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Rumble Stripes and Pavement Marking Delineation

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16. Abstract

Pavement markings serve an important role on the highway and must be visible in day, night, and wet conditions. Pavement markings placed in grooved pavement are receiving considerable interest due to their potential for greater durability by providing protection from plow blades used during winter maintenance. Raised pavement markers (RPMs) are also used for roadway delineation, and the failure rate of RPMs in and in between rumble depressions is also of interest. This study evaluated white edge lines and yellow edge lines on roads in Indiana and other northern states, as well as RPMs in and in between rumble depressions. Data for pavement markings was collected by use of a hand-operated retroreflectometer as well as a mobile retroreflectometer, while RPM data collection consisted of documenting the total number of RPMs, number of missing reflectors, and castings. Results showed that for both white and yellow edge lines, grooved preformed tape has the highest durability for greater than ten winter seasons, and grooved thermoplastic could last five winter seasons. Grooved multi-component may last three or four winter seasons while non-grooved paint will last one or perhaps two winter seasons. RPMs in rumble stripes have a higher failure rate than RPMs installed between rumble stripes. Based upon data collected during this project, grooved thermoplastic and multi-component have the lowest lifetime costs for durable markings, and additional performance data should be collected to determine if either has a distinct economic advantage. It is also recommended that RPM installation in rumble depressions be further evaluated.

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EXECUTIVE SUMMARY

RUMBLE STRIPES AND PAVEMENT MARKING DELINEATION

Introduction

Pavement markings serve an important role on the highway. They must provide visibility in daytime, nighttime, and wet conditions, while also being durable and cost-effective for government agencies. In recent years, non-grooved paint, grooved multi-component, grooved preformed tape, and grooved thermoplastic have been the types of pavement markings applied on most state highways in Indiana. Although there have been few studies related to pavement marking durability, anecdotal reports have proved that grooved installations maintain higher retroreflectivity and are protected from damage by snowplows and traffic. This project evaluated white and yellow edge lines on roads in Indiana and other northern states. Additionally, Indiana has installations of raised pavement markers (RPMs) in and in between rumble stripes, and this project also examined their failure rate.

Evaluations

During this study, data was collected by use of both a hand-operated retroreflectometer and a mobile retroreflectometer. The hand-operated retroreflectometer collected data on a 400-foot section of white edge line, with 16 measurements per section. Additionally, data shared by 3M was used in the evaluation of white and yellow edge lines. The RPM data collection consisted of driving 3-mile segments of roads and documenting the total number of RPMs, number of reflectors missing, and number of castings missing. As the study advisory team reached out to stakeholders during the study, the automotive lighting industry expressed interest in understanding the types of retroreflective materials used by INDOT (and other states) and how those materials respond to new wavelengths being introduced in headlights as well LiDAR sensors.

Findings and Implementation

Results showed that for both white and yellow edge lines, grooved preformed tape has the highest dry retroreflectivity performance for greater than ten winter seasons. Based upon a small sample size and extrapolation, it is plausible that the grooved thermoplastic could last five winter seasons while grooved multi-component may have a slightly shorter life expectancy of four winter seasons. Non-grooved paint will last one or perhaps two winter seasons. Also, RPMs in rumble stripes have a higher failure rate than RPMs between rumble stripes.

With regard to retroreflectivity performance of wet elements, grooved preformed tape evaluated after two seasons provided the best performance using the ASTM Standard 2177 wet recovery test protocol. No performance evaluation of grooved tape with wet elements beyond two years was obtained.

Recommendations

A life cycle cost analysis was conducted to compare the performance of material types over a ten-year analysis period. From the expected durability and cost from the INDOT Unit Price Summaries, the total cost for each pavement marking was calculated. Although grooved preformed tape has the longest life expectancy, the life cycle cost of this material is twice the cost of grooved thermoplastic, grooved multi-component, or non-grooved paint. However, since grooved multi-component, grooved thermoplastic, and non-grooved paint must be replaced more often than preformed tape, there may be significant (but hard to quantify) additional benefits associated with preformed tape due to reduced maintenance of traffic activities and reduced exposure of maintenance workers to traffic hazards. Higher retained retroreflectivity values also offer a safety benefit to motorists in daytime, nighttime, and wet weather conditions. Based upon data collected during this project, the following recommendations were made by the project team.

1. Grooved thermoplastic and multi-component have the lowest lifetime costs for durable markings. Additional performance data (particularly after three, four, and five winter seasons) should be collected to determine if either has a distinct economic advantage.
2. RPMs installed in rumble stripes appear to have a higher failure rate. It is recommended that RPMs be installed in between rumble millings on the pavement surface.
3. Characterizing how retroreflective roadway markings respond to emerging vehicle lighting technology and LiDAR is of strong interest to the automotive sector. INDOT has an opportunity to partner with Valeo (based in Seymour, Indiana) to help define new ways that state DOTs can prepare their infrastructure for the next generation of connected and autonomous vehicles.

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1. INTRODUCTION AND LITERATURE REVIEW

The Indiana Department of Transportation (INDOT) is interested in determining the types of pavement markings that are the most durable, cost-effective, and visible in day, night, and wet conditions. It is desired that these markings have a maintenance-free life of several years. Pavement marking daytime and nighttime visibility significantly degrades after several winter seasons of plowing, therefore grooved pavement markings have been deployed in Indiana recently to improve pavement marking durability. These markings are typically placed in grooves from 50–100 miles in depth at speeds of up to 4 mph.

Numerous state agencies have conducted research on grooved and wet reflective pavement markings. The Colorado Department of Transportation (CDOT) researched recessed striping in concrete pavement and concluded that installing pavement markings in a groove protects the markings from damage caused by snowplows and traffic (Outcalt, 2004). The Illinois Center for Transportation conducted a study on all-weather pavement markings and found that only 15% of all-weather products yielded a retroreflectivity of 50 $mcd*m^{-2}*lx^{-1}$ under continuous wetting conditions (Hawkins, Smadi, Knickerbocker, Pike, & Carlson, 2015). In the study pursued by the Virginia Center for Transportation Innovation and Research, it was found that grooved installations maintain a higher retroreflectivity than non-grooved installations and when grooved, wet reflective tape and thermoplastic maintain the highest retroreflectivity (Gibbons & Williams, 2012). In addition, the Missouri Department of Transportation (MoDOT) once used grooved wet reflective tape but now uses high build waterborne paint on most major routes.

One agency that has conducted numerous studies on pavement marking retroreflectivity is the Texas Transportation Institute (TTI). This agency conducted an extensive study regarding pavement markings in wet-weather conditions and found that rumble stripes and larger beads in pavement markings provide increased detection distance for motorists (Carlson, Miles, Pike, & Park, 2007). The TTI also studied two-lane, rural highways in Michigan and concluded that more crashes occur on highways with lower pavement marking retroreflectivity (Avelar & Carlson, 2014). This study included crash data from a five-year period, and a statistical association between nighttime safety and pavement marking retroreflectivity was discovered (Avelar & Carlson, 2014).

The following types of pavement markings (Figure 1.1) are currently used in Indiana: paint, thermoplastic, multi-component, and preformed tape. Paint is the least expensive of these materials, but it typically only lasts one or perhaps two winter seasons. Paint is typically used on highways with an annual average daily traffic (AADT) of less than 10,000 vehicles and where the remaining surface life of the pavement is less than eight years (INDOT,

(a) Paint (not grooved)

(b) Multi-component (grooved)

(c) Preformed tape (grooved) (Photo courtesy Andrew Meeks, 3M.)

(d) Thermoplastic (grooved)

Figure 1.1 Pavement marking types investigated.

(a) In rumble (b) In between rumble

Figure 1.2 RPM types investigated.

2013). In addition, paint is typically used for rumble stripes (INDOT, 2013). Durable pavement markings are currently used on highways with an AADT of greater than 10,000 vehicles and a surface life of greater than eight years (INDOT, 2013). INDOT is considering reducing the AADT threshold from 10,000 vehicles per day to 5,000 vehicles per day. Preformed tape has the highest durability and overall retroreflectivity but is typically used only for lane lines on divided highways due to its higher cost (INDOT, 2013). Almost all installations of durable markings are now grooved, and as of 2018, Indiana has locations with wet reflective elements in the thermoplastic or multi-component material.

Additionally, the Oregon Department of Transportation conducted a study on LiDAR application for maintenance of pavement markings and retroreflective signs. These researchers concluded that mobile LiDAR point clouds can be used to determine accurate retroreflectivity estimates (Olson, Parrish, Che, Jung, & Greenwood, 2018). LiDAR can also be used to assess the retroreflectivity of the reflectors in raised pavement markers (RPMs). Indiana currently has locations with RPMs in rumble stripes, in between rumble stripes, and not in rumble stripes. In this study, locations with either RPMs in between rumble stripes or in rumble stripes were investigated (Figure 1.2). Also, data from two locations were assessed to determine the capabilities of LiDAR scanners in RPM casting and reflector detection. Research in LiDAR application for retroreflectivity is an area of interest for future work at Purdue University.

2. METHODOLOGY

2.1 Data Collection

Before retroreflectivity values were recorded in the field, an inventory of pavement markings was created for sites across the state of Indiana. The primary source of information to construct this inventory was INDOT's database of awarded construction projects. All projects listed with a known date in which the segment was open to traffic were considered. Using the contract numbers, the Contract Information Book (CIB) could be viewed from INDOT records. The schedule of pay items was then used to determine the type of pavement marking material used, along with any potential grooving for markings. This database information was kept in mind during field visits, and any markings with visual discrepancies (e.g., evidence of repainting) was not used in the final dataset. As for RPMs, a database was generated from information sent by traffic engineers from various INDOT districts. The RPM database included the following information: year of last road resurface, year of last casting and reflector refurbishment, and rumble stripe information. Figure 2.1 is a map of Indiana with all locations where retroreflectivity measurements and RPM investigations were conducted.

A variety of other data sources were used to obtain retroreflectivity data. INDOT has mobile retroreflectometer data that were shared for implementation in this project. Retroreflectivity data from studies conducted by the Illinois Center for Transportation and CDOT were included in the analysis of durable pavement markings. 3M and Beck Enterprises have obtained an extensive dataset, and the data for grooved, durable pavement markings were included in this project.

2.2 Field Procedures

The hand-operated retroreflectometer used was the Delta model LTL-X Mark II (Delta Light, 2015). Using the hand-operated retroreflectometer, all retroreflective pavement marking readings were held in compliance with ASTM Standard D7585. Evaluation sections measuring at least 400 feet in length were selected, and for longitudinal edge lines, measurements were recorded at 16 equidistant points along the segment. The intent of documenting 16 measurements was to take enough measurements to be confident that the mean recording was close to the actual mean retroreflectivity while also minimizing the number of measurements needed (ASTM, 2015). After recording the 16 measurements, the average was calculated and designated as the sole retroreflectivity value for the evaluation section. As for skip lines, two measurements per skip line were obtained for eight skip lines. For assessing the performance of pavement markings in wet weather conditions, ASTM Standard 2177 was used to perform the wet recovery test. A bucket of 3 L of water was poured on the pavement marking, and after 45 s, a reading was recorded

Figure 2.1 Map of retroreflectivity measurements and RPM investigations in Indiana.

Figure 2.2 Data collection on a longitudinal edge line.

(ASTM, 2018). All wet continuous testing data was obtained from 3M or the report published by the Illinois Center for Transportation.

For the safety of the individuals collecting the data (as shown in Figure 2.2), longitudinal edge lines were primarily measured as part of this data collection. INDOT provided traffic control for data collection on skip lines. Sites were selected based on accessibility, road type, material, placement, and available information. Sites from each of the six INDOT districts were considered, with most measurements taking place within the Crawfordsville, Fort Wayne, and LaPorte districts.

RPM data collection consisted of counting the number of castings beforehand by either driving the segment or using Google Maps. The segment was investigated to assess casting and reflector performance, and the number of missing castings and reflectors were obtained for each segment. The LiDAR data were obtained from the Digital Photogrammetry Research Group (DPRG) at Purdue University.

3. RESULTS

3.1 Dry Pavement Marking Performance

Figure 3.1, Figure 3.3, and Figure 3.5 plot the retroreflectivity of non-grooved paint (line i), grooved multi-component (line ii), grooved thermoplastic (line iii), and grooved preformed tape (line iv). The data points for lines i, ii, iii, and iv include an exponential trendline to represent the degradation of the materials. The x-axis in each figure is labeled as number of winter seasons rather than age since almost all pavement markings are installed in the summer, and pavement markings experience great deterioration from snowplows in the winter months. In Figure 3.2, Figure 3.4, and Figure 3.6, the following information for each pavement marking type is included: number of winter seasons, retroreflectivity, state, source, installation year, and observation year.

In Figure 3.1, line iv shows a highest life expectancy of greater than ten years. Line iii has a life expectancy of six years while line ii has a life expectancy of four years. Line i shows a life expectancy of one winter season. For line iii, points v and vi have endured three winter seasons. Point v has a retroreflectivity of 248 while point vi has a retroreflectivity of 232. For line ii, points vii and viii have also endured three winter seasons; point vii has a retroreflectivity of 166 while point viii has a retroreflectivity of 160.

In Figure 3.3, line iv shows a life expectancy of greater than ten years. Trendlines were not developed for lines ii and iii due to the small sample size for these marking types. The same line i was used for Figure 3.1, Figure 3.3, and Figure 3.5 since non-grooved paint in white skip lines or yellow edge lines could not be obtained. In Figure 3.5, line iv shows a life expectancy of greater than ten years. Line iii has a life expectancy of four years while line ii has a life expectancy of three years.

The minimum retroreflectivity value of 130 $mcd*m^{-2}*lx^{-1}$ was obtained from a policy developed by INDOT. The policy is for white edge lines, and the policy was used for white skip lines and yellow edge lines in this analysis since there was not a known policy for white skip lines and yellow edge lines at the time of this writing. In Indiana, retroreflectivity measurements are obtained on all state highways each spring to determine which roads should be repainted (Jones, 2012). Roads with an average retroreflectivity of <130 $mcd*m^{-2}*lx^{-1}$ are repainted the following summer while roads with an average retroreflectivity of >130 $mcd*m^{-2}*lx^{-1}$ are not repainted. The minimum retroreflectivity value of 130 $mcd*m^{-2}*lx^{-1}$ is indicated by the gray line in Figure 3.1 and Figure 3.3, and by the yellow line in Figure 3.5.

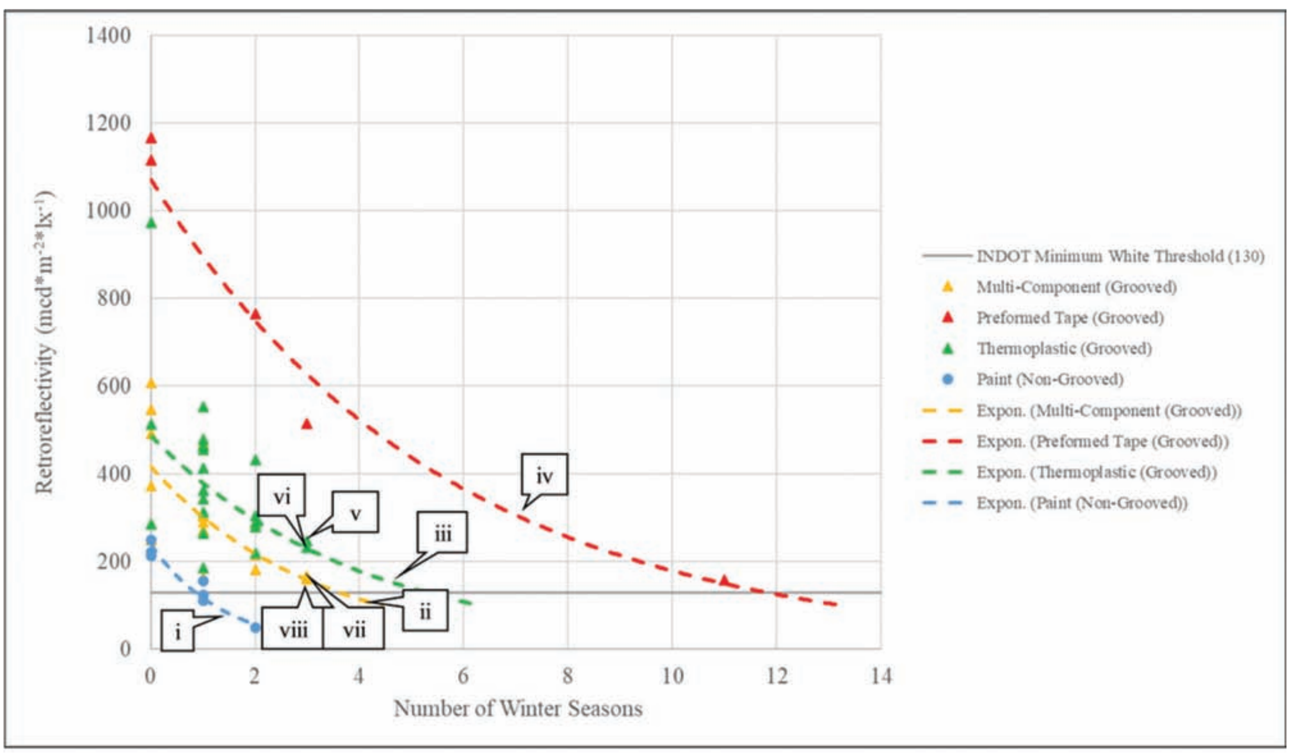


Figure 3.1 White edge line pavement marking performance.

# of Winter Seasons	Retro-reflectivity	State	Source	Installation Year	Observation Year
0	1167	MN	3M	2018	2018
0	1116	MN	3M	2018	2018
0	974	IN	Purdue	2018	2018
0	608	IL	IDOT	2013	2013
0	548	IN	Purdue	2018	2018
0	514	IL	IDOT	2013	2013
0	493	IL	IDOT	2013	2013
0	373	IN	Purdue	2018	2018
0	286	IN	Purdue	2018	2018
0	250	IN	Purdue	2018	2018
0	249	IN	Purdue	2018	2018
0	223	IN	Purdue	2018	2018
0	213	IN	Purdue	2018	2018
1	554	IL	IDOT	2013	2014
1	480	IN	INDOT	2016	2017
1	469	IN	Purdue	2017	2018
1	465	IN	Purdue	2017	2018
1	457	IN	INDOT	2016	2017
1	414	IN	Purdue	2018	2019
1	362	IN	Purdue	2017	2018
1	343	IN	Purdue	2017	2018
1	313	IN	Purdue	2017	2018
1	307	MN	3M	2016	2017
1	303	IL	IDOT	2013	2014
1	290	IL	IDOT	2013	2014
1	270	MN	3M	2016	2017
1	265	IN	Purdue	2017	2018
1	186	IN	Purdue	2017	2018
1	163	MN	3M	2016	2017
1	156	IN	Purdue	2017	2018
1	125	IN	Purdue	2017	2018
1	112	IN	Purdue	2017	2018
2	765	CO	CDOT	2000	2002
2	433	IL	IDOT	2013	2015
2	306	CO	CDOT	2000	2002
2	290	IN	Purdue	2016	2018
2	287	IN	Purdue	2016	2018
2	279	IN	Purdue	2016	2018
2	219	IN	Purdue	2016	2018
2	216	IL	IDOT	2013	2015
2	182	IN	Purdue	2016	2018
2	49	IN	Purdue	2016	2018
3	515	CO	CDOT	2000	2003
3	248	IN	Purdue	2016	2019
3	232	IN	Purdue	2016	2019
3	166	IN	Purdue	2016	2019
3	160	IN	Purdue	2016	2019
11	158	ND	3M	2005	2016

Figure 3.2 White edge line pavement marking performance (table).

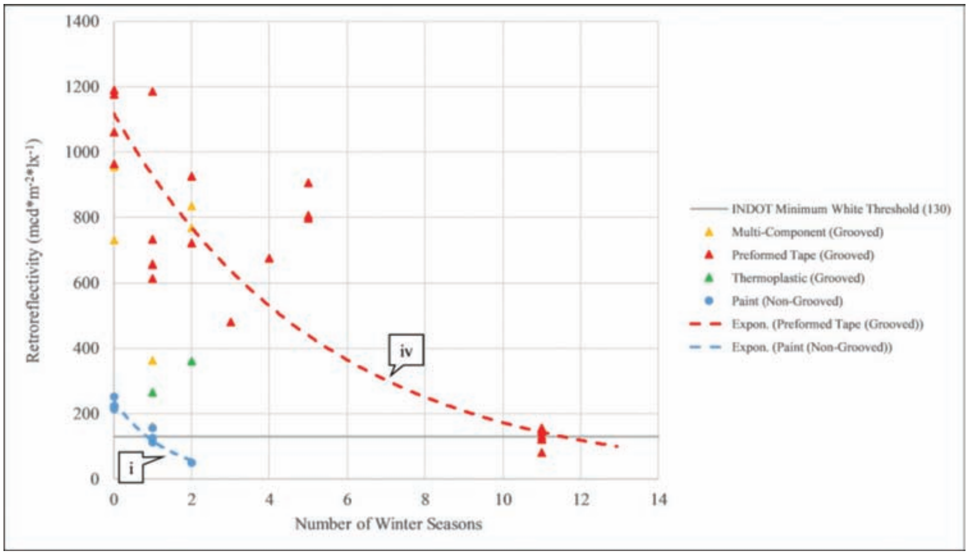


Figure 3.3 White skip line pavement marking performance.

3.2 Wet Element Pavement Marking Performance

Figure 3.7, Figure 3.9, Figure 3.11, and Figure 3.13, along with Figure 3.8, Figure 3.10, Figure 3.12, and Figure 3.14 illustrate the performance of white and yellow markings with wet elements in the wet recovery and continuous tests. Using those wet testing protocols, grooved preformed tape with wet elements retained the highest retroreflectivity readings for white edge and skip lines in both test types, followed by grooved multi-component. Grooved multi-component and thermoplastic retain similar retroreflectivity values for yellow edge lines in both the recovery and continuous test types. There is recovery test data for three sites with white edge lines in Indiana; the highest reading was 268 on the grooved multi-component on US 20 near LaPorte. The readings on the grooved thermoplastic were much lower—14 on US 41 near Vincennes and 28 on SR 1 near Fort Wayne. The provider of wet elements has urged caution on these tests due to concern about the application rate of the wet elements when the lines were installed.

3.3 RPM Casting and Reflector Performance

For RPMs, Figure 3.15 illustrates an RPM casting with a missing reflector as well as a hole in the pavement where an RPM casting and reflector became dislodged. Table 3.1 and Table 3.2 include the number and percent of castings and reflectors missing at six locations in the INDOT Seymour district. Locations with RPMs in between rumble stripes at three and nine winter seasons have a lower failure rate than RPMs in rumble stripes at three winter seasons. The age of each location was determined by verifying the year of the last road resurface and RPM refurbishment with INDOT. A combination of locations with typical and sinusoidal rumble stripes were investigated and photos of each location are provided in the Appendix.

3.4 LiDAR Application for RPM Detection

The HDL32E, VLP-16, Riegl, and Z+F LiDAR scanners were used to obtain data for two segments of state highways (Figure 3.16). In Figure 3.16, the VLP-16 **(1)** and HDL32E **(2)** are mounted to the Ford Transit van. Additionally, the Riegl **(3)** and Z+F **(4)** are mounted to the Ford F-150 truck. The HDL32E and VLP-16 scanners were used for a data collection on US 52/231 in West Lafayette, Indiana while the Riegl and Z+F scanners were used on I-65 in Indianapolis, Indiana. Figure 3.17 illustrates a typical image for an RPM with the casting and reflector in place, while Figure 3.18 illustrates a missing casting for each scanner type. The HDL32E and VLP-16 are low fidelity scanners while the Z+F captures information at the highest fidelity.

3.5 Life Cycle Cost Analysis

To effectively compare the performance of the material types on a cost basis, a life cycle cost analysis was utilized for white and yellow edge lines. A life cycle cost analysis was not conducted for the white skip line data due to the small size of the data set. For each material, an expected durability was determined using the developed degradation curves. Based on the INDOT minimum retroreflectivity value of 130 mcd*m^{-2}*lx^{-1}, the age value when each curve falls below this minimum was determined and rounded up to the nearest whole number. This value will serve as the average number of years before a line of such material would need to be repainted.

To determine the costs associated with each material, the INDOT Unit Price Summaries for the 2017 calendar year were consulted (INDOT, 2017). From this list of unit prices, the weighted average cost per linear foot of each marking type could be determined (Table 3.3 and Table 3.6). Table 3.4 and Table 3.7 include the total cost for each marking when installed in a groove.

# of Winter Seasons	Retro-reflectivity	State	Source	Installation Year	Observation Year
0	1188	MN	3M	2018	2018
0	1176	MN	3M	2018	2018
0	1060	MN	3M	2018	2018
0	963	IL	IDOT	2012	2012
0	953	MN	3M	2018	2018
0	729	IL	IDOT	2013	2013
0	250	IN	Purdue	2018	2018
0	223	IN	Purdue	2018	2018
0	213	IN	Purdue	2018	2018
1	1184	IN	Purdue	2017	2018
1	732	IL	IDOT	2012	2013
1	657	MN	3M	2016	2017
1	655	IN	Purdue	2018	2019
1	612	MN	3M	2016	2017
1	362	IL	IDOT	2013	2014
1	265	IN	Purdue	2018	2019
1	159	MN	3M	2016	2017
1	156	IN	Purdue	2017	2018
1	125	IN	Purdue	2017	2018
1	112	IN	Purdue	2017	2018
2	926	IL	IDOT	2012	2014
2	833	MN	3M	2016	2018
2	768	MN	3M	2016	2018
2	722	CO	CDOT	2000	2002
2	359	CO	CDOT	2000	2002
2	49	IN	Purdue	2016	2018
3	479	CO	CDOT	2000	2003
4	674	IN	Purdue	2014	2018
5	906	IN	INDOT	2012	2017
5	806	IN	INDOT	2012	2017
5	796	IN	INDOT	2012	2017
11	156	IN	INDOT	2004	2015
11	154	IN	INDOT	2004	2015
11	148	IN	INDOT	2004	2015
11	144	ND	3M	2005	2016
11	131	IN	INDOT	2004	2015
11	122	ND	3M	2005	2016
11	121	IN	INDOT	2004	2015
11	79	IN	INDOT	2004	2015

Figure 3.4 White skip line pavement marking performance (table).

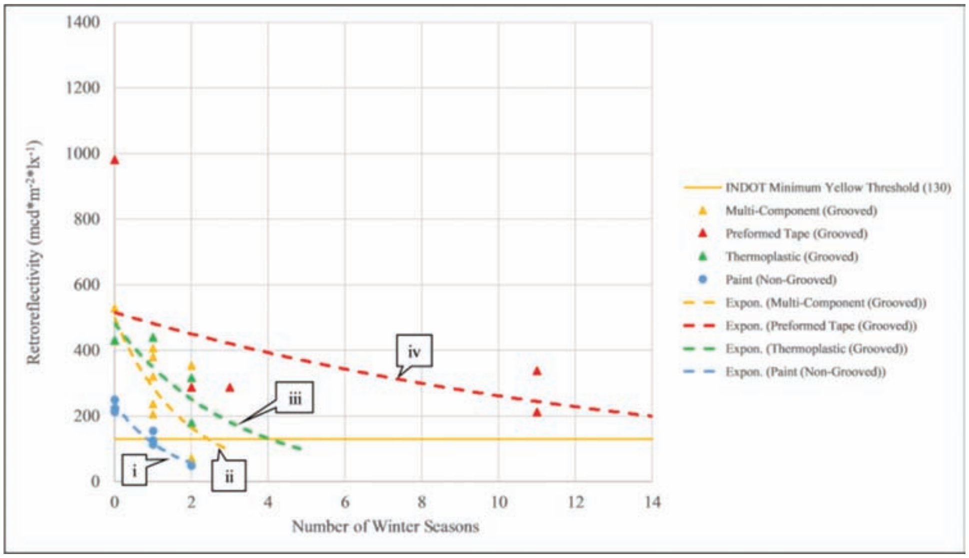


Figure 3.5 Yellow edge line pavement marking performance.

# of Winter Seasons	Retro-reflectivity	State	Source	Installation Year	Observation Year
0	981	MN	3M	2018	2018
0	528	IL	IDOT	2013	2013
0	431	IL	IDOT	2013	2013
0	428	IL	IDOT	2013	2013
0	250	IN	Purdue	2018	2018
0	223	IN	Purdue	2018	2018
0	213	IN	Purdue	2018	2018
1	439	IL	IDOT	2013	2014
1	406	IL	IDOT	2013	2014
1	381	IL	IDOT	2013	2014
1	321	IN	INDOT	2016	2017
1	237	MN	3M	2016	2017
1	205	MN	3M	2016	2017
1	156	IN	Purdue	2017	2018
1	125	IN	Purdue	2017	2018
1	112	IN	Purdue	2017	2018
2	354	IL	IDOT	2013	2015
2	316	IL	IDOT	2013	2015
2	288	CO	CDOT	2000	2002
2	179	CO	CDOT	2000	2002
2	70	CO	CDOT	2000	2002
2	49	IN	Purdue	2016	2018
3	287	CO	CDOT	2000	2003
11	338	ND	3M	2005	2016
11	212	ND	3M	2005	2016

Figure 3.6 Yellow edge line pavement marking performance (table).

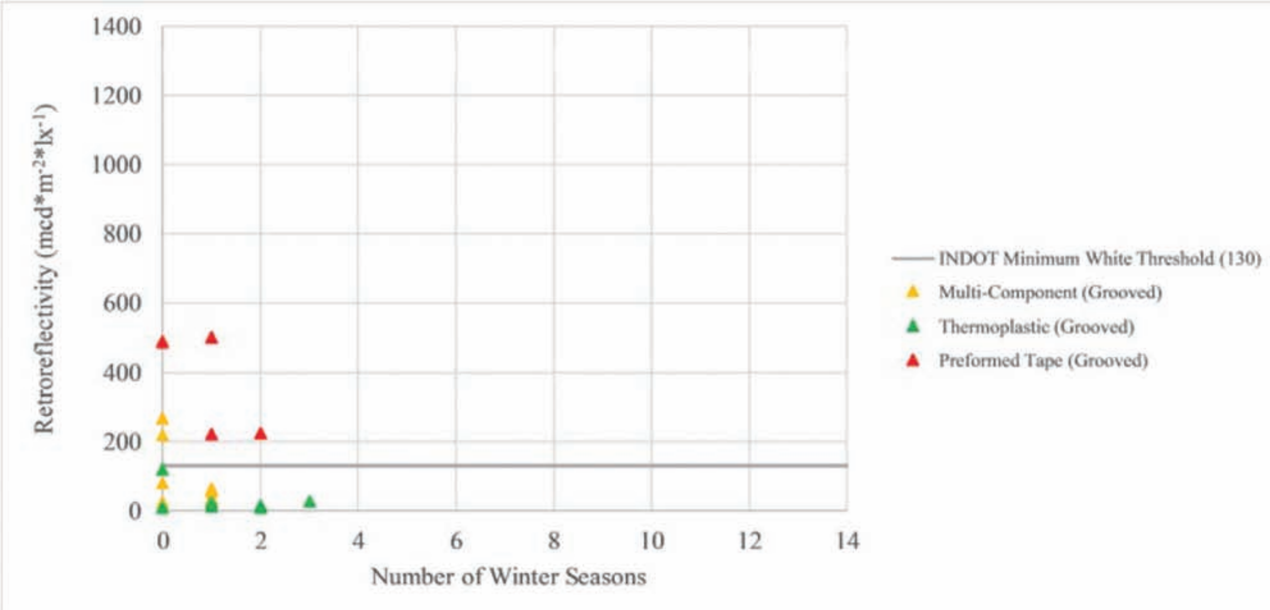


Figure 3.7 White recovery pavement marking performance.

# of Winter Seasons	Retro-reflectivity	Type	State	Source	Installation Year	Observation Year
0	489	Skip	IL	IDOT	2012	2012
0	268	Edge	IN	Purdue	2018	2018
0	219	Skip	IL	IDOT	2013	2013
0	121	Edge	IL	IDOT	2013	2013
0	80	Edge	IL	IDOT	2013	2013
0	24	Edge	IL	IDOT	2013	2013
0	10	Edge	IN	Purdue	2018	2018
1	503	Skip	MN	3M	2016	2017
1	222	Skip	IL	IDOT	2012	2013
1	66	Edge	IL	IDOT	2013	2014
1	57	Skip	MN	3M	2016	2017
1	57	Edge	MN	3M	2016	2017
1	35	Skip	IL	IDOT	2013	2014
1	25	Edge	IL	IDOT	2013	2014
1	16	Edge	IL	IDOT	2013	2014
1	14	Edge	IN	Purdue	2018	2019
2	224	Skip	IL	IDOT	2012	2014
2	15	Edge	IL	IDOT	2013	2015
2	12	Edge	IL	IDOT	2013	2015
2	10	Edge	IN	Purdue	2016	2018
3	28	Edge	IN	Purdue	2016	2019

Figure 3.8 White recovery pavement marking performance (table).

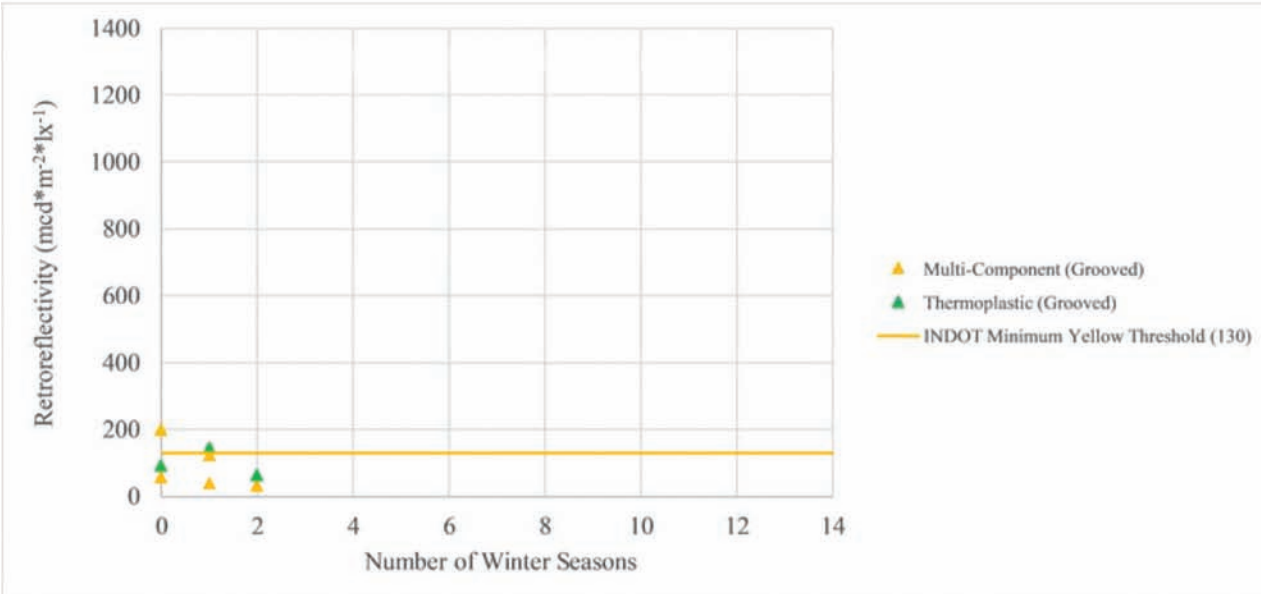


Figure 3.9 Yellow recovery pavement marking performance.

# of Winter Seasons	Retro-reflectivity	Type	State	Source	Installation Year	Observation Year
0	202	Edge	IL	IDOT	2013	2013
0	93	Edge	IL	IDOT	2013	2013
0	59	Edge	IL	IDOT	2013	2013
1	147	Edge	IL	IDOT	2013	2014
1	126	Edge	IL	IDOT	2013	2014
1	41	Edge	IL	IDOT	2013	2014
2	65	Edge	IL	IDOT	2013	2015
2	32	Edge	IL	IDOT	2013	2015

Figure 3.10 Yellow recovery pavement marking performance (table).

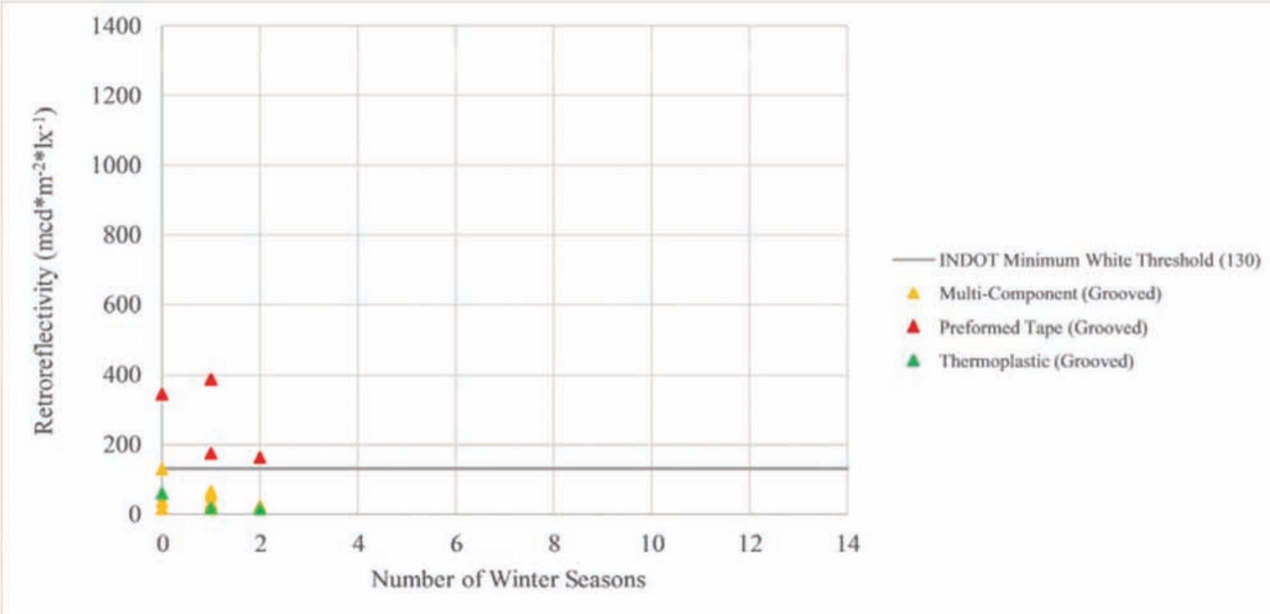


Figure 3.11 White continuous pavement marking performance.

# of Winter Seasons	Retro-reflectivity	Type	State	Source	Installation Year	Observation Year
0	346	Skip	IL	IDOT	2012	2012
0	129	Skip	IL	IDOT	2013	2013
0	58	Edge	IL	IDOT	2013	2013
0	36	Edge	IL	IDOT	2013	2013
0	14	Edge	IL	IDOT	2013	2013
1	387	Skip	MN	3M	2016	2017
1	175	Skip	IL	IDOT	2012	2013
1	66	Skip	MN	3M	2016	2017
1	54	Edge	MN	3M	2016	2017
1	33	Edge	IL	IDOT	2013	2014
1	27	Skip	IL	IDOT	2013	2014
1	16	Edge	IL	IDOT	2013	2014
1	15	Edge	IL	IDOT	2013	2014
2	162	Skip	IL	IDOT	2013	2015
2	24	Edge	IL	IDOT	2013	2015
2	14	Edge	IL	IDOT	2013	2015

Figure 3.12 White continuous pavement marking performance (table).

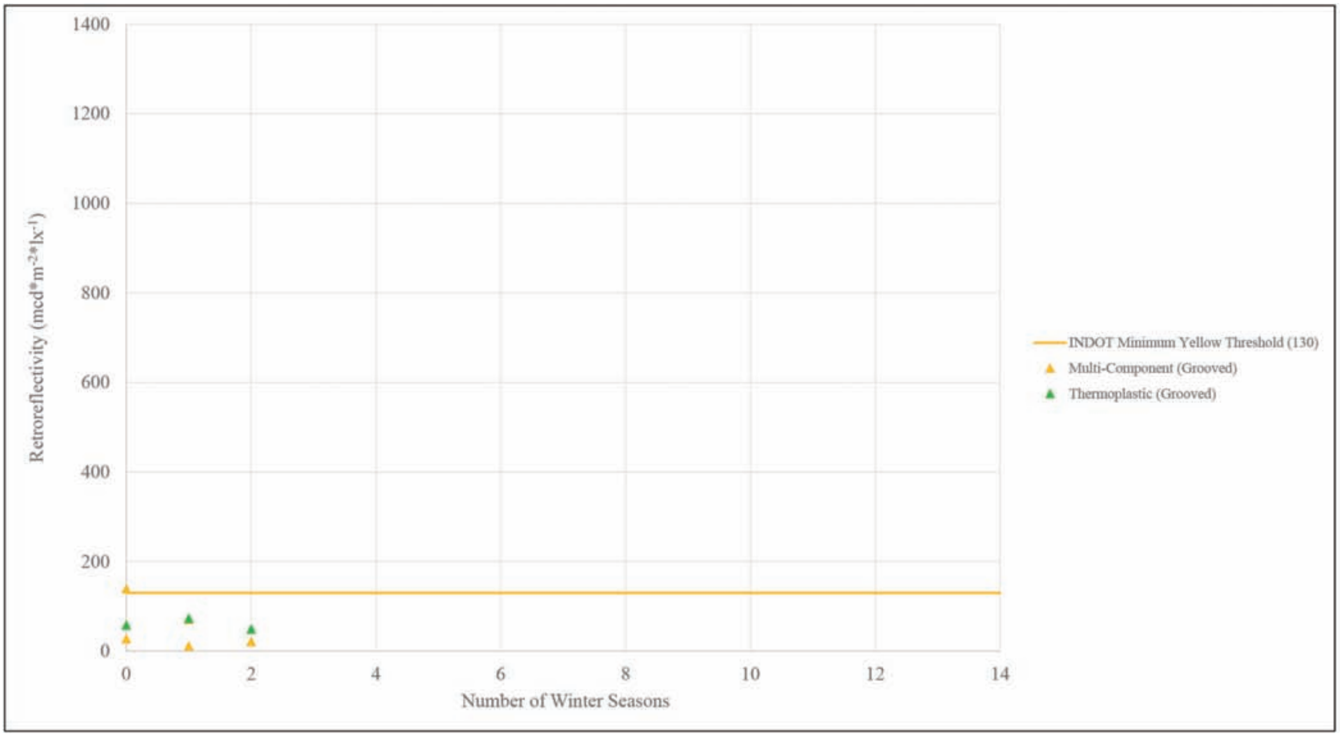


Figure 3.13 Yellow continuous pavement marking performance.

# of Winter Seasons	Retro-reflectivity	Type	State	Source	Installation Year	Observation Year
0	139	Edge	IL	IDOT	2013	2013
0	58	Edge	IL	IDOT	2013	2013
0	27	Edge	IL	IDOT	2013	2013
1	73	Edge	IL	IDOT	2013	2014
1	71	Edge	IL	IDOT	2013	2014
1	11	Edge	IL	IDOT	2013	2014
2	49	Edge	IL	IDOT	2013	2015
2	21	Edge	IL	IDOT	2013	2015

Figure 3.14 Yellow continuous pavement marking performance (table).

(a) RPM Casting with missing reflector

(b) Missing RPM casting and reflector

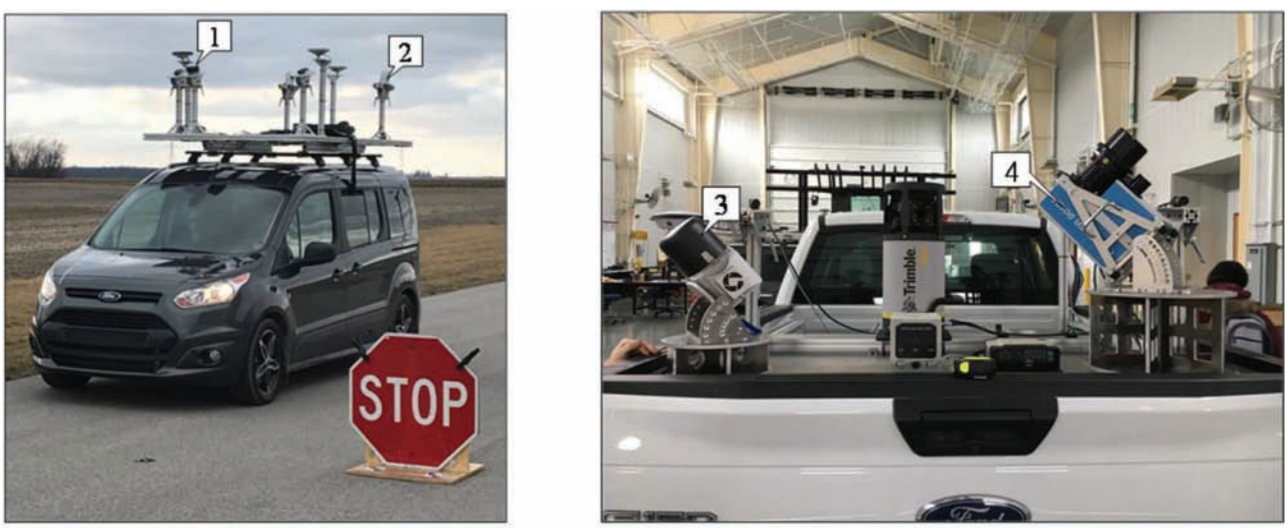
Figure 3.15 Missing RPM photos.

TABLE 3.1
In between rumble RPM performance

Location/Type	Castings with Missing Reflector (%)	Missing Castings (%)	Castings In Place, with Reflectors (%)	Castings with Missing Reflector (#)	Missing Castings (#)	Castings In Place, with Reflectors (#)	Age (Winter Seasons)
SR 135–Bargersville (Sinusoidal)	1.1	0.0	98.9	2	0	188	9
SR 7–Elizabeth-town (Sinusoidal)	0.5	2.6	96.9	1	5	190	9
SR 56–Scottsburg (Typical)	0.0	0.9	99.1	0	0	253	3

TABLE 3.2
In rumble RPM performance

Location/Type	Castings with Missing Reflector (%)	Missing Castings (%)	Castings In Place, with Reflectors (%)	Castings with Missing Reflector (#)	Missing Castings (#)	Castings In Place, with Reflectors (#)	Age (Winter Seasons)
US 50–Brownstown (Typical)	0.0	1.2	98.8	0	2	171	3
US 31–Seymour (Sinusoidal)	0.0	5.3	94.7	0	11	195	3
SR 11–Seymour (Sinusoidal)	0.7	3.5	95.7	1	5	133	3



(a) VLP-16 and HDL32E (b) Riegl and Z+F

Figure 3.16 LiDAR scanners used for RPM detection.

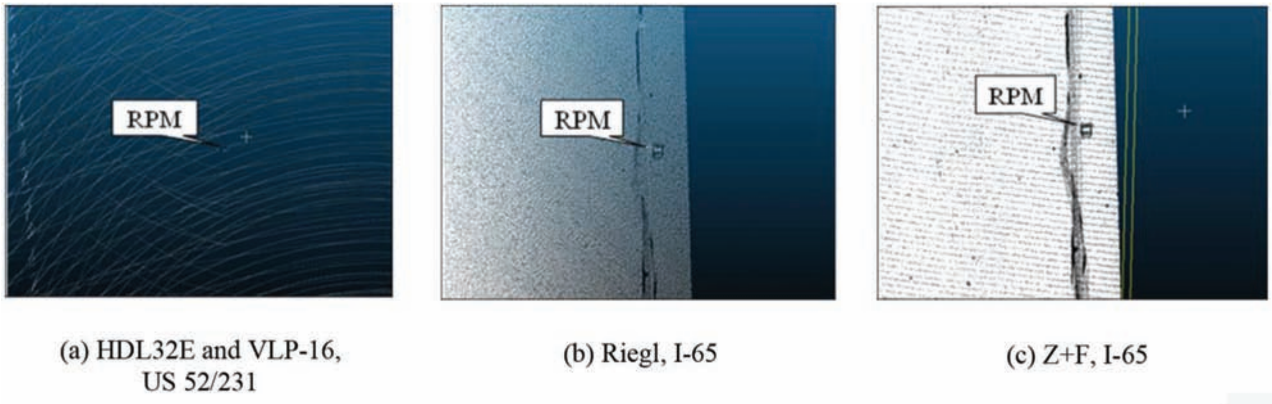


Figure 3.17 Scanner comparison for RPMs (casting and reflector in place).

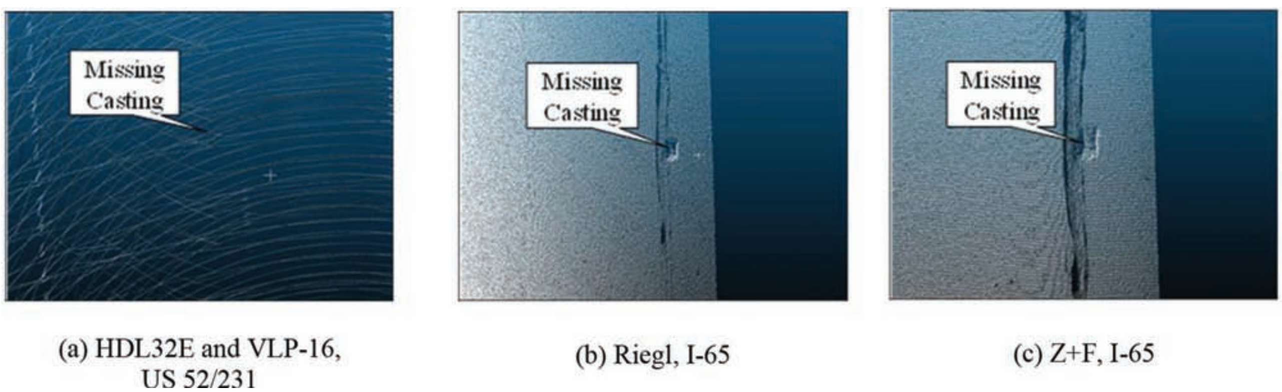


Figure 3.18 Scanner comparison for RPMs (missing casting).

TABLE 3.3
INDOT unit cost data for white edge line

Item	Unit	Weighted Average Unit Cost ($)
Line, Thermoplastic, Solid, White, 4″	LFT	0.45
Line, Paint, Solid, White, 4″	LFT	0.14
Line, Multi-component, Solid, White, 4″	LFT	0.32
Line, Preformed Plastic, Solid, White, 4″	LFT	2.66
Grooving for Pavement Markings	LFT	0.33

TABLE 3.4
Total cost for white edge line

Item	Unit	Total Cost ($)
Line, Thermoplastic, Solid, White, 4″	LFT	0.78
Line, Paint, Solid, White, 4″	LFT	0.14
Line, Multi-component, Solid, White, 4″	LFT	0.65
Line, Preformed Plastic, Solid, White, 4″	LFT	2.99

TABLE 3.5
Economic cost analysis summary for white edge line

Material Type	Life Expectancy (Years)	Installation Cost Per Mile ($)	Total Cost for Ten Years ($)
Non-grooved Paint	1	739.20	8,131.20
Grooved Thermoplastic	6	4,118.40	7,814.40
Grooved Multi-component	4	3,432.00	8,606.40
Grooved Preformed Tape	10	15,787.20	15,787.20

TABLE 3.6
INDOT unit cost data for yellow edge line

Item	Unit	Weighted Average Unit Cost ($)
Line, Thermoplastic, Solid, Yellow, 4″	LFT	0.47
Line, Paint, Solid, Yellow, 4″	LFT	0.15
Line, Multi-component, Solid, Yellow, 4″	LFT	0.31
Line, Preformed Plastic, Solid, Yellow, 4″	LFT	2.57
Grooving for Pavement Markings	LFT	0.33

TABLE 3.7
Total cost for yellow edge line

Item	Unit	Total Cost ($)
Line, Thermoplastic, Solid, Yellow, 4″	LFT	0.80
Line, Paint, Solid, Yellow, 4″	LFT	0.15
Line, Multi-component, Solid, Yellow, 4″	LFT	0.64
Line, Preformed Plastic, Solid, Yellow, 4″	LFT	2.90

TABLE 3.8
Economic cost analysis summary for yellow edge line

Material Type	Life Expectancy (Years)	Installation Cost Per Mile ($)	Total Cost for Ten Years ($)
Non-grooved Paint	1	792.00	8,712.00
Grooved Thermoplastic	5	4,224.00	8,976.00
Grooved Multi-component	3	3,379.20	9,715.20
Grooved Preformed Tape	10	15,312.00	15,312.00

Using the INDOT cost data in conjunction with the calculated life expectancy of each material, a cost analysis could be performed. An analysis period of ten years was selected for a one-mile-length marking of each material type. For this analysis, it is assumed that once a marking reaches the end of its service life, the line will be repainted yearly. The installation cost per mile and total cost for the 10-year period were calculated assuming an interest rate of 0%. These results are shown in Table 3.5 and Table 3.8 as well as Figure 3.19 and Figure 3.20. In Figure 3.19 and Figure 3.20, the cost of thermoplastic and multi-component with a life expectancy of three years was calculated as well since this is a more realistic scenario.

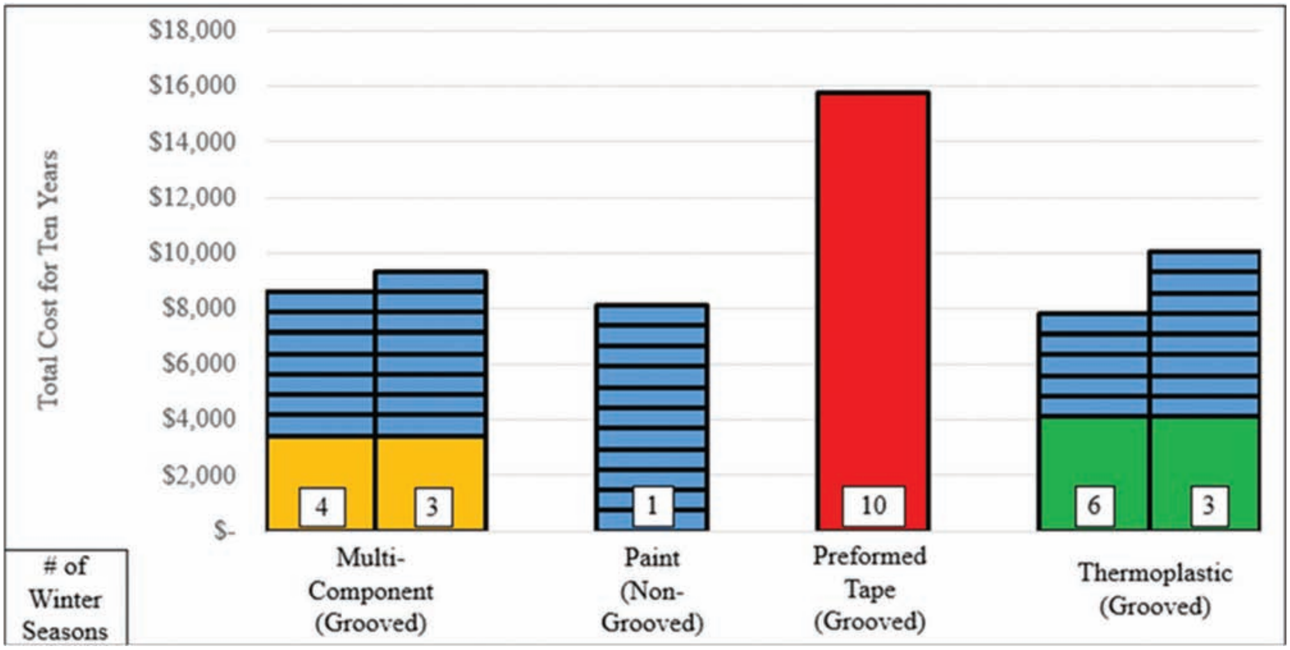


Figure 3.19 Hypothesized life cycle cost for white edge line.

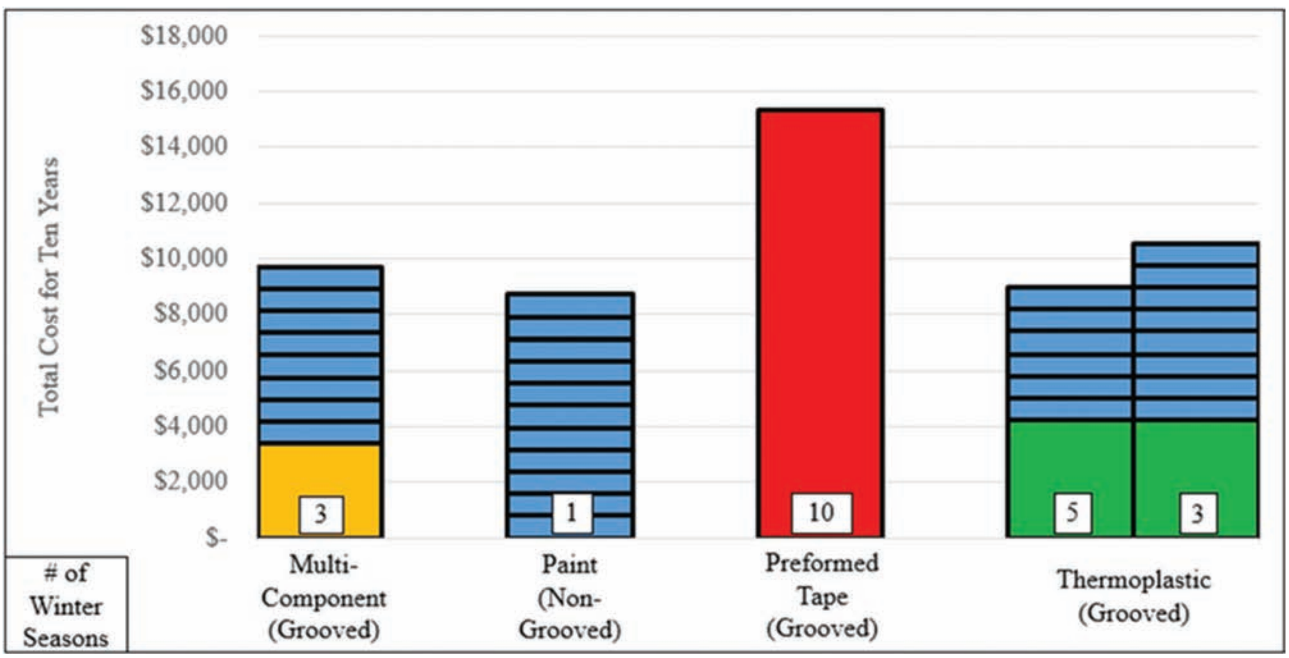


Figure 3.20 Hypothesized life cycle cost for yellow edge line.

4. RECOMMENDATIONS

Although grooved preformed tape has the longest life expectancy, the life cycle cost of this material is twice the cost of grooved thermoplastic, grooved multi-component, or non-grooved paint. However, since grooved multi-component, grooved thermoplastic, and non-grooved paint must be replaced more often than preformed tape, there may be significant (but hard to quantify) additional benefits associated with preformed tape due to reduced maintenance of traffic activities and reduced exposure of maintenance workers to traffic hazards. Based upon data collected during this project, grooved thermoplastic and multi-component have the lowest lifetime costs for durable markings. Additional performance data (particularly after three, four, and five winter seasons) should be collected to determine if either has a distinct economic advantage. RPMs installed in rumble stripes appear to have a higher failure rate. It is recommended that RPM installation in rumble depressions be further evaluated. For RPM detection with LiDAR, the Z+F scanner is recommended since data collected by the Z+F is the most visible and has the highest fidelity.

5. FUTURE RESEARCH

As grooved installations are relatively new in Indiana, the retroreflectivity of the markings will continue to be assessed. Grooved installations began in 2016, and almost all new installations of durable pavement markings are now grooved. For future retroreflectivity measurements, LiDAR or other sensors on mobile platforms may be used, because these sensors may be present on autonomous vehicles. LiDAR will also be used to compare and contrast pavement marking visibility with an auto-certified LiDAR sensor. Additionally, there will be coordination with Valeo to construct plywood or sheet metal pavement marking specimens to test alternative lighting.

MoDOT has recently conducted widespread implementation of high build waterborne paint, and this material has recently gained interest from INDOT. High build waterborne paint has an initial retroreflectivity between 300 and 400 mcd*m^{-2}*lx^{-1} and performs well in wet weather events. Table 5.1 and Table 5.2 illustrate the differences between MoDOT and INDOT's pavement marking acceptance values (INDOT, 2018). In Indiana, all pavement markings with a retroreflectivity of 130 mcd*m^{-2}*lx^{-1} are expected to last through winter and the pavement marking failure point is 100 mcd*m^{-2}*lx^{-1} (Jones, 2012). The minimums in Missouri overall are similar to the minimums for paint, multi-component, and thermoplastic in Indiana. Contractors in Indiana and Missouri may receive a quality adjustment or penalty if the pavement marking retroreflectivity is not above the required minimum. Additionally, MoDOT has a new specification for contracts where the contractor is entitled to a bonus if the initial retroreflectivity is well above the required minimum (Table 5.3).

TABLE 5.3
MoDOT's new contract specifications

White (mcd*m^{-2}*lx^{-1})	Yellow (mcd*m^{-2}*lx^{-1})	% Payment
≥450	≥350	105
400–449	300–349	100
300–399	225–299	80

TABLE 5.1
MoDOT pavement marking acceptance table

	Pavement Marking Acceptance Table (mcd/m^2/lux)	
	White	Yellow
New Pavement Markings	300	225
Existing Pavement Markings Expected to Last Through Winter (Measured in the Fall)	200	175
Pavement Marking Failure Point	150	125

TABLE 5.2
INDOT pavement marking acceptance table

Material Type	White (mcd*m^{-2}*lx^{-1})	Yellow (mcd*m^{-2}*lx^{-1})	Quality Adjustment	Retained White (mcd*m^{-2}*lx^{-1})	Retained Yellow (mcd*m^{-2}*lx^{-1})
Paint	≥250	≥175	1	N/A	N/A
Paint Required Minimum	150 to 249	125 to 174	0.7	—	—
Thermoplastic	≥300	≥200	1	See 808.09	See 808.09
Thermoplastic Required Minimum	250 to 299	150 to 199	0.7	—	—
Multi-component	≥300	≥200	1	See 808.09	See 808.09
Multi-component Required Minimum	250 to 299	150 to 199	0.7	—	—
Preformed Tape	≥650	≥450	1	See 808.09	See 808.09
Preformed Tape Required Minimum	550 to 649	350 to 449	0.7	—	—

Note: Quality adjustments do not apply to the retained retroreflectivity values.

Wet reflective pavement marking technologies, preformed tape, raised pavement markers (RPMs), and rumble stripes will also continue to be studied in the future. Indiana began installing wet reflective longitudinal pavement markings in 2016, and wet reflective tape and pavement markings with wet reflective elements are becoming more common on Indiana highways. Wet reflective markings are less expensive to maintain than other types of markings, and they yield a 25% reduction in crashes on multilane roads when compared to other types of markings (Meeks, 2018). Preformed tape will continue to be monitored as there are safety benefits to motorists and highway maintenance workers due to higher retained retroreflectivity values. RPMs provide excellent nighttime visibility, but RPMs are prone to becoming flying projectiles when dislodged by snowplows. The installation of RPMs in depressions is also relatively new, and these locations will continue to be monitored in the future. When additional data is obtained for RPMs and wet reflective pavement markings, the life cycle cost analysis will continue to be improved.

6. ACKNOWLEDGMENTS

The authors would like to thank Paul Michael, Bill Sledge, and the staff at the INDOT Crawfordsville office for letting us borrow their Delta LTL-X retroreflectometer for the data collection. Michael Pelham and Andrew Blackburn at the INDOT Office of Materials Management also let us borrow their retroreflectometer, and John McGregor and Roy McMillan at the INDOT Traffic Management Center assisted with traffic control. David Getman from INDOT Fort Wayne assisted with traffic control at multiple locations with skip lines. The DPRG at Purdue University provided LiDAR data that was used for RPM detection. Additionally, the authors would like to thank Andrew Meeks of 3M and Beck Enterprises for contributing data from preformed tape and durable pavement markings with wet reflective elements.

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APPENDIX: RPM PHOTOS

APPENDIX: RPM PHOTOS

In Between Rumble, Sinusoidal

(a) SR 135 – Bargersville
(Photo courtesy of Google Maps.)

(b) SR 7 – Elizabethtown

In Between Rumble, Typical

SR 56 - Scottsburg

In Rumble, Typical

US 50 – Brownstown
(Photo courtesy Google Maps.)

In Rumble, Sinusoidal

(a) US 31 – Seymour

(b) SR 11 – Seymour

About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 199 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

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

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

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