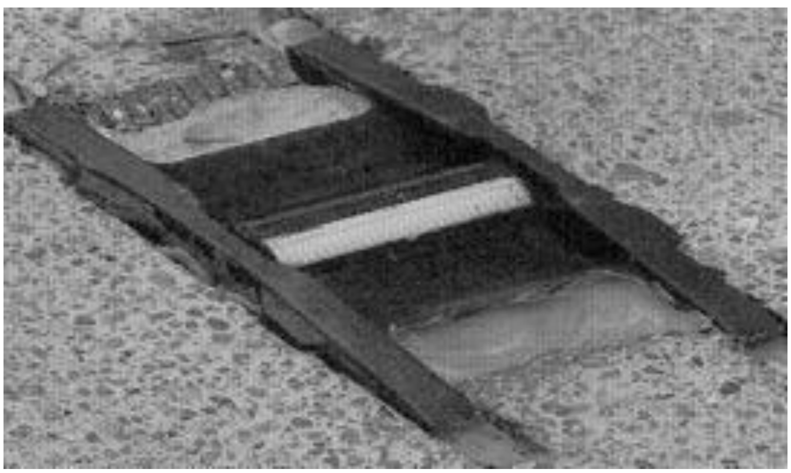
- Will degrade the strength of the adhesive and possibly lead to de-bonding.



Incorrect Installations

Insufficient epoxy to ensure an adequate bond

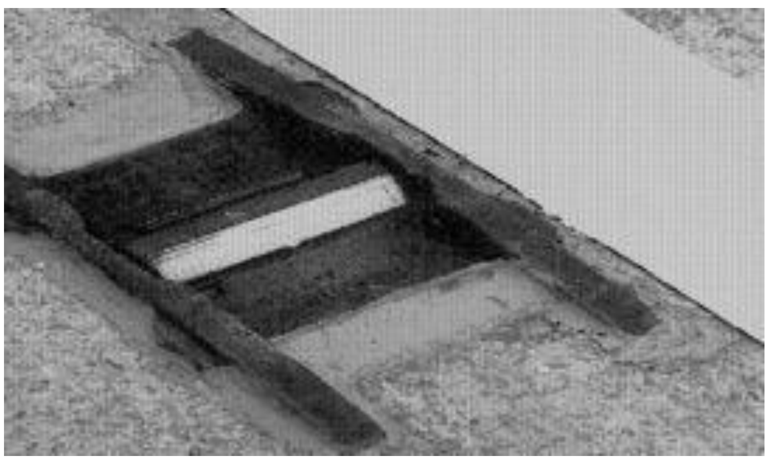
- High potential for marker de-bonding.



Incorrect Installations

Marker is too close to pavement striping

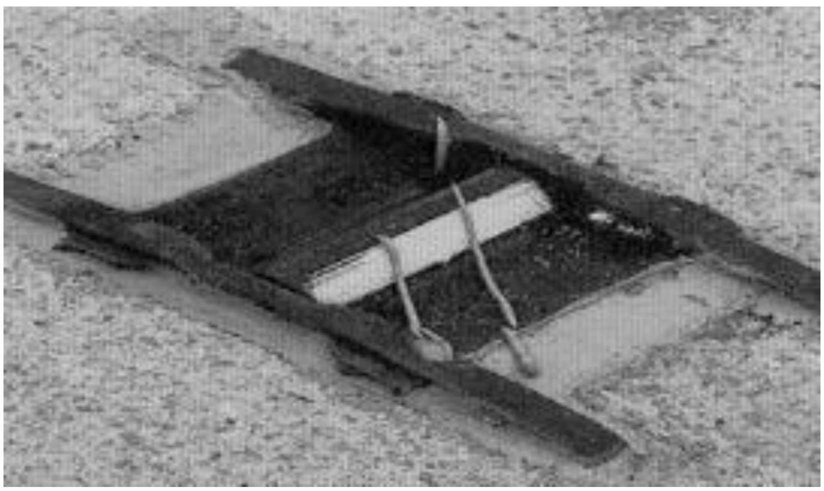
- Future striping operations will likely cover the lens face, eliminating reflectivity.



Incorrect Installations

Epoxy on the reflective lens face

- Results in diminished reflectivity.



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