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Improving pavement marking performance through contrasting new methods to quantify marking presence and increasing installation efficiencies through an evaluation of prototype bead guns

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Improving pavement marking performance through contrasting new methods to quantify marking presence and increasing installation efficiencies through an evaluation of prototype bead guns

by

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Program of Study Committee:
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Abstract

Agencies continue to search for ways to measure and improve pavement marking performance. With regard to measuring performance this research first conducted a comparative study on the pavement marking evaluation process through a comparison of subjective and objective pavement marking durability rating techniques. The subjective and objective performance evaluation processes reported slight differences. In an effort to address pavement marking quality and efficiencies during installation another study was conducted to develop a methodology for evaluating different bead guns used in the pavement marking application process. An experiment evaluated the performance of the bead guns at various speeds. The SpeedBeader™ application gun dispensed more beads than the Zero-Velocity™ prototype in most cases, however, the Zero-Velocity™ gun worked effectively to reduce bead roll.

Chapter 1. General Introduction

1.1 Introduction

Pavement markings convey important information about the roadway to drivers. Although pavement markings are placed on the roadway in a variety of ways (longitudinal, transverse, text, and symbols), longitudinal markings (lane lines, centerlines, edge lines) are most common. The Manual on Uniform Traffic Control Devices (MUTCD) establishes standards for pavement markings in terms of appearance and placement. Before any new highway, paved detour, or temporary route is opened to traffic, all necessary markings should be in place (1). MUTCD also specifies that pavement markings shall be retroreflective (visible at night) unless ambient illumination assures adequate visibility. Longitudinal pavement markings must provide delineation of the roadway during all conditions (weather, lighting, etc.). Agencies today have a wide variety of pavement marking materials to choose from, these materials can vary widely in cost and performance. Agencies face a significant challenge in maintaining these markings to appropriate performance levels typically characterized in terms of color, durability, daytime presence, and nighttime retroreflectivity. Weather often challenges an agencies ability to place new markings on the roadway. Particularly in seasonal areas, any increases in the ability to place markings more efficiently would result in improved marking performance and overall motorist safety.

The Federal Highway Administration (FHWA) is currently considering publishing minimum retroreflectivity benchmark requirements for pavement markings. In 1992, Congress mandated that minimum retroreflectivity requirements for signs and pavement markings be developed (2). The FHWA continues to conduct research in order to develop minimum retroreflectivity standards. Requirements could be initiated once research has concluded and the results are analyzed and considered. Previous research is being updated due to changes in roadway user characteristics, vehicle preferences, headlamp performance, and available research tools (2). These requirements may require agencies to maintain markings by implementing a strict paint schedule or developing a pavement marking management system.

This research focuses on two specific components to overall pavement marking performance. These include: 1.) evaluation techniques for marking presence and 2.) pavement marking installation efficiency. While the FHWA minimum standards are anticipated to focus on retroreflective characteristics, the presence of a marking is also important during daylight conditions. For some agencies, marking performance is guided primarily by the percent of material remaining or presence. Pavement marking presence is currently a subjectively rated performance measure. This research contrasted a new automated presence evaluation tool with the help of the National Transportation Product Evaluation Program (NTPEP). Photographs of pavement markings subjectively rated by trained NTPEP officials were analyzed using the new automated photo-based method (Pavement Marking Analysis Tool). This software tool evaluates pavement marking images to obtain a percentage of paint remaining. The NTPEP durability rating procedure takes place in the field; however, images were obtained of the actual pavement markings that officials rated in the field. These images were used as calibration in the pavement marking presence evaluation study.

The second topic area of research evaluated pavement marking installation efficiency specific to bead gun performance. The Iowa DOT realized that to get adequate pavement marking performance they had to slow their waterborne paint application rates down to around 8 mph. However, slow application rates limit the miles that can be covered in a season. Increasing the speed of the truck resulted in improper bead embedment which resulted in poor retroreflectivity. Therefore, the Iowa DOT was searching for techniques and equipment that would increase application rates but would maintain quality. This study evaluated the ability of four bead guns (two prototype and two standard) to operate at application rates of 8 to 14 mph. Performance of each gun was contrasted through the use of high-speed video as well as through observation of bead distribution, bead roll, and initial retroreflectivity.

These results could be used to improve the productivity of the prototype guns as well as overall pavement marking application techniques. In summary this thesis includes two papers: 1) Evaluating Pavement Marking Durability: An Objective Approach and 2) Pavement Marking Application: A Bead Gun Evaluation Study Using a High-Speed Camera.

1.2 Thesis Organization

This thesis is divided into four chapters. Chapter 1 provides a general introduction into the two research topics. Chapter 2 is an evaluation of a new method to measure pavement marking presence using NTPEP procedures and ratings as a comparative study. Craig Mizera performed all of the analysis and evaluation of the study. Omar Smadi and Neal Hawkins were involved with the design and development of the Pavement Marking Analysis Tool. Reginald Souleyrette provided supervision and guidance during the comparative study. Chapter 3 reports the findings of a field demonstration to increase the productivity of the waterborne pavement marking installation process. This research presents a comparative study to evaluate different bead guns operations at various speeds in terms of bead distribution, bead roll, initial retroreflectivity, and bead trajectory. Craig Mizera collected and analyzed the data for this experiment. Omar Smadi and Neal Hawkins were involved with the design of the experiment setup. Chapter 4 provides general conclusions of this research and recommendations for future research.

References

1. Manual on Uniform Traffic Control Devices for Streets and Highways. Federal Highway Administration, United States Department of Transportation, Washington, D.C., 2003.

2. Debaillon, C., P. Carlson, Y. He, T. Schnell, and F. Aktan. *Updates to Research on Recommended Minimum Levels for Pavement Marking Retroreflectivity to Meet Driver Night Visibility Needs.* Report FHWA-HRT-07-059. FHWA, U.S. Department of Transportation, 2007.

Chapter 2. Evaluating of Pavement Marking Durability: An Objective Approach

Craig Mizera, Omar Smadi, Neal Hawkins, Reginald Souleyrette

A paper to be submitted for publication in *Transportation Research Record*, Journal of the *Transportation Research Board*

2.1 Abstract

Each year, highway agencies spend millions of dollars on pavement marking. Effectively managing these assets requires system wide information. Many agencies collect data on retroreflectivity, the most important attribute for nighttime performance. However, daytime performance is best indicated by presence, or what is sometimes referred to as durability and this attribute is typically measured by visual inspection. Unlike the more automated procedures used to collect retroreflectivity data, visual inspection is performed manually, and can be very costly at the systems level. Further, inspection can be considered a subjective process. This paper reports on a study of an automated procedure for determining pavement marking presence. The Pavement Marking Analysis Tool (PMAT), utilizing image processing technology, was investigated and results are compared to standard visual inspection methods developed and used by the National Transportation Product Evaluation Program (NTPEP). The effect of image quality (resolution) was also investigated. In general, PMAT was found to produce results similar to NTPEP ratings.

2.2 Introduction

Pavement markings provide guidance to drivers on the roadway during daylight and non-daylight hours. While some agencies evaluate presence of markings, most evaluate only retroreflectivity. These evaluations are typically conducted concurrently with pavement condition assessment. Some agencies have adopted standards to evaluate marking presence, which is commonly referred to as pavement marking durability. If manual (windshield) inspection is performed for pavement condition assessment, a visual inspection based approach to marking presence seems appropriate. However, for large systems where automated methods are used for pavement condition assessment, an automated method of marking presence evaluation is desired.

The industry standard for visual inspection and rating of markings has been developed and promoted by the National Transportation Product Evaluation Program, or NTPEP (1). To date, no method for automatically rating marking presence has yet been developed. Recently, researchers sponsored by the Iowa Department of Transportation developed a software package that can be useful in beginning to automate the evaluation of marking presence (2). This "Pavement Marking Analysis Tool" or PMAT utilizes image processing technology to provide an objective evaluation of these markings. This paper discusses PMAT operating procedures, considers the effect of image resolution on outputs, and compares resulting ratings to those of NTPEP-type visual inspections.

2.3 Background

Durability is a measure of a marking material's resistance to wear and loss of adhesion to the pavement over time (3). Factors affecting the wear of pavement markings include traffic, winter maintenance activities, and weather. As pavement markings are critical during non-daylight conditions, many agencies use retroreflectivity to evaluate the condition of their markings. Presence of the marking is also important during daylight hours. Some agencies evaluate this presence as part of their roadway maintenance schedule, while others conduct periodic measures of durability similar to those developed by NTPEP. Visual inspections are conducted by an individual, who estimates the percentage of marking material remaining (3). The most commonly used approach is to measure durability by the percentage of material remaining; results are reported on a zero to ten scale. A zero rating means that no marking material is visible, while a rating of ten conveys that 100% of the material remains (3).

The Standard Practice for Conducting Road Service Tests on Fluid Traffic Marking Materials (ASTM D713) provides specifications for determining the useful life of pavement markings under actual road conditions using transverse test lines. The Standard Test Method for Evaluating Degree of Resistance to Wear of Traffic Paint (ASTM D913) provides a specification for assessing pavement marking durability using photographic standards for comparative evaluation. This standard is commonly used in conjunction with ASTM D713, but could be used on markings in service as well. NTPEP field test sections (decks) are evaluated in accordance with these standards.

2.3.1 NTPEP

The National Transportation Product Evaluation Program (NTPEP) was founded in 1994 through the regional testing facilities that were organized by the FHWA, Southeastern Association of State Highway and Transportation Officials (SASHTO), and Northeast Association of State Transportation Officials (NASTO). The program is currently chartered by the American Association of State Highway and Transportation Officials (AASHTO). This collaborative partnership between state DOTs and vendors is designed to conduct lab testing and field performance evaluations on transportation products. NTPEP assists state DOTs with decision making and the development of qualified product lists (QPL). They provide alternative ways to evaluate transportation products such as traffic control and safety products, construction and maintenance materials (4). The program evaluates pavement marking materials in the lab and on test decks.

2.3.2 NTPEP Procedures

NTPEP conducts field evaluations and lab testing of pavement marking materials. Typically, field test decks are installed each year in two different geo-climatic zones (within the US). Each marking material submitted for evaluation undergoes lab testing by state DOT materials labs. Lab facilities are currently located in Pennsylvania, New York, Louisiana, Minnesota, and Kansas. These tests reduce the need for individual agencies to conduct tests on their own.

NTPEP field evaluation consists of appearance/color tests, retroreflectivity, durability assessment, and weather condition documentation at the test site. Durability evaluation consists of visual assessment of percentage of marking material remaining in an 18 inch sample, centered at the midpoint of, and perpendicular to the wheel path (these transverse lines are exposed to much higher levels of wheel traffic than longitudinal markings would be). Figure 2.1 shows Utah's NTPEP Test Deck. The average rating of three trained evaluators using the D913 standard is reported as the final score for the marking (1).

Figure 2.1: Utah's NTPEP Test Deck.
Source: Utah T2 Center

2.4 Methodology

The study included an evaluation of pavement marking presence as reported by PMAT (image processing) compared to NTPEP (visual inspection) durability ratings. NTPEP conducted a field evaluation of 22 test samples and provided film-based photographs of the rated samples for analysis by PMAT. Samples were provided for both asphalt and PCC pavements.

To facilitate image analysis, the photographs were scanned at 300 dpi. These scans were cropped and saved at resolutions of 300, 200 and 100 dpi. Images at all three resolutions were then analyzed and results were compared to NTPEP field results.

PMAT makes use of a processing technique known as image segmentation, which groups sets of image pixels to regions having common characteristics. The tool attempts to segment images into foreground (pavement marking) and background (pavement) parts (2). PMAT then reports the areal percentage of white or yellow paint in the image.

As shown in Figure 2.2, PMAT executes in three stages: 1) image enhancement, 2) clustering, and 3) analysis. Image enhancement involves an application of filters to maximize the probability of separating the white and yellow color markings that are to be distinguished from the pavement surface. These filters employ histogram equalization in the RGB color space as well as color separation filters in other color spaces. Filter values were chosen empirically based on color characteristics for yellow (2). Clustering is independent of marking color and includes gray level conversion, binary image conversion, and connected component analysis. Gray level conversion assigns a value to each color pixel in the range of 0-255. Each pixel in the grey level image is then labeled as either foreground or background based on the value of the pixel compared to a threshold which is determined empirically, based on calibration of pavement marking images, in the binary image conversion. In connected component analysis, adjacent pixels with similar labels are grouped (2). The final stage of the process, analysis, establishes the ratio of foreground (white or yellow marking material) to background (pavement) pixels using the number and area of each contiguous foreground pixel (2).

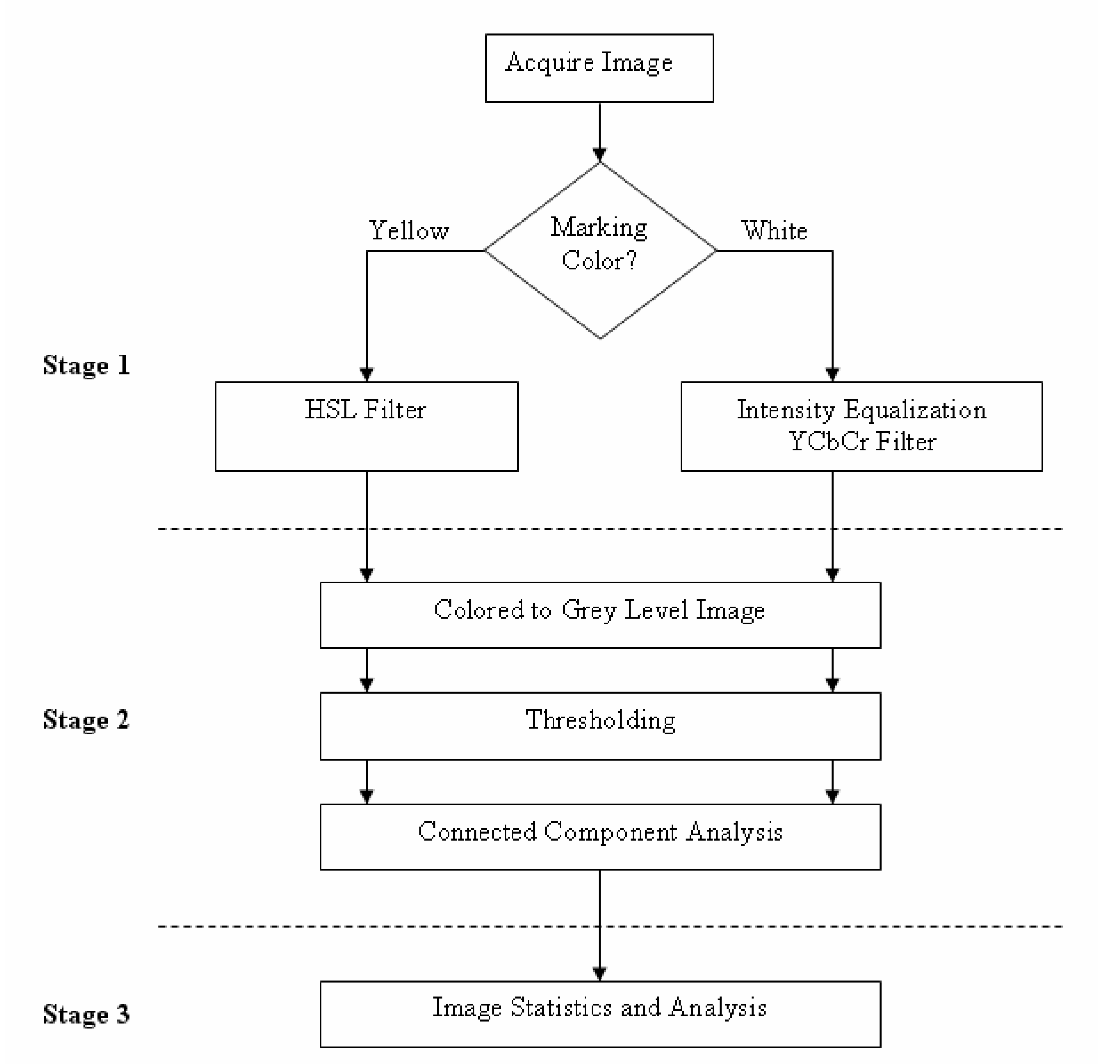


Figure 2.2: Three major stages for calculating percent paint remaining.
Source: Smadi, El-Nasan, Hawkins 2007

Figure 2.3 shows the layout of PMAT's "original image" window, displaying a cropped image. Using the "presence" menu the appropriate marking color and pavement surface type is selected. The processed image can then be viewed under the "processed images" tab as shown in Figure 2.4. The number of groups of pavement marking pixels and the "percent paint" are shown at the bottom of the screen. The different colors represent interconnected sections of marking material as detected by the image analysis. PMAT checks for differences in the color of pixels in the digital image and reports a percentage estimate of pavement marking material.

After image processing, PMAT allows the user to select a “region of interest” using a typical click and drag procedure (see Figure 2.5). Analysis can then be performed on that region. All analysis conducted in the reported study was conducted on complete images to eliminate potential differences that could be caused by subjective selection of “area of interest”.

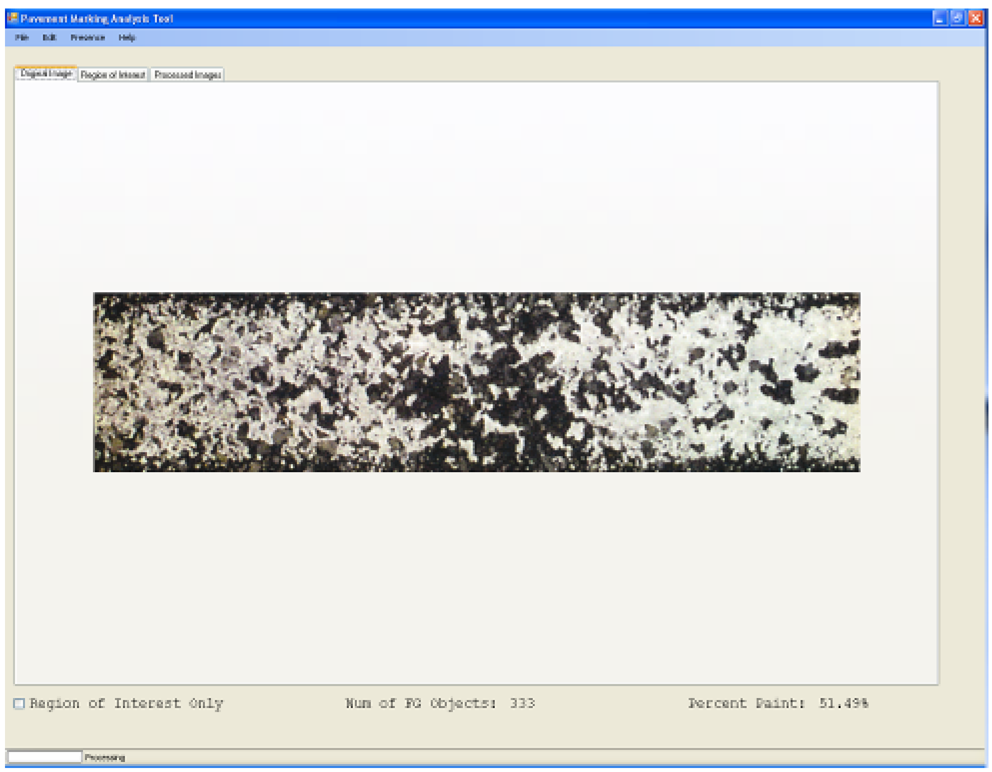


Figure 2.3: Pavement Marking Analysis Tool original image tab.

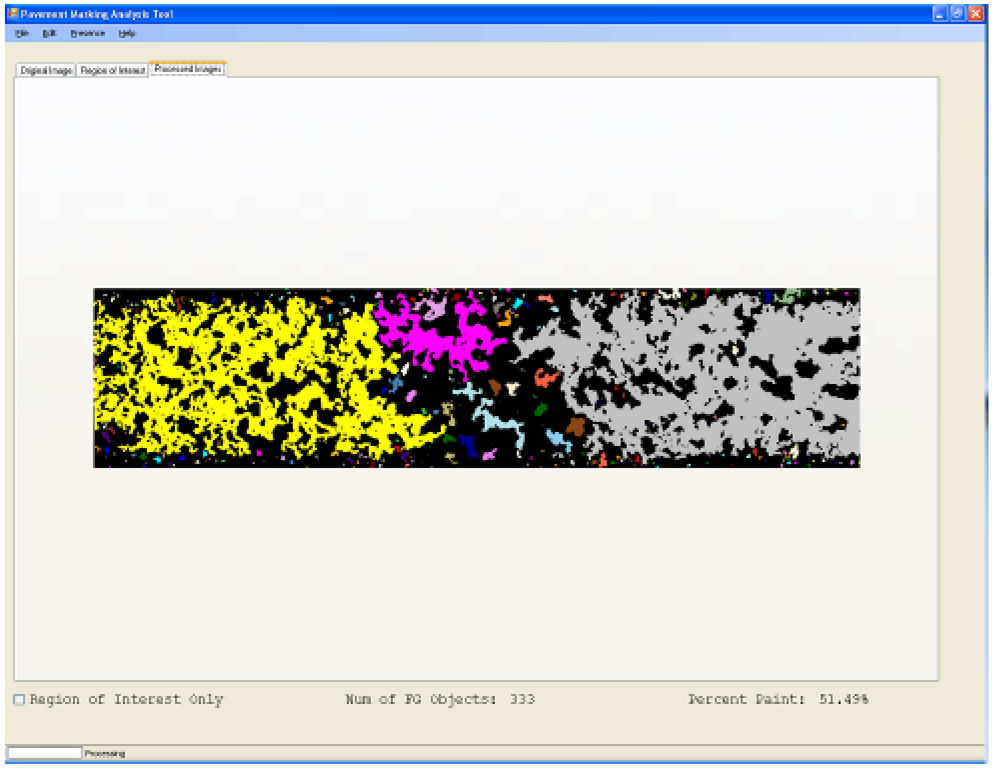


Figure 2.4: Pavement Marking Analysis Tool processed image tab.

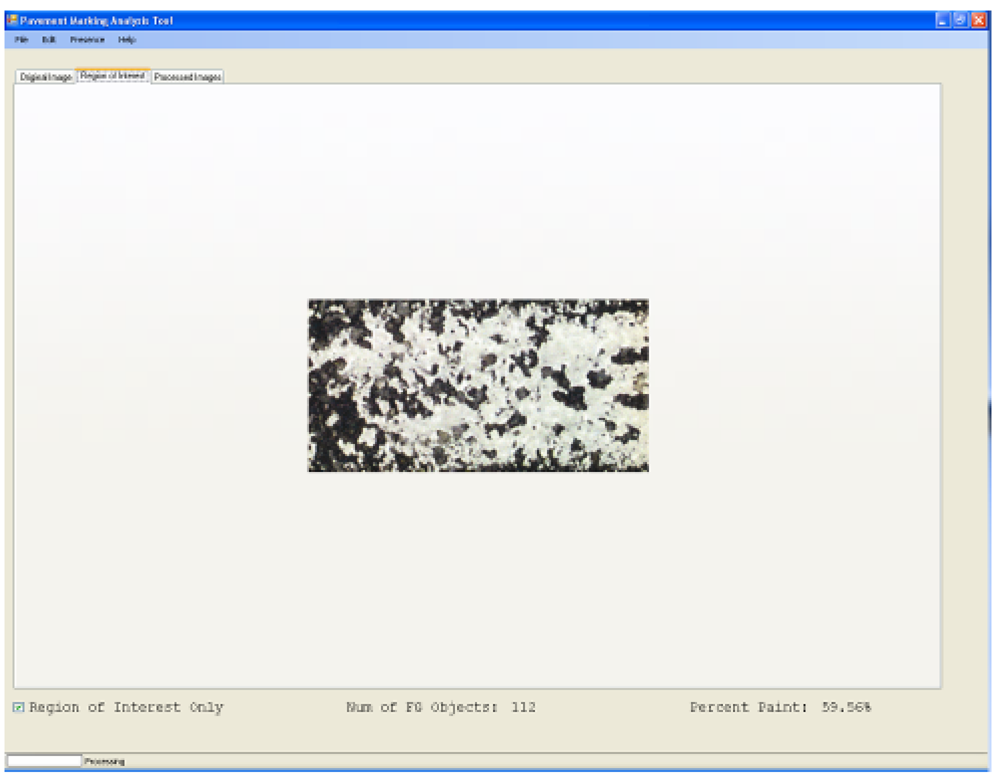


Figure 2.5: Pavement Marking Analysis Tool region of interest tab.

To improve the effectiveness of image analysis, calibration of each specific section of pavement was investigated. As lightly colored exposed aggregate or cement could potentially be falsely identified as marking material, a baseline “marking presence” was established for a nearby section of bare pavement. However, as Figure 2.6 indicates, PMAT can estimate a significant percentage of marking material for bare PCC pavement. Therefore, it was not possible to perform simple calibration using this technique.

As shown in the paint image (Figure 2.6 top row), white paint is easily detected in the processed image. However, without the contrast provided by the marking material, some of the white to grayish colored PCC pavement was detected as paint by PMAT’s color filters (63% paint). PMAT’s white marking processing methodology searches for color contrasts rather than a color threshold, as does its yellow marking ID method.

A similar calibration test was conducted for asphalt pavement. Figure 2.7 shows that PMAT indicates only a small percentage of paint (13% paint) for asphalt. The processed images (right) confirm that grayish aggregate or cement may be classified as paint for bare surfaces, as may portions of bare asphalt pavement (albeit smaller amounts). Adjustments to the color contrast settings may improve the accuracy of white marking analysis in PMAT.

A calibration procedure was also tested for yellow markings. However, only minimal amounts of yellow are indicated for bare pavements of either type. This is expected as yellow filters and threshold values can more effectively differentiate yellow from gray shades normally found in bare pavement images. PMAT’s white marking evaluation procedure may benefit from the use of filters and thresholds such as those used in its yellow marking ID method.

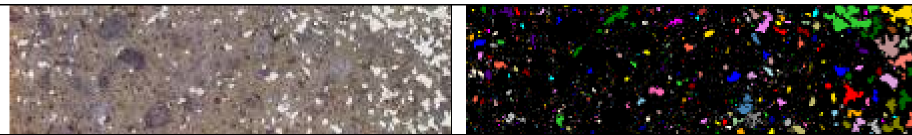
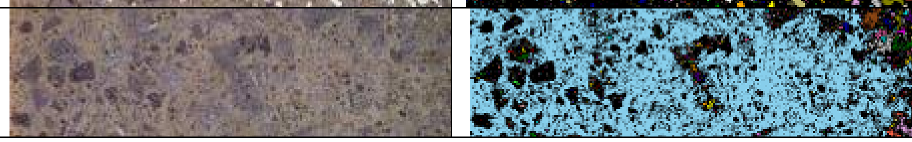
Paint Image 15.74 % Paint	
PCC Pavement Image 63.08 % Paint	

Figure 2.6: PCC pavement images used in test calibration procedure.

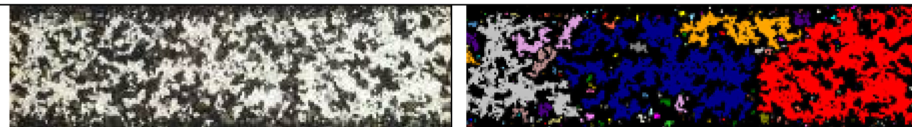
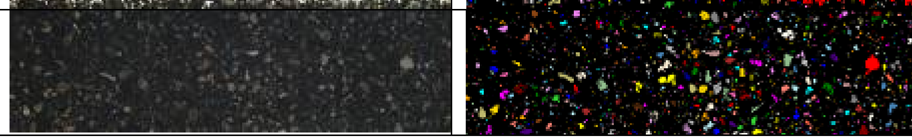
Paint Image 44.93 % Paint	
Asphalt Pavement Image 12.95 % Paint	

Figure 2.7: Asphalt pavement images used in test calibration procedure.

2.5 Data Analysis

The durability ratings provided by NTPEP for the 22 samples were compared to PMAT's presence results using images of varying resolution (see Table 2.1.) The effect of resolution on PMAT rating is negligible and would not result in differences large enough to change equivalent NTPEP rating by 1.0 or more. Generally, reported percent paint decreased with decrease in resolution, while a few samples showed variability with the changes in resolution. All samples consisted of white marking material.

Table 2.1: PMAT pavement marking presence evaluation.

Marking	NTPEP Rating	300 dpi	File Size (KB)	200 dpi	File Size (KB)	100 dpi	File Size (KB)
PCC 1	1	15.74	1256	14.44	868	13.15	637
PCC 2	2	23.78	1307	22.55	884	21.49	645
PCC 3	3	52.45	1512	51.10	992	50.20	679
PCC 4	4	48.68	1161	47.84	829	46.46	632
PCC 5	5	62.65	1247	62.65	852	62.49	631
ACC 5	5	44.93	1251	44.91	874	44.23	648
PCC 6	6	70.09	1214	69.95	850	69.67	641
ACC 6	6	51.49	1147	51.35	830	50.74	633
PCC 7	7	73.95	1105	73.74	803	73.40	626
ACC 7	7	76.66	1129	76.54	836	76.20	639
PCC 8-1	8	80.14	1373	81.38	911	82.12	650
PCC 8-2	8	77.68	1083	79.29	785	82.13	615
PCC 8-3	8	87.22	1053	87.09	778	86.70	617
PCC 8-4	8	89.76	984	89.75	752	89.63	610
ACC 8	8	91.14	1019	91.16	756	91.21	609
ACC 8-2	8	83.37	1198	83.34	867	83.33	652
PCC 9	9	93.77	1034	93.94	765	93.87	609
PCC 9-2	9	74.97	1335	80.37	883	85.21	633
ACC 9	9	84.88	1190	85.27	832	85.04	627
ACC 9-2	9	71.16	1166	71.02	835	71.56	632
ACC 9-3	9	92.67	1436	93.21	927	93.96	645
ACC 10	10	54.60	1357	58.21	891	60.89	635

Figure 2.8 shows an example sample photograph provided by NTPEP. Figure 2.9 shows the sample image after scanning, cropping and image analysis. Example processed images are also displayed to illustrate the image segmentation procedure with different colors representing contiguous sections of marking material.

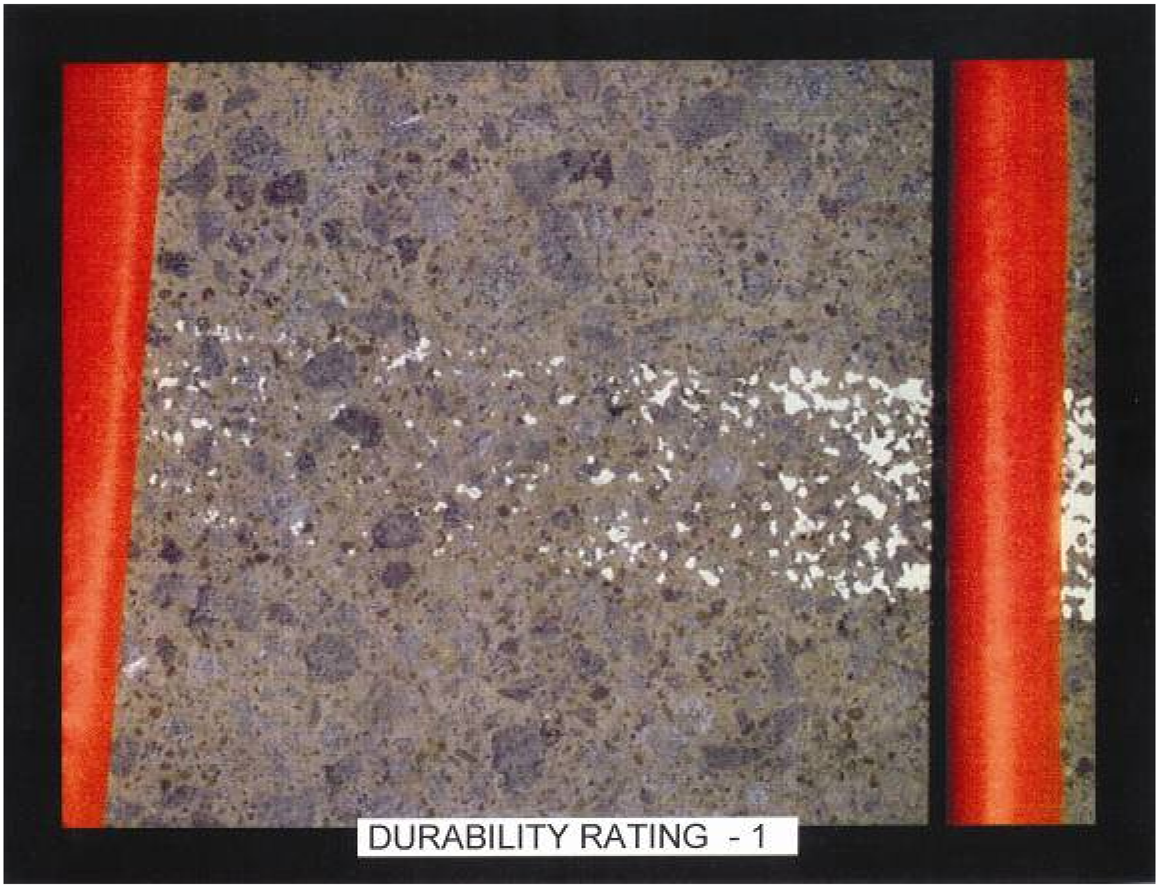


Figure 2.8: NTPEP image with durability rating of 1.

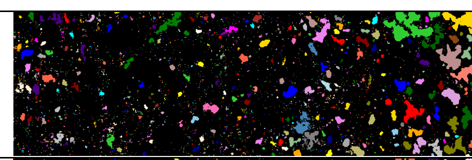
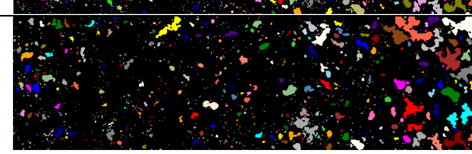
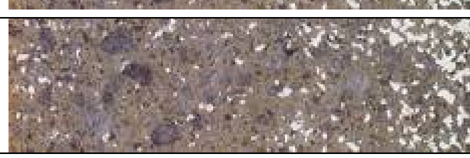
300 dpi 15.74% Paint		
200 dpi 14.44% Paint		
100 dpi 13.15% Paint		

Figure 2.9: PMAT analysis of NTPEP sample PCC 1.

Results of image processing for PCC 8-1 are shown in Figure 2.10. PMAT presence ratings ranged from 80.14 % at 300 dpi to 82.12% paint at 100 dpi. NTPEP and PMAT ratings are similar at all three resolutions. Figure 2.11 displays the results of PMAT evaluation of the first NTPEP sample with durability rating of 9. All ratings round to 94%.

Figure 2.12 shows the results of the PMAT evaluation of image ACC 9-2. As shown, the results also show some variability from 300 dpi to 100 dpi, but they are once again very small differences and ratings are as expected for a section rated as a nine. Small differences may be due to slight imperfections in markings not observed in the field.

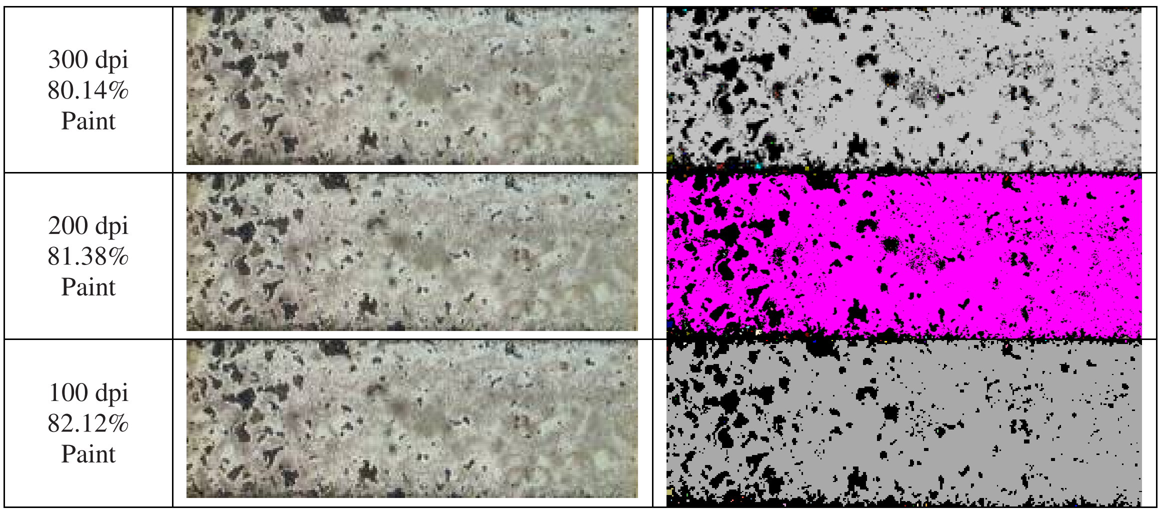


Figure 2.10: PMAT analysis of NTPEP sample PCC 8-1.

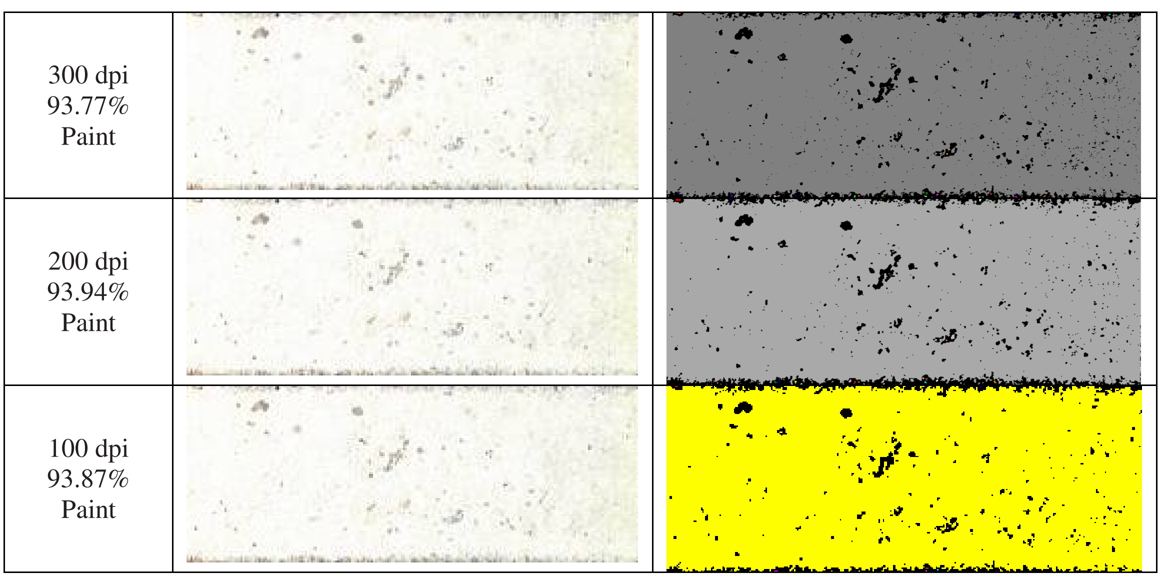


Figure 2.11: PMAT analysis of NTPEP sample PCC 9.

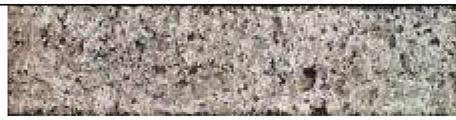
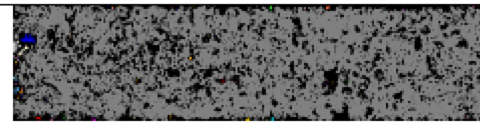
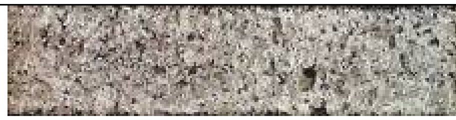
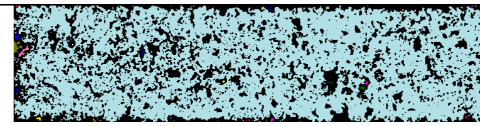
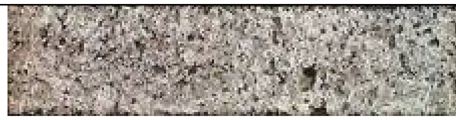
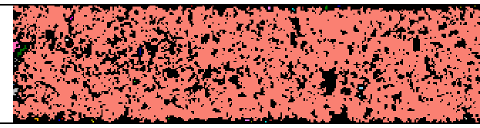
300 dpi 71.16% Paint		
200 dpi 71.02% Paint		
100 dpi 71.56% Paint		

Figure 2.12: PMAT analysis of NTPEP sample ACC 9-2.

Figure 2.13 displays a distribution of rating differences between NTPEP "durability" ratings and the PMAT "percent paint" ratings. The difference between the ratings is displayed on the y-axis and the x-axis displays the NTPEP ratings (ten percent of the PMAT ratings are compared to the NTPEP ratings). As shown in the figure, all PMAT ratings are within 2 points of NTPEP ratings with the notable exception of ACC 10.

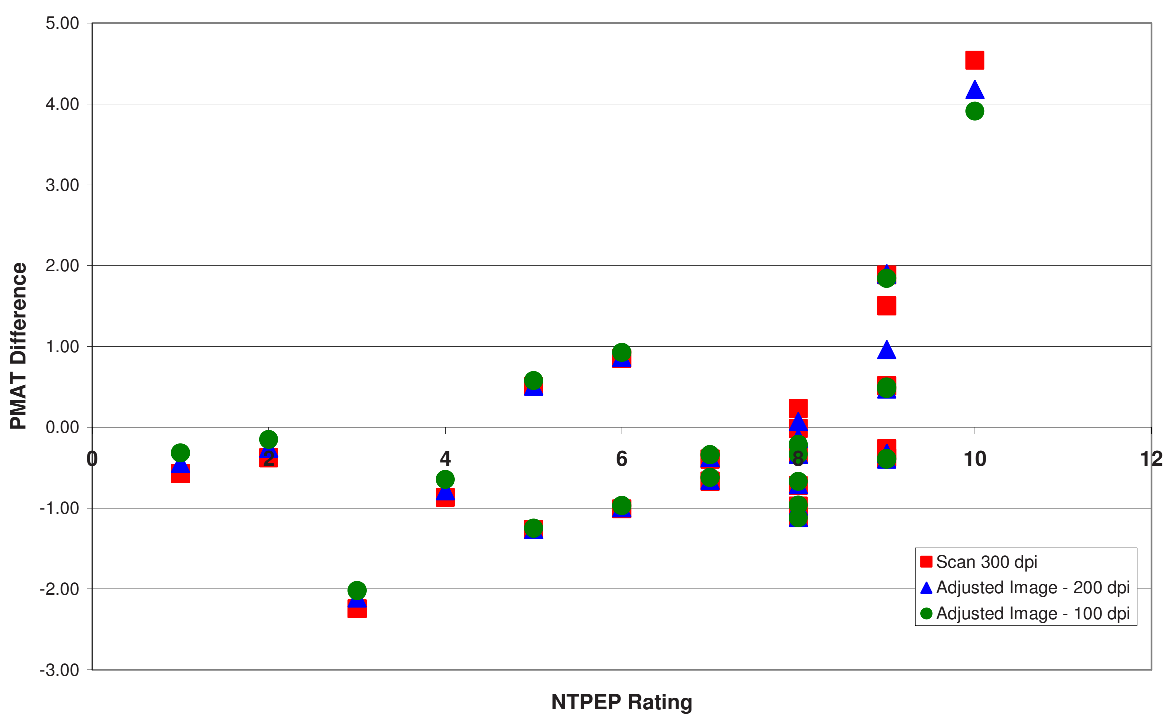


Figure 2.13: Plot of the difference between PMAT and NTPEP evaluations.

For the sample with a rating of ten (perfect marking), the software had a difficult time finding contrasts in the white pavement marking. To assist the tool in establishing contrast, a small amount of pavement may be left on the edges when cropping. This allows PMAT to recognize the paint and indicate percent paint at 90% or above (see Figure 2.14) which is much closer to the rating of 10 given by NTPEP.

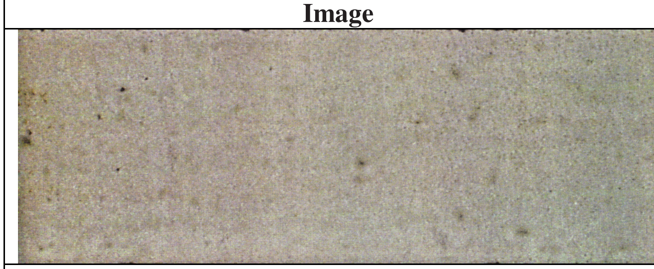
Image	PMAT Percent Paint
	54.60 %
	90.89 %

Figure 2.14: Results of the NTPEP durability rating 10 image analysis.

2.6 Discussion of Results

PMAT was shown to produce results similar to the NTPEP visual inspection. Figure 2.15 shows the distribution of differences in ratings (PMAT – NTPEP) of the two methods. It can be seen that a majority of differences are close to zero.

An assessment of variation caused by image resolution was also conducted. Differences between PMAT and NTPEP ratings using 300 dpi images resulted in a standard deviation of 0.97, while 200 dpi images produced a standard deviation of 0.90. 100 dpi image ratings were closest to the NTPEP ratings and differences had standard deviation of 0.84.

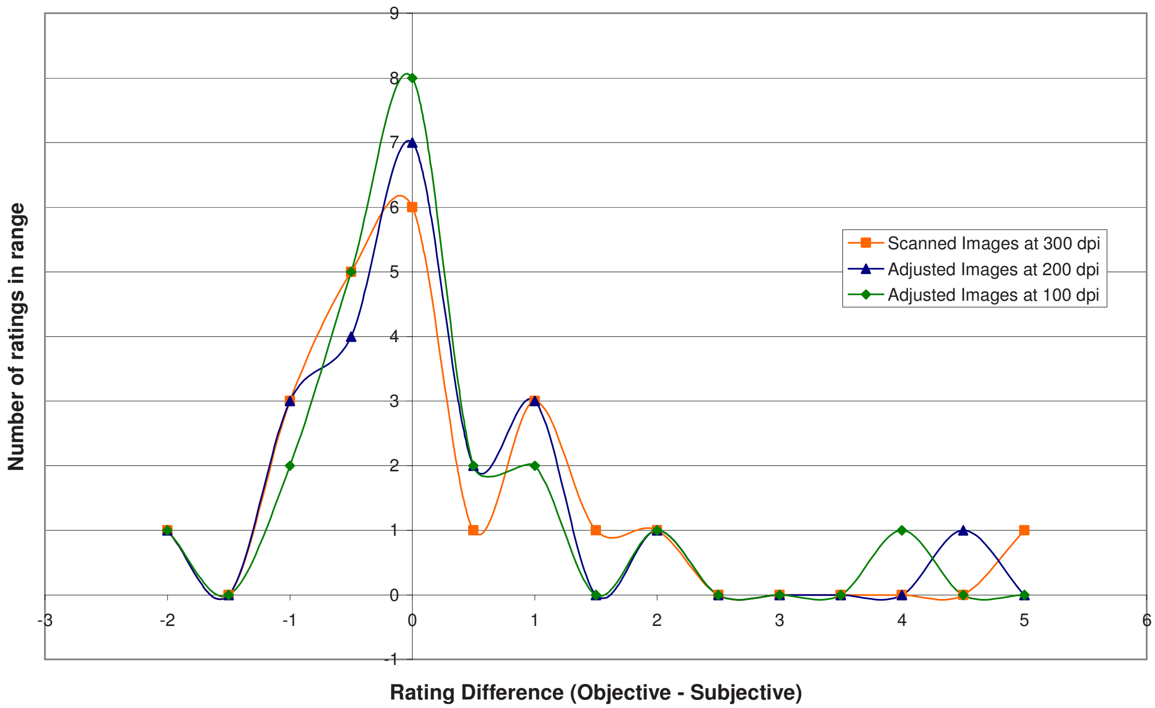


Figure 2.15: Distribution of rating differences.

Difficulty with classifying perfect markings can be resolved by including small portions of pavement in the analysis area, allowing the software to detect contrast and distinguish between pavement and marking material pixels. It is suggested inclusion of filters and thresholds for the white pavement markings may improve reliability similar to the yellow markings.

2.7 Conclusion

This study was conducted to determine the feasibility of the PMAT beta version. Further modifications and experimentation of the image processor may result in a release of the software tool to public agencies. In general, PMAT produces results similar to ratings provided by NTPEP. Subject to further validation, agencies may consider implementing procedures that include PMAT evaluation of pavement markings. The software produces consistent results and does not require extensive training. The potential for subjective rating may be reduced with the use of an image processing based tool. Cost savings may also result from reduced field work requirements, and automating the process may provide a safer working environment for analysts.

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Chapter 3. Pavement Marking Application: A Bead Gun Evaluation Study Using a High-Speed Camera

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A paper to be submitted for publication in *Transportation Research Record*, Journal of the *Transportation Research Board*

3.1 Abstract

Waterborne paint is used by 78% of agencies and comprises 60% of total centerline mileage in the United States. The majority of pavement markings in the state of Iowa are composed of waterborne paint and glass beads as well. Glass beads are applied to the wet paint surface to obtain retroreflectivity during nighttime driving. An experiment was conducted to compare the paint/bead interaction characteristics of four bead dispensers at various speeds. The analysis includes the evaluation of test panels and high-speed video. However, analysis was only conducted on two of the dispensers because metrics of the Type II beads could not be quantified. The results from this study could help decision makers choose the appropriate equipment and paint truck speed in order to optimize the productivity of the application process without sacrificing performance. Each gun had attributes that contributed to the performance and production of the pavement marking application process.

3.2 Introduction

The Iowa Department of Transportation (DOT) continues to evaluate and upgrade longitudinal pavement marking materials and application techniques. The majority of pavement markings maintained by the Iowa DOT are rural two- and four-lane roadways. Waterborne paint is the most common material applied because of its low cost. Pavement markings are normally evaluated by retroreflectivity. This is obtained by the application of glass beads to the pavement marking during the striping process. Characteristics that affect the retroreflectivity include the distribution of beads across the markings, bead embedment, and bead roll. Beads must be distributed across the marking and should be embedded into the marking material without being completely buried. Distribution can be explained by the number of beads and the uniformity of the beads throughout the stripe. Embedment is the partial submersion of the glass bead in the marking material. Ideally, the glass beads submerge part way into the binder, becoming suspended as the binder dries and cures around them. If the beads are over-embedded or under-embedded the marking becomes less retroreflective. Bead roll occurs when the glass bead becomes covered with the binder material. As the bead contacts the wet paint surface it rolls covering the surface with paint, thus preventing light from entering the bead resulting in a reduction in retroreflectivity. These attributes are controlled by the speed of the striping truck, type and settings of the bead guns, and characteristics of the paint. This paper provides information to assist decision makers in choosing the most cost effective application process for pavement marking operations.

An experiment was conducted to evaluate four bead guns used in the pavement application process. This analysis included the use of AASHTO Type II and Type III glass beads. The quantitative analysis of this study focused on the Type III beads. SpeedBeader™ and Zero-Velocity™ bead guns were used with the Type III beads. To increase productivity of the marking process, striping trucks must be able to apply effective markings at higher speeds resulting in more miles of fresh markings during the paint season. The effects of truck speed on bead distribution, bead roll, initial retroreflectivity, and bead trajectory are evaluated in this paper.

3.3 Review of Literature

As part of the study, a literature review was conducted with the objective to obtain information on definitions, materials and specifications, and previous research that has been conducted in evaluating pavement marking performance and application. A significant amount of information was found on modeling the service life of pavement markings and evaluating the safety of markings.

According to NCHRP Synthesis 306 (1), the total value spent in pavement markings by the 50 states, 13 Canadian provinces and territories, US counties, and US cities was $1.5 billion on 3.8 million centerline miles. Iowa reported pavement marking expenditures of $3.2 million on just over 11 thousand miles of centerline in 2000.

3.3.1 Marking Material

The Manual on Uniform Traffic Control Devices (MUTCD) provides specifications for the placement of road markings. Longitudinal pavement markings provide delineation of the traveled way as well as communicate messages to drivers such as lines indicating passing or no passing zones. However, MUTCD does not specify the material to be used for the markings. Materials are chosen based on an agency's pavement marking specifications (2). Sixteen different materials are currently used for longitudinal pavement markings (1). Although material selection specifications are based on several factors, the two most common materials are waterborne and thermoplastic paint. Waterborne paint became more popular after the Environmental Protection Agency (EPA) established standards on volatile organic compounds (VOC) in 1995 (3). Conventional solvent-based paints had VOC concentrations greater than 450 g/l. The EPA regulation set the upper VOC concentration of 150 g/l. Agencies were forced to find marking materials under the set regulation, thus waterborne materials were quickly adopted. The most common material being used is 100% acrylic waterborne paint that has VOC concentrations between 98 and 120 g/l. Because of its low price, waterborne paint accounts for only 17% of total expenditures on pavement markings (1). The more expensive and durable thermoplastic material is used by 69% of the agencies surveyed and comprises 23% of the total mileage. Because of its higher price, 35% of total expenditures on pavement markings are attributed to thermoplastic material (1).

The University of Hampshire performed a research project for the New Hampshire DOT to analyze possibilities of improving acrylic waterborne paints (3). The report mainly focused on paint formulations and application techniques to improve the durability of the marking. The research recommended a revision of the pavement marking specifications and the development of a test deck to introduce new retroreflective bead and paint combinations.

3.3.2 Retroreflective Materials

Previous research of retroreflective elements show the characteristics evaluated in this study are important for maximizing pavement marking performance. Pavement markings guide drivers on the roadway whether it is during daylight or non-daylight conditions. Pavement markings perform effectively during non-daylight hours by providing retroreflectivity. This characteristic is either provided as a matrix or a glass bead applied to the surface of the marking during application. Retroreflectivity represents the amount of light that is reflected back to the source. Reflection gives drivers appropriate information at a safe distance to give the driver sufficient reaction time. Figure 3.1 is a diagram of retroreflectivity. Light from the headlamp enters the glass bead and is reflected back to the driver's eye. Proper bead embedment is necessary to reflect light back to the driver at the appropriate angle. Improper embedment causes the light to scatter making it difficult for the driver to see the marking. Bead roll also causes a loss in retroreflectivity because paint covering the glass bead prevents light from entering the sphere. These attributes contribute to the delineation of pavement markings during nighttime conditions.

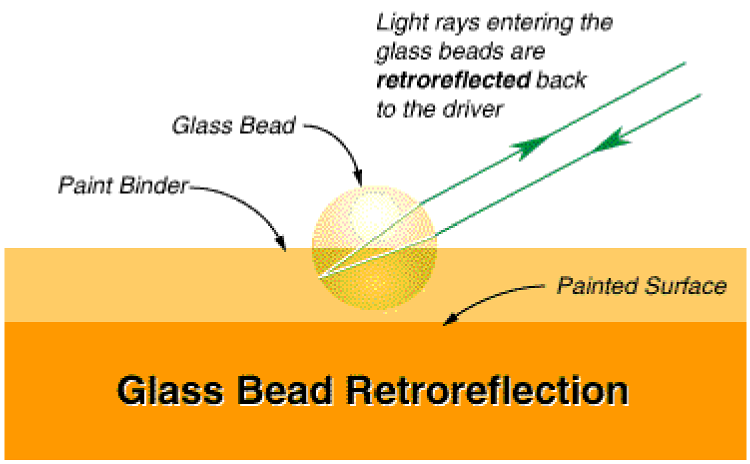

Figure 3.1: Diagram of retroreflectivity.
Source: HIGHWAY TECHNET

Glass beads are the most commonly used retroreflective element with waterborne paint. There are several different types of beads available on the market with varying size and refractive indexes. Bead types I and II are specified by AASHTO, whereas the FHWA specifies gradations for types 3, 4, and 5. Type I beads are the smallest bead on the market and are commonly used in thermoplastic markings. The most common drop-on glass bead used with paint is the Type II glass bead.

Large beads (types 3, 4, and 5) are known for their ability to improve wet-night visibility. Large beads' higher profile allows the surface to protrude through a thin film of water unlike small beads (Type I and II) (4). Wet markings with small beads become invisible in wet-night conditions because a thin film of water over the beads refracts the light before it can reach the glass bead.

The Texas DOT developed a pavement marking handbook to assist pavement marking personnel with marking material selection, installation, and inspection (3). The handbook discusses installation and inspection that includes bead application properties. The two most important field-controlled properties are the amount and dispersion of exposed beads across a line and the depth of bead embedment (4). These properties are controlled by bead drop rate, speed of the striping truck, temperature, and viscosity of the paint. The amount of glass beads being applied and the dispersion is difficult to observe and inspect. Pavement marking crews often observe embedment and dispersion by close-up visual examination and the sun-over-shoulder method (4). Other crews make adjustments based on retroreflectivity readings taken on fresh markings. The handbook recommends beads are embedded at 60% of the bead diameter. Bead embedment under the recommended depth results in loss of light in different directions and beads that can be easily worn away by traffic and maintenance activities. Beads that are located at depths greater than 60% of the bead diameter still reflect light; however the retroreflectance is not as high as a properly embedded bead (4). Proper bead dispersion and embedment are important properties in maximizing the retroreflectivity of longitudinal pavement markings.

3.3.3 Marking Performance

Several research studies have been conducted on the service life of pavement markings and projecting the life cycle of markings. These studies attempted to quantify the performance of pavement markings by retroreflectivity. This is accomplished by maintaining minimum levels, however, minimal research has looked at the application process to increase the performance of pavement markings. The FHWA continues to research the effect of implementing a minimum retroreflectivity level for pavement markings. Maintaining a minimum retroreflectivity level may require a monitoring program or the implementation of a pavement marking management system. Research continues to develop in the area of performance to predict the service life of pavement marking materials.

Driver preference is for pavement markings to exhibit retroreflectivity readings greater than 100 millicandelas per square meter per lux (mcd/m^2/lux) (5). Several studies have set the minimum threshold retroreflectivity at 100 or 150 mcd/m^2/lux. Research findings and expert opinions continue to be assessed and transportation agencies may struggle to maintain minimum acceptable retroreflectivity. Pavement marking management systems may help agencies maintain requirements by providing striping schedules.

The implementation of the VOC concentration regulations by the EPA brought on several studies of waterborne pavement markings. The Missouri DOT conducted a study in 2005 that analyzed the properties and durability of different bead and waterborne paint combinations (6). Test sections throughout the state of Missouri DOT's district roadways were evaluated to find results of different combinations. The project presented the need for a minimum initial retroreflectivity of 350 mcd/m^2/lux for white lines and 225 mcd/m^2/lux for yellow lines, to obtain a service life of 2 years (6). The study also recommended restriping of white lines at 200 mcd/m^2/lux and 175 mcd/m^2/lux for yellow longitudinal pavement markings. The Utah DOT performed a study on waterborne traffic paint to provide more information about the effects of traffic and other road activities on the markings (7). The study reported that waterborne paint retroreflectivity failure (100 mcd/m^2/lux) occurs between 8 and 17 months after painting depending on the AADT of the roadway. The primary factors affecting the life of a pavement marking include snowplowing, curvature of a roadway, pavement type, and condition (7). The research report resulted in the development of a pavement marking decision matrix to be used by Utah DOT decision makers.

Clemson University looked at analyzing retroreflectivity levels in the process of developing degradation models of pavement markings (8). They concluded that several factors affected the performance and retroreflectivity of pavement markings, which include pavement surface, marking material and color, and maintenance activities. A service life study that included 19 states evaluated the service life of pavement markings over a period of four years and found that regression models best fit the relationship between service life and functions of time and cumulative traffic passages (9). The evaluation was done on several marking materials and variations that can be attributed to roadway type, regional location, marking specifications, contractor installation procedures and quality control, and winter maintenance activities. The Washington State Transportation Center conducted a study with the intent of developing retroreflectivity degradation curves for pavement markings (10). They found a high variability in data concluding that striping performance predictions cannot be determined with a high level of statistical confidence.

Different materials have been evaluated extensively in an attempt to help decision makers choose cost-effective materials. Thomas, Iowa State University, completed a research project for the Iowa DOT to develop a program that evaluated various products used as pavement markings (11). This program would assist state and local agencies with decision making by providing a database of performance and cost information of different materials. Michigan State University was contracted by the Michigan DOT to investigate the use of different pavement marking materials (12). The Michigan DOT wanted to develop guidelines governing the cost-effective use of pavement marking materials. Results of the study showed that retroreflectivity did not vary much between different materials, however, winter maintenance appeared to be the main factor affecting the decay of retroreflectivity.

Additional research of pavement marking performance has led to the development of pavement marking management systems. Transportation Research Record 1794, 2002, contained two research papers on the development of pavement marking management systems. Abbound and Bowman (13) established a way to set striping schedules that account for factors affecting scheduling, application cost, service life, and user cost relative to crashes during the stripes lifetime.

Rich, Maki, and Morena studied the performance and durability of longitudinal pavement markings in Michigan to develop a practical marking management system (14). Their efforts included evaluation of the glass sphere content. Two techniques were used to quantify the glass sphere content in the paint. Aluminum plates were fastened to the roadway and painted by the striping operation in the first method. The plates were pyrolyzed at elevated temperatures, from which a mass fraction of glass spheres before and after the pyrolyation can be calculated (14). The second method dealt with photographs of the plates at low magnifications. The images were converted to binary images that were evaluated using image analysis software. The software was able to determine the number of spheres per area, average size, and aerial percent (14). The research concluded that retroreflectivity is directly related to glass sphere content and the decay of retroreflectivity is related to seasonal maintenance activities.

The Minnesota DOT used the general public to evaluate markings to establish a threshold value of retroreflectivity to be used in a pavement marking management program

(15). Minnesota citizens drove vehicles on several different facilities with an interviewer that asked questions pertaining to detection distance of the pavement markings along the route. As a result, the Minnesota DOT established a minimum retroreflectivity threshold of 120 mcd/m^2/lux.

3.3.4 Safety Benefits

Highway safety has been linked to several attributes of the roadway. Several transportation officials and researchers have attempted to relate visibility and retroreflectivity to safety. Transportation agencies continue to look for ways to accommodate the rise in the average age of drivers on the roadway. The Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for User (SAFETEA-LU) contains provisions that include improving pavement markings in all States, specifically targeted at older drivers (16). The article supports bigger and brighter signs, more conspicuous signals and wider pavement marking in an attempt to make highways safer for older drivers. The University of Iowa completed a study in 2003, Enhancing Pavement Markings Visibility for Older Drivers, to determine the effects of increasing the width and retroreflectivity of pavement markings (17). The study was trying to determine an effective method to increase the detection distance and found that distances are driven by retroreflectivity rather than width.

NCHRP Project 17-28 attempted to quantify the relationship between retroreflectivity and safety over time. The research concluded that there is no safety benefit of higher retroreflectivity for longitudinal markings, however, it is important that the markings are present and visible to drivers (18). Cottrell Jr. and Hanson (2001) conducted a research project to determine the safety, motorist opinion, and cost-effectiveness of pavement marking materials used by the Virginia DOT. Motorists indicated in surveys that people prefer pavement markings with higher retroreflectivity. They also concluded that more data was needed to determine if the type of pavement marking affects the safety of the facility (19). Recent research has not proven the significance of higher retroreflectivity, but drivers indicated that they feel more comfortable with brighter pavement markings.

Run-off-the-road crashes are one of the most common types of crashes on rural facilities. One study attempted to find a relationship between retroreflectivity and crashes on rural facilities. The research proposed that lower retroreflectivity values were a contributing factor in crashes (20). Previous research has been done in this area, however, no other study has determined a statistically significant relationship. The study managed to identify a statistically significant relationship between low pavement marking retroreflectivity and safety performance (20). Agencies should look to reduce the number of crashes by making more informed decisions about their pavement marking management programs in the areas that low retroreflectivity values exist.

3.3.5 Literature Summary

Previous research has helped decision makers choose pavement marking materials to improve durability and service life. Limited research has been done to improve the efficiency of pavement marking application techniques. Striping crews are given limited resources on proper installation of equipment and techniques to improve the efficiency of pavement marking application. Improved application techniques would result in more centerline miles of striping each year without sacrificing retroreflectivity or paint presence with increased striping truck speeds.

3.4 Equipment Background

The Iowa Department of Transportation (DOT) has been experimenting with different bead guns to maximize the number of centerline miles painted each year. The Department uses four different bead guns in their pavement marking practices. The guns include: Potters Industries' SpeedBeader™ and Visigun™, Binks™ Model 30, and the Zero-Velocity™ prototype being developed by EZ-Liner. This study evaluated different bead guns at various speeds to maximize centerline marking miles without losing retroreflectivity, durability, and service life. Experimentation took place at the District 1 shop in Ames, Iowa and the District 6 shop in Marion, Iowa. The evaluation included distribution of glass beads across the marking, bead roll, initial retroreflectivity, and the analysis of bead trajectory.

Information was gathered for the four different bead guns that are used by the Iowa DOT. Each gun has distinct properties that make it different from the others. Manufacturers of the bead guns produced literature that includes the information below.

3.4.1 Binks™ – Model 30

The Model 30 Glass Bead Dispensing Gun is a pneumatically operated bead gun manufactured by Binks™, who was acquired by Illinois Tool Works Industrial Finishing in 1998. The Binks™ bead gun is one of the most popular guns on the market. Several agencies use this product on their striping truck as part of the pavement marking application process. The gun can deliver glass beads at a rate up to 20 pounds per minute. The pneumatic gun requires a minimum air pressure of 50 psi. The gun includes four nozzle inserts having openings 7/32, ¼, 9/32, and 11/32 inch. A boring kit can be purchased to deliver glass beads at a rate of 60 pounds per minute at 70 psi (21). The Binks™ Model 30 can be mounted on various types of line striping equipment. Figure 3.2 is an image of two Binks™ Model 30 bead dispensers on a striping truck.

Figure 3.2: Binks™ Model 30 bead dispensers.

3.4.2 SpeedBeader™

Potters Industries started manufacturing the SpeedBeader™ to improve pavement marking efficiency. The gun allows speeds in excess of 8 mph which saves time and resources. The gun is designed to be used with different bead sizes and can be easily adjusted with the single-knob flow adjustment. An air injection system is designed to reduce bead roll at speeds over 8 mph. SpeedBeader™ provides more uniform bead distribution, which reduces waste and increases the bead concentration on the line (22). Potters Industries is looking to improve the efficiency of pavement marking application with the development of the SpeedBeader™. Figure 3.3 is an image of vendors making adjustments to the SpeedBeader™.

Figure 3.3: SpeedBeader™ bead dispenser.

3.4.3 Visigun™

The Visigun™ is manufactured by Potters Industries as well. The design of the gun adjusts for an even distribution of all sizes of glass beads. The Visigun™ can be used on both pressurized and gravity bead application systems. The rubber shroud controls bead dispersion by placing beads within one inch of the pavement, which reduces the amount of bead loss due to overspray or wind. With over 20 years of application experience Potters Industries developed this gun for optimal application of any type of highway marking sphere on any field site (23). An image of the Visigun™ can be seen in Figure 3.4.

Figure 3.4: Visigun™ bead dispenser.

Potters Industries put together a table that compares the features of the Visigun™ and SpeedBeader™. Table 3.1 below compares the features of each bead application gun.

Table 3.1: Potters bead gun comparison.
Source: Potters Industries Inc.

	VISIGUN	SPEEDBEADER
Bead specification	Accepts all	Accepts all
Application speed	VISIGUN performs effectively at speeds up to 8 MPH	SPEEDBEADER is designed to perform effectively in excess of 8 MPH
Bead roll reduction	Some bead roll common at speeds over 8 MPH	Patent pending injection air system significantly reduces roll
Bead flow adjustment	3 calibration components	1-touch calibration
Binder systems	May be used with paint, thermoplastic and plural component systems	Recommended for paint applications; can be used with plural component systems, however, speed advantages are limited
Mounting	Accepts 1/2" round stock; easily mounted to existing equipment	Accepts 1/2" round stock; easily mounted to existing equipment. More mounting configurations available with SPEEDBEADER
Line widths	4" shroud comes standard; Optional shrouds for 5", 6", and 8" diameters	Adjustable chute nozzle accommodates up to 6" line widths. A wide chute nozzle is available for wider lines
Special requirements	Operator training recommended	Operator training recommended; air regulator(s) required
Advantages	Excellent application results, low maintenance, easy to use	Greater coverage in less time, reduced cost, increased retroreflectivity, increased productivity

3.4.4 Zero-Velocity™ Bead Gun

The Zero-Velocity™ bead gun is a prototype gun being developed by EZ-Liner Industries. This device attempts to account for the striping truck's speed by passing beads through rollers at the same velocity in the opposite direction that the truck is traveling. This concept attempts to deliver the beads to the fresh marking surface at near zero horizontal velocity. An automatic speed dial can adjust the roller velocity to match the speed of the truck or it can be set on manual which dispenses beads at a constant rate. The Zero-Velocity™ prototype is pictured in Figure 3.5.

Figure 3.5: Zero-Velocity™ prototype bead dispenser.

3.5 Experiment Setup

Experimentation took place at the District 1 and District 6 shops of the Iowa Department of Transportation (DOT). The Zero-Velocity™ and Visigun™ bead application guns were evaluated using Type II beads on November 13, 2007 at the District 1 shop in Ames, IA. The SpeedBeader™ and Binks™ Model 30 guns were evaluated using Type II beads on November 14, 2007 at the District 6 shop in Marion, IA. The Zero-Velocity™ and SpeedBeader™ were evaluated a second time with Type III beads at the District 1 shop on

November 15, 2007. The bead guns were evaluated at speeds of 8, 10, 12, and 14 miles per hour.

Data collection took place on the side of the roadway as the striping truck passed by. A Photron Fastcam® SA-1 High-Speed Camera and appropriate lighting was set up along the roadway to capture high speed video of the bead trajectory. The camera is capable of capturing high-speed video with mega pixel resolution at 5,000 frames per second. The camera was set up perpendicular to the direction of the truck to obtain footage that would allow the subjective evaluation of horizontal and vertical velocity of the glass beads. Additional video captured at an angle that showed the distribution of glass beads as they exit the bead gun. This video footage showed bead gun distribution across the width of the stripe before the beads reach the paint. Figure 3.6 shows the setup on the side of roadway that was used to capture the high-speed video. Notice the test panel in front of the camera that was collected for each run. These plates were used to further examine paint/bead interaction. The analysis helped decide the maximum truck speed and bead gun combination that allows the glass beads to drop vertically without causing bead roll when the beads enter the paint.

Figure 3.6: High-speed camera setup on side of roadway.

Test panels from each pass were collected for the evaluation. Aluminum plates were placed at the same location that the video was captured. The 10”x24” plates were analyzed to examine the bead distribution, bead roll, and initial retroreflectivity. Distribution and roll contribute to the retroreflectivity and durability of a longitudinal pavement marking. Proper bead distribution across the width of the marking increases the retroreflectivity of the marking. Bead roll hinders the retroreflectivity by covering the face of the bead with paint thus light cannot enter the bead and reflect light back to the source. Bead distribution and roll are affected by truck speed, which may be altered with gun settings.

The experimentation of the SpeedBeader™ and Zero-Velocity™ bead guns on November 15, 2007 used Type III glass beads. After examining the plates, the difficulty of assessing bead roll and distribution with the use of Type II glass beads was evident. Therefore, analysis only included the SpeedBeader™ and Zero-Velocity™ bead guns that used the large Type III beads.

3.6 Data Analysis

High-speed video and aluminum plates were used to analyze the different bead guns at various speeds. The video enabled subjective evaluation of the glass bead particles as they travel through the air displaying distribution and trajectory. The aluminum plates allowed the properties of bead distribution, bead roll, and initial retroreflectivity to be assessed.

3.6.1 Bead Distribution

Bead distribution, bead roll, and initial retroreflectivity were analyzed by random sampling of the test panels. A 1"x1" cut out was placed on four random locations throughout the length and width of the paint stripe. The random selections were photographed with a digital camera in digital macro zoom to enable the visibility of individual beads. Figure 22 shows a random sample taken from a 12 mile per hour pass with the SpeedBeader™. The amount of retroreflectivity varies for a number of reasons, which include the amount of beads and the number of beads rolling. As shown in Figure 3.7, it is very easy to see the individual beads and see the beads that have rolled as well.

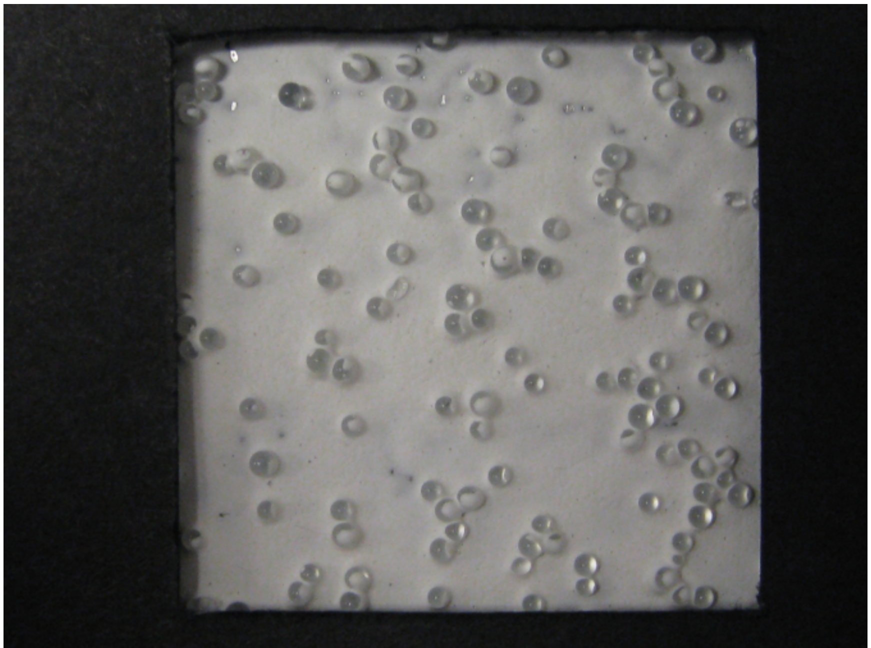

Figure 3.7: SpeedBeader™ (12 mph) 1" x 1" random sample.

Four random samples were collected from each 24" plate. Glass beads located within the four cutouts were counted. These four totals were averaged to get the average number of beads per cutout (1"x1"). The average number of beads per cutout was multiplied by the area of the stripe to obtain the number of expected beads per test panel. Figure 3.8 displays the results for the average distribution of the Zero-Velocity™ and SpeedBeader™ at 8, 10, 12, and 14 mph. This graph shows the relationship between speed and the distribution of glass beads. As expected, the average distribution decreased with increasing speed since the amount of bead distribution (bead rate) was not changed for the different speed runs. The SpeedBeader™ was able to dispense more beads than the Zero-Velocity™ up to 12 mph, at 14 mph the distribution of the two guns was similar. The bead rates of the guns were not adjusted for the varying speeds. The SpeedBeader™ was dialed in at 10 lbs/100 ft^2 and the Zero-Velocity™ was set at 9 lbs/100 ft^2 with the timer set on manual at 14 mph. Thus, the speed of the truck controlled the bead dispersion rate.

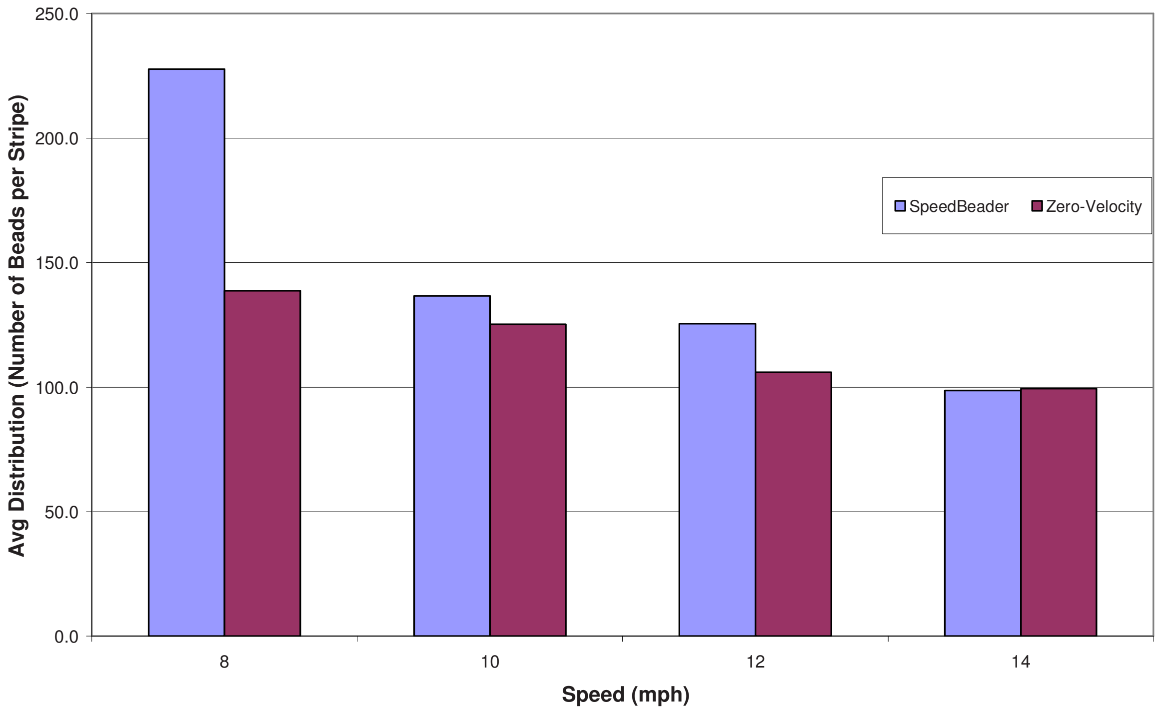

Figure 3.8: Average distribution of SpeedBeader™ and Zero-Velocity™ bead guns.

3.6.2 Bead Roll

The same concept that analyzed distribution was used to evaluate bead roll at varying speeds. The four random samples that were used for the distribution analysis were used to count the number of beads rolling. The beads that appeared to be partially covered with paint were counted as beads rolling. These beads do not provide retroreflectivity because the paint blocks light from entering the glass sphere. The number of beads rolling is expected to increase with increasing truck speed as shown in Figure 3.9. The graph displays the percentage of beads rolling per 1" x 1" sample. This was accomplished by dividing the average number of beads rolling by the average distribution. The number of beads counted in each sample is displayed on the graph. The Zero-Velocity™ bead gun had minimal bead roll at 14 mph, but did not exhibit any roll at slower speeds. The concept of obtaining zero velocity when the glass beads reach the wet pavement marking appears to be effective against bead roll at speeds greater than 8 mph.

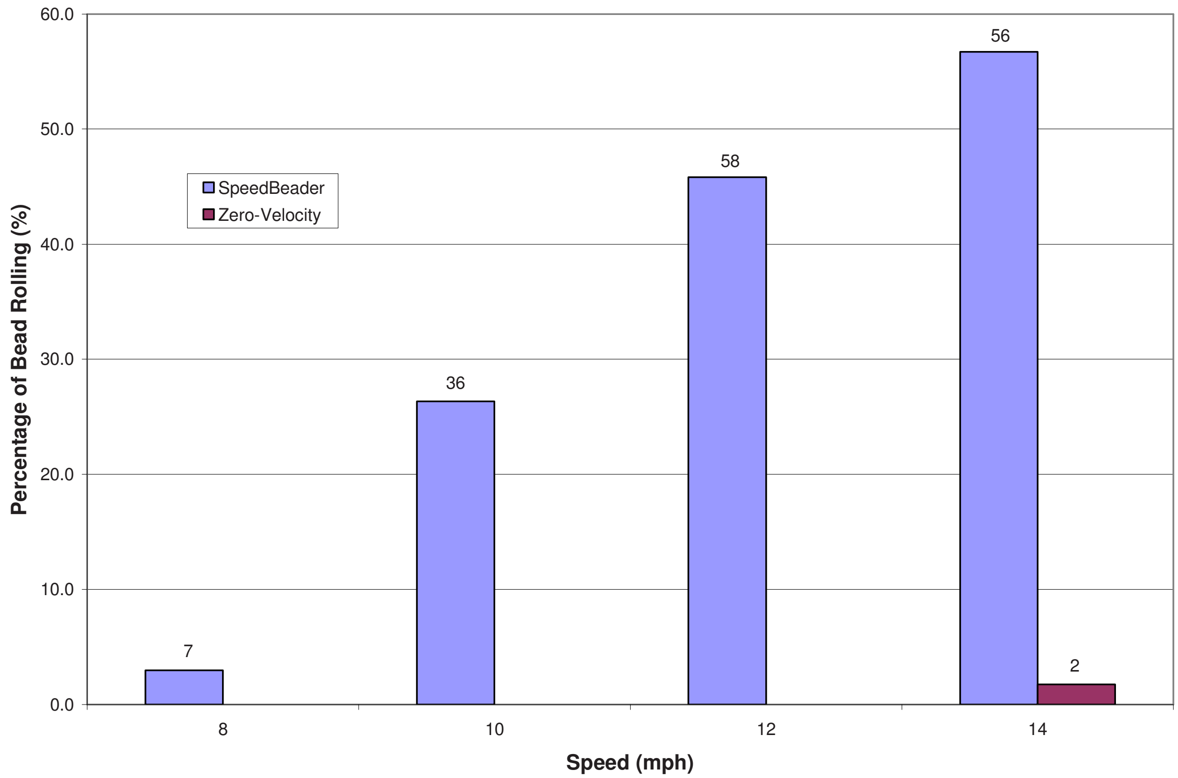

Figure 3.9: Average bead roll of SpeedBeader™ and Zero-Velocity™ bead guns.

3.6.3 Initial Retroreflectivity

Most agencies use retroreflectivity values to determine the performance of the pavement marking. As the pavement marking train moves down the roadway, agencies monitor the condition of the marking by taking retroreflectivity readings. These readings provide quick feedback which allows the crew to make adjustments when needed. When readings are out of specification or drastically change the crew can quickly adjust without sacrificing a significant amount of time and material on poor marking quality.

Retroreflectivity of the test panels was measured using the hand-held LTL-X Retrometer®. The average value of four readings was reported as the initial retroreflectivity in Table 3.2. Four random locations of the test panel were chosen, without taking readings too close to the edge of the plate. Twenty-six days after the panels were painted the measurements were taken; while the plates were being stored the painted surfaces were protected to prevent the marking from any damage. Keep in mind that the SpeedBeader™ was used in conjunction with white paint and the Zero-Velocity™ with yellow paint. Yellow paint typically produces lower retroreflectivity values than white paint. Some of the retroreflectivity values of the white paint were lower than the yellow, which may have been caused by differences in bead distribution or bead roll. As we saw in the distribution evaluation, the SpeedBeader™ had a very high number of beads at 8 mph then a drastic decrease in distribution at 10 mph. This is reflected in the initial retroreflectivity values as a large decrease occurs from 8 to 10 mph. The large number of beads rolling above 8 mph could have also influenced the poor retroreflectivity of the SpeedBeader™ test panels. Figure 3.10 shows the overall trend that retroreflectivity decreases with increasing speed. Higher striping truck speeds result in less distribution and more bead roll which has been proved to reduce retroreflectivity. The percentages in the figure represent the percentage of beads rolling.

Table 3.2: Initial retroreflectivity values.

Bead Gun	Speed (mph)	Paint Color	Reading 1	Reading 2	Reading 3	Reading 4	Initial Retroreflectivity (mcd/m^2/lux)
SpeedBeader	8	White	289	302	354	341	322
SpeedBeader	10	White	187	179	189	195	188
SpeedBeader	12	White	172	170	168	164	169
SpeedBeader	14	White	148	150	173	186	164
Zero Velocity	8	Yellow	266	274	262	262	266
Zero Velocity	10	Yellow	305	326	319	308	315
Zero Velocity	12	Yellow	249	319	326	316	303
Zero Velocity	14	Yellow	262	246	282	262	263

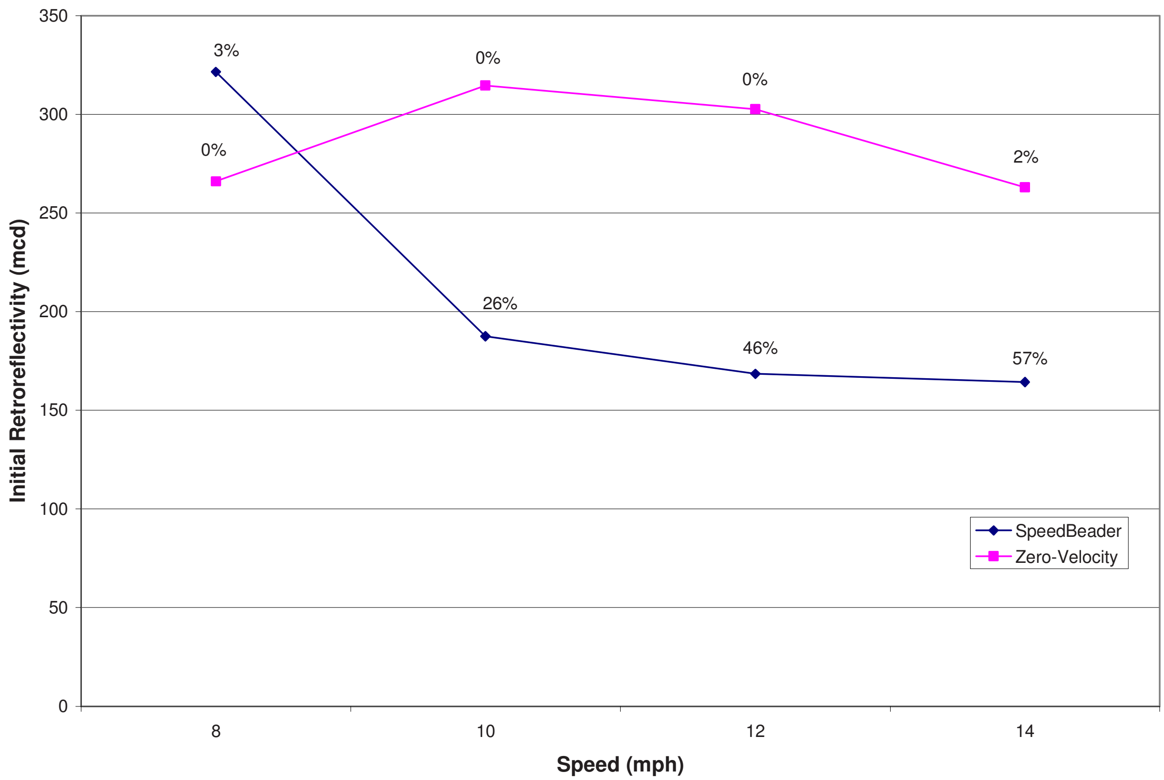

Figure 3.10: The relationship between initial retroreflectivity and striping truck speed.

3.6.4 Bead Trajectory

A high-speed camera was used to capture footage of the glass beads as they passed through the air. This footage shows how the speed of the truck affects the trajectory of the beads. Horizontal and vertical speed of the beads could be obtained from the footage with the appropriate software. However, this study was limited to subjective evaluation of bead trajectory and velocity. These speeds show the effect of the truck speed on the bead application process. A large horizontal speed caused the bead to roll when it reached the paint surface. The vertical speed of the bead has an effect on the embedment of the glass beads.

Some screenshots of the video footage were taken to show the beads as they reach the marking surface. Figure 3.11 displays the performance of the Zero-Velocity™ bead gun at 8 mph. The striping truck was moving from right to left in the image, but the beads appear to be moving from left to right. The beads are moving at a higher velocity in the opposite direction because the device was set on manual at 14 mph for the duration of the experiment. Therefore, the beads were moving faster than the truck in the opposite direction. Figure 3.12 shows the Zero-Velocity™ prototype at 14 mph. Glass beads appear to be falling at near zero horizontal velocity as the prototype has been designed to accomplish.

Figure 3.11: Screenshot of Zero-Velocity™ bead gun video at 8 mph.

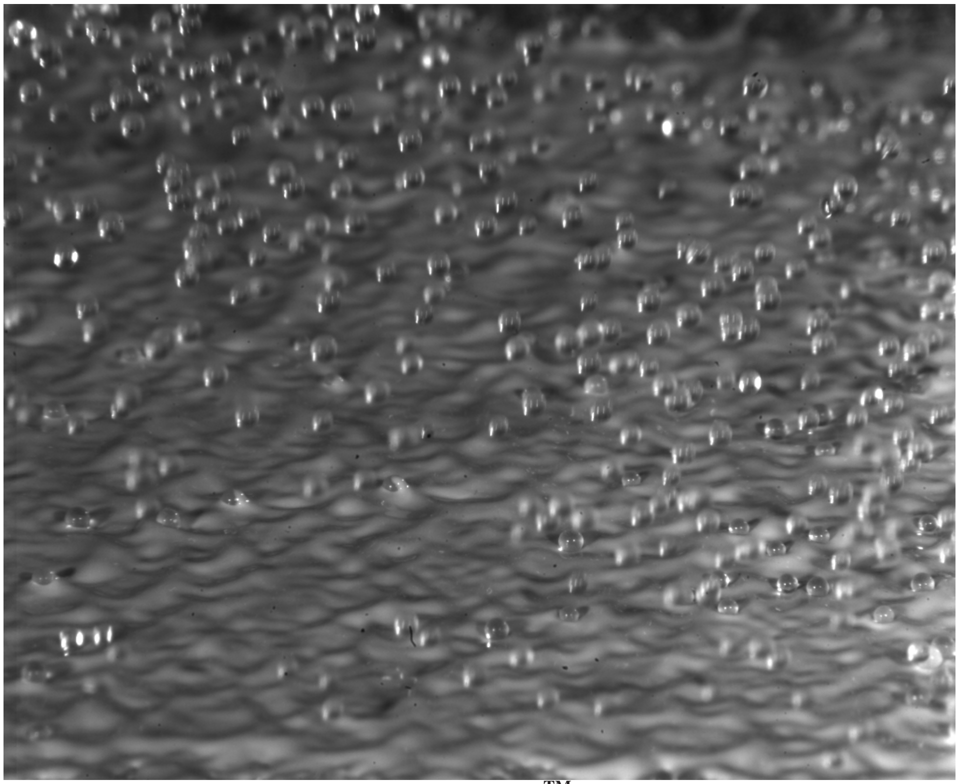
Figure 3.12: Screenshot of Zero-Velocity™ bead gun video at 14 mph.

Video images of the large beads were also captured for the SpeedBeader™. The screenshot in Figure 3.13 shows the beads passing through the air as the striping truck is traveling at 8 mph. The striping truck is passing from left to right in the image. However, the beads appear to be reaching the paint surface with minimal horizontal velocity. The SpeedBeader™ effectively counter acts the velocity of the striping truck at 8 mph by dispensing glass beads in the opposite direction keeping bead roll to a minimum.

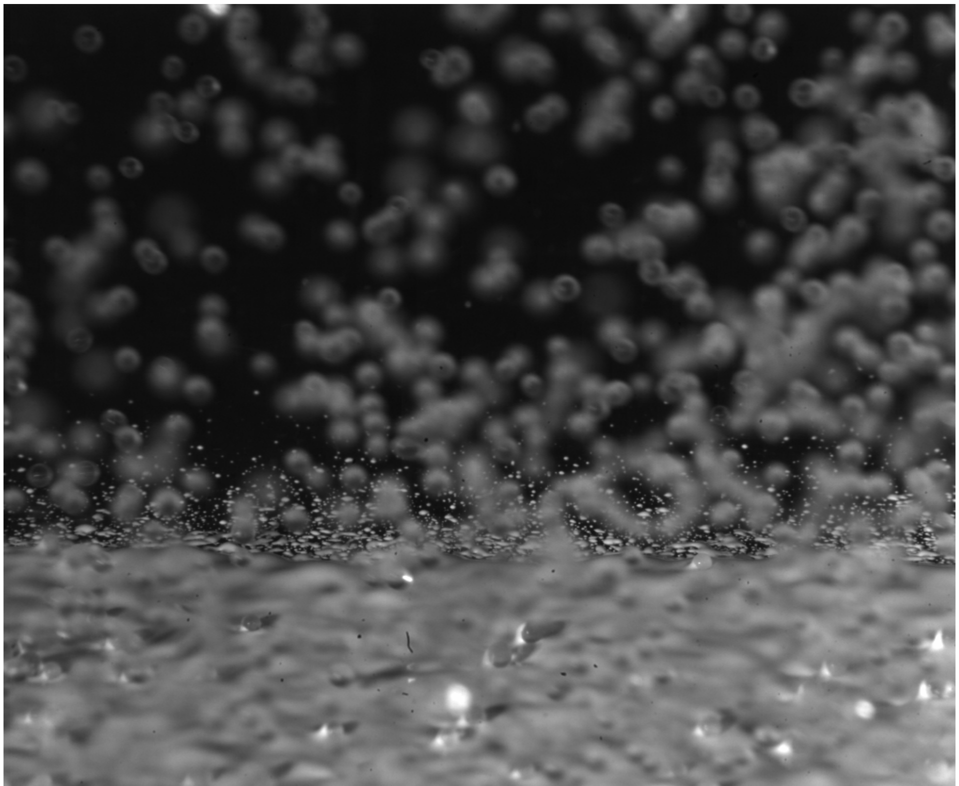

Figure 3.13: Screenshot of SpeedBeader™ video at 8 mph.

The cloud of beads in Figure 3.14 below shows how the increased velocity has caused the beads to travel at a higher horizontal velocity in the same direction as the truck. The striping truck is moving from left to right in this image as well. The beads have a higher horizontal velocity which contributes to bead roll which is confirmed by previous results in the experiment.

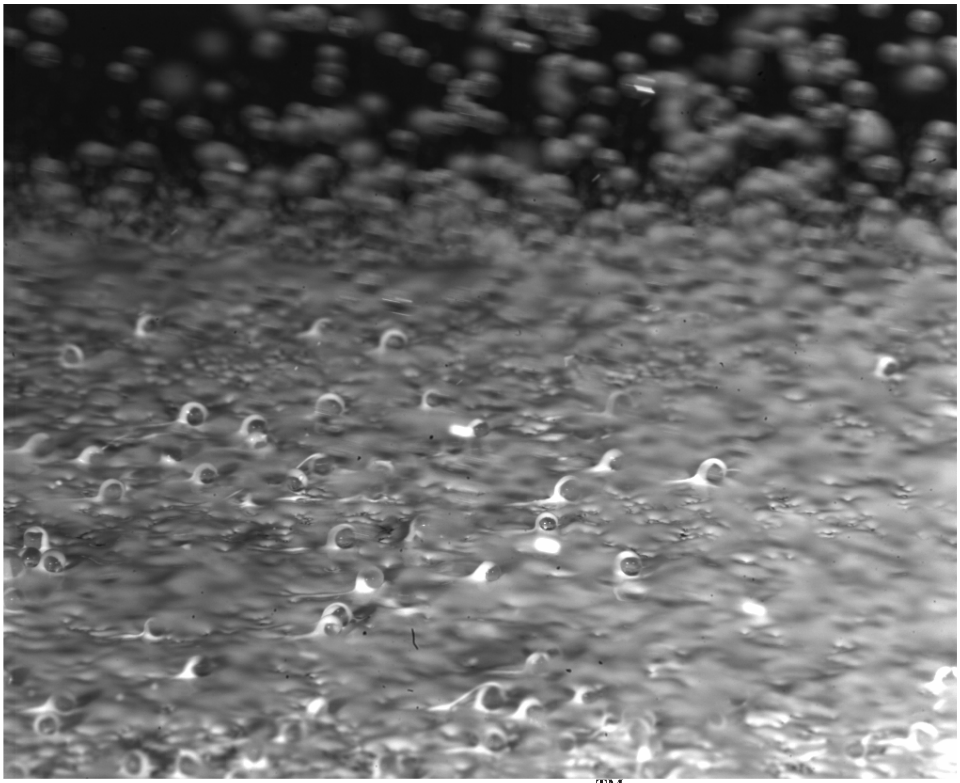

Figure 3.14: Screenshot of SpeedBeader™ video at 14 mph.

Video was also shot to capture the distribution of glass beads as they left the bead application gun. To accomplish this the high-speed camera was set up at approximately a 45 degree angle rather than perpendicular to the edge line. This footage showed the pattern of beads as they pass through the air to the paint surface. Figure 3.15 shows the Zero-Velocity™ prototype at 8 mph, remember the rollers have a velocity of 14 mph in the opposite direction. The distribution looks as though it is even across the marking with minimal bead loss. The distribution of glass beads being dispensed from the SpeedBeader™ is shown in Figure 3.16. The distribution is a little difficult to see since the truck is moving toward the camera, but it appears that the SpeedBeader™ is dispensing a large amount of beads. Further footage of the video shows several beads being lost because of the large amount of beads. Beads tend to collide and bounce off one another on the paint causing bead loss.

Figure 3.15: Screenshot of Zero-Velocity™ dispersion at 8 mph.

Figure 3.16: Screenshot of SpeedBeader™ dispersion at 8 mph.

These images were used to show some of the footage that was captured. Although, the images do not do justice compared to what is seen in the videos. These images give an example of the bead cloud that is present as the striping truck passes over the wet pavement marking.

3.7 Discussion of Results

The Zero-Velocity™ prototype and SpeedBeader™ bead guns are designed to increase productivity of the pavement marking process. Both devices try to compensate the striping truck speed by dispensing beads in the opposite direction of travel. This allows striping trucks to travel at higher speeds to enable more miles of fresh pavement markings per year. Results of this study could assist decision makers with choosing the most appropriate equipment help improve productivity of the pavement marking process.

Proper bead distribution can increase the performance of pavement marking retroreflectivity. In this experiment distribution was measured by the number of glass beads in randomly selected areas. The SpeedBeader™ showed that it was capable of dispersing a sufficient amount of glass beads to the marking. The Zero-Velocity™ threw out less beads at every speed except the 14 mph pass, but produced higher retroreflectivity values on yellow lines at the higher speeds than the white lines at those same speeds. Screenshots of the high-speed video also showed that the SpeedBeader™ was dispensing a higher volume of beads than the Zero-Velocity™ prototype. Further experimentation and adjustment of the Zero-Velocity™ prototype could increase the volume of glass beads being dispensed. However, this could lead to a significant increase in bead loss due to the beads colliding and not being able to contact the wet paint surface as seen by the high volume from the SpeedBeader™.

Several agencies link retroreflectivity to pavement marking performance. Reflectivity measurements are quick and easy to collect and decision makers use the data to make quick adjustments in the field. Bead roll can have a direct influence on the retroreflectivity as the glass beads become covered with paint. The SpeedBeader™ shows an increase in the percentage of beads rolling at the truck speed increases. Striping truck speed is related to the horizontal velocity of the beads as they are dispensed from the gun. Glass beads that have significant horizontal velocity roll when they encounter the wet paint. This concept of horizontal velocity is easily seen in the high-speed video footage as the beads hit the wet paint. The Zero-Velocity™ prototype is able to handle the increase in striping truck speed. The design of the prototype gun effectively reduces bead roll.

The analysis showed that the striping truck speed is linked to the retroreflectivity readings of the pavement markings. Analysis showed that increased striping truck speed affected bead distribution and bead roll. As the number of beads decrease, the retroreflective elements are not present to provide retroreflectivity. Bead roll also covers the face of the glass beads preventing the material from being reflective. Some of these beads may become reflective elements with time as traffic and weather elements help clean the paint from the reflective elements. The results of the study show that the Zero-Velocity™ bead gun produces less bead roll, thus provides more retroreflective pavement markings.

Footage of the high-speed video allows the bead application process to be analyzed at great detail. The video showed the trajectory of the glass beads as they pass through the air. The SpeedBeader™ footage showed that the glass beads had a significant horizontal velocity above 8 mph. Previous analysis confirms that a significant amount of horizontal velocity results in bead roll. The Zero-Velocity™ bead gun video shows that the glass beads drop to the paint surface with very little or small amounts of horizontal velocity. Based on the footage the Zero-Velocity™ prototype prevents the glass beads from traveling at significant horizontal velocities to prevent bead roll.

3.8 Summary and Conclusions

The evaluation of the SpeedBeader™ bead application gun and Zero-Velocity™ prototype has produced mixed results. The high-speed video added great value to the analysis by enabling the view of each particle. However, the video footage makes it difficult to assess values to the factors analyzed such as bead distribution and bead roll. The SpeedBeader™ dispenses more beads than the Zero-Velocity™, but produces more bead roll. Contrary to the literature provided by Potters Industries, the SpeedBeader™ did not perform effectively above 8 mph. The average distribution dropped from 228 to 137 beads per square inch from 8 to 10 mph. However, the SpeedBeader™ was able to throw out more beads than the Zero-Velocity™ bead gun up to 14 mph when the two guns exhibited approximately the same distribution. Keep in mind that distribution can be changed by adjusting the bead rate of the bead dispensers. Therefore, the evaluation of bead roll and initial retroreflectivity are more appropriate for this study. A majority of the initial retroreflectivity values of the Zero-Velocity™ bead gun are higher than the SpeedBeader™ even though the Zero-Velocity™ prototype was evaluated with yellow paint rather than white paint. The SpeedBeader™ exhibited a large decrease in initial retroreflectivity from 8 to 10 mph. This could be expected as the distribution reduced significantly and the bead roll increased with the increase in speed. From these results one can conclude that distribution and bead roll effect the initial retroreflectivity of pavement markings. The prototype bead gun reduces the horizontal velocity of the glass beads and allows for separation of the beads as they pass through the air. The Zero-Velocity™ prototype would have out performed the SpeedBeader™ if the gun was able to disperse more beads.

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Chapter 4. General Conclusions

4.1 General Discussion

Pavement markings provide delineation of the traveled way, which is important for motorist safety during daylight and nighttime conditions. As the average age of drivers using highway facilities continues to rise, visibility becomes an increasingly significant safety issue. Effectively maintaining pavement markings has become a more pressing issue for agencies as the FHWA implements a minimum retroreflectivity standard. Adding standards for pavement marking durability to a comprehensive pavement marking management program could improve the condition of longitudinal pavement markings and thus visibility of roadways. Traditionally, visual inspection takes extensive training and time, while the automated rating of markings is quick with less need for a large amount of training. The Pavement Marking Analysis Tool (PMAT) provides a largely automated, objective pavement marking durability rating that could be used by agencies to help manage pavement markings more efficiently.

Pavement marking schedules are limited by the weather in many areas of the United States. Weather conditions limit the amount of time that crews can paint each year. Increasing striping truck speed would result in more miles of freshly painted pavement markings. This increased productivity could result in a higher retroreflectivity of markings on the roadway system. Better delineated highway facilities could in turn result in a safer environment for users as shown in previous research that determined there is a correlation between low quality markings and high crash rates.

Unfortunately, higher striping truck speeds may also negatively affect the performance of longitudinal pavement markings. This preliminary field study indicates that the Zero-Velocity™ prototype bead gun produced the best results at the higher striping truck speed (above 8 mph). Reduction in bead roll improved the initial retroreflectivity of the pavement markings. Additionally, more controlled condition research could help confirm the results of this study.

4.2 Limitations

The pavement marking presence evaluation was limited to the images provided by the National Transportation Product Evaluation Program (NTPEP) officials. Increasing the number of images analyzed by both visual inspection and image processing evaluation would increase confidence in the comparison between subjective and objective evaluation. Evaluating digital images using image processing and having them visually rated would provide another comparison to consider. The image processing evaluation was conducted using the Pavement Marking Analysis Tool. This software tool could continue to develop as different pavement marking materials and pavement surfaces are introduced. Currently, the program does not have a user's guide or guidelines to assist users with problems or questions. Documentation is something that would greatly improve the usefulness of the tool.

The pavement marking application study was conducted late in the pavement marking season in Iowa. The limited size of the study led to some limitations in the data collection. The short distance of the striping truck runs caused some complications with paint and bead application. Although the striping truck was given sufficient distance to get up to the appropriate speed, the length of the paint stripe was only about 300 feet. Short run distances create problems with pressure variability in the paint and bead application guns. Variability can be in the form of surges or lags. Paint and glass bead rates could not be obtained from the trucks monitoring system because of the short run distance. Further, the bead rates were not calibrated for each speed which could cause some variability in the bead application rates. Smaller type II glass beads were used with the Binks™ and Visigun™ making it difficult to analyze. Larger type III glass beads were easier to visualize for the analysis procedures used in the study. Longer striping run distances and better calibration would improve the credibility of the study.

4.3 Recommendations

Future research could expand on the comparative study of the automated versus subjective (NTPEP) evaluation. Although NTPEP officials rate pavement markings in the field, digital images evaluated by the software tool could be sent to be rated by NTPEP officials. This would offer another comparison of the software tool to the visual inspection rating system. Further evaluations could be conducted with image cropping or choosing the region of interest. This could be accomplished by a few individuals familiar with the software tool. Each of the individuals could evaluate the same digital images and crop or choose the region of interest to be evaluated. The results of each rating could be compared to assess the degree of variation involved with choosing the region of interest. Continuing analysis and evaluation of the Pavement Marking Analysis Tool could lead to the development of guidelines or standards to assist users and insure that the tool is used in an effective manner.

The pavement marking evaluation has concentrated on marking presence. Pavement marking color has not been stressed in this study. Future research may want to consider pavement marking color in addition to durability. The color evaluation of the Pavement

Marking Analysis Tool could be investigated to see if the tool could be modified to include some color analysis. The color of the marking conveys important information to road users and the ability to see color may affect the safety of the facility. Reliability of the objective evaluation process may be an issue. Further experimentation could evaluate different ambient light conditions to see how the software reacts to images with differing light conditions. All of the images evaluated were taken directly above the pavement marking. Along with light conditions, camera angle could also be analyzed to see how the software tool output is affected. These tests could indicate how robust the Pavement Marking Analysis Tool is in the objective evaluation of markings.

Several changes should be considered to increase the accuracy of the bead gun evaluation process. The striping process consisted of a 300 foot run at each speed. Meter readouts are not effective on such short runs. Thus, the meter readouts were not working for the bead and paint application rates. Longer runs to give the meters sufficient distance to report rates would have been helpful in the analysis. Cool temperatures (in the mid-40s) had some effect on the paint. Minimal paint thickness was apparent with the white paint used for the SpeedBeader™ evaluation. The paint thickness may have affected the bead loss and bead roll as bead embedment can be affected by the paint thickness. Minimal thickness of paint could have prevented the beads from reaching proper embedment causing them to hit the aluminum surface and roll. The same effect could have caused beads to bounce off the aluminum surface with the lack of paint. Although data was obtained from the Binks™ and Visigun™ with small beads, the guns need to be analyzed while applying large beads to increase the accuracy of the experiment. It can be difficult to visualize bead roll and distribution with the smaller type II glass beads. The large type III beads are easier to follow in high speed video as well. The high-speed video footage could be analyzed with software to determine the velocity of the individual beads. These values would provide data that could reveal relationships between striping truck speed and bead velocity. Improvements in the data collection process could provide additional information for the bead gun evaluation.

Agencies may be interested in a study involving bead loss. As the striping truck passes down the roadway not all glass beads reach the wet paint marking. Excess beads, wind, and bead velocity are some attributes leading to the cause of bead loss. Bead loss not only has an effect on the retroreflectivity by losing retroreflective elements, but also contributes excess cost to the pavement marking process. Additional research could quantify the amount of beads that are being lost using the different bead dispensers at different speeds. The number of beads in each test panel was represented by the average distribution. Calibrating the bead guns at the different speeds could provide the expected bead rate. The expected bead rate could be reduced to obtain the weight of beads in the specific area and this value could be compared to the actual number of beads being applied. This methodology could be used to help decision makers choose a bead dispenser and speed that produces the least amount of bead loss.