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Effectiveness Study on Temporary Pavement Marking Removals Methods

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By

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Effectiveness Study on Temporary Pavement Marking Removals Methods

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This study was conducted to identify effective temporary marking removal methods and procedures on concrete and asphalt pavements. Pavement markings provide guidance to road travelers and can lead to accidents when not properly removed. Current state guidelines on removal do not provide clear and objective methods of measurement. After testing the most common removal methods, this research concluded that removing markings by chemical was not only cost and results-oriented effective compared to other methods, but it was also safe to the environment and road users. Finally, a baseline of measurements was developed for this project, along with the feasibility of using digital image processing to objectively determine whether or not a removal method could be deemed effective.

Acknowledgments

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CHAPTER 1 INTRODUCTION

1.1 Problem Statement

Reconstruction and improvements of roads are a major cause of traffic lane shifts and the requisite pavement marking removal therein. Alteration of pavements' colors and/or textures as well as incomplete removal of pavement markings can confuse motorists as to the navigable lanes when driving through work zones (Haas, 2001). To make matters worse, under different lighting and weather conditions, the removed markings are often more visible than the new ones. Motorists or drivers rely heavily on pavement markings for roadway guidance; therefore, a method that will completely remove old markings is imperative to reduce possible accidents due to lane confusion.

In the United States, the Manual on Uniform Traffic Control Devices (MUTCD) sets the guidelines for signs, traffic, and pavement markings. However, the removal method of temporary markings is not clearly defined and does not provide clear guidance. The MUTCD requires that "markings that are no longer applicable for roadway conditions or restrictions and that might cause confusion for the road user shall be removed or obliterated to be unidentifiable as a marking as soon as practical" (FHWA, 2009). The MUTCD is supplemented by specific standards determined by the entity in each state that oversees highway transportation and administration. The Nebraska Department of Roads (NDOR) construction manual requires that the method of removal selected "shall not cause damage to the final pavement surface"

(Nebraska, 2002). The lack of details on the level of damage, or even a method of measurement can lead to subjective conclusions.

1.2 Goal and Objectives

The goal of this study is to determine ways for the safe, cost-effective, and environmentally acceptable removal of temporary markings in work zones with minimal damage to the underlying pavement or visible character of the surface course. These objectives will accomplish the goal of this study:

1) Investigate emerging techniques that would not adversely affect the pavement and the environment,
2) Study the effectiveness of selected current methods to remove temporary markings in the State of Nebraska, and
3) Develop tested and proven guidelines to appropriately select the most effective temporary marking removal with minimal visual damage to the pavement by non-subjective measures with the aid of digital image processing technology.

1.3 Methodology

1.3.1 Approach to Objective 1

A survey questionnaire link, shown in Appendix I and approved by the University of Nebraska Institutional Review Board (IRB) # 20101111321 EX, was sent to a list composed of the American Association of State Highway and Transportation Officials (AASHTO) subcommittee on construction—to study other agencies' experience with temporary pavement marking removal techniques. The results were then summarized and analyzed to identify common removal technique trends among the agencies.

1.3.2 Approach to Objective 2

Evaluation criteria were developed to analyze various methods that were all tested on both asphalt and concrete pavements to select the most effective method.

1.3.2.1 Testing

Several current temporary marking removal methods were selected for the field tests based on the survey results and literature reivews on emerging technologies (objective 1). The selected methods include water blasting, dry ice blasting, grinding (regular grinder, scarifier and Polycrystal diamond), shot blasting, and heat torching for tape. For research purposes, the chemical removal method has been added to those methods that were investigated.

The NDOR District 1 office parking lot and yard was used as concrete and asphalt test sites. Marking lines were applied onto each site for testing. A total of 40 lines were made with yellow paint, each measuring about 50 feet in length. To test differences in paint types, 12 and 20 mils of water-based and oil based paint were used to make lines 6 inches wide on both the concrete and asphalt pavements. Additionally, 5 preformed foil-backed tape lines also measuring about 50 feet were installed on both sites.

1.3.2.2 Evaluation Criteria

The marking removals were initially evaluated based on the completeness of removal; condition of the surface after removal, or the degree of scarring; and the rate of removal, measured in feet per minute. This last analysis measures how long it takes to remove the marking after one pass, which was sufficient to remove the markings. Completeness of removal was also evaluated using a scale of 0 to 5, 0 being not complete at all and 5 being very complete. This evaluative measure provides a clear idea of the effectiveness of each removal method at eliminating markings. Finally, a cost analysis was performed to determine the most cost effective removal method. Once an ideal method was selected, a visibility test was conducted at night to identify which methods can be the most distracting to motorists.

1.3.3 Approach to Objective 3

After a subjective manner of evaluation, a developed digital image analyzing program was used to objectively evaluate the state of the pavement after the markings were removed. These results were later compared with the subjectively analyzed results from objective No. 2. With the aid of grayscale and saturation image analysis, guidelines and objective measurements of ratings were determined to determine whether or not the markings had been properly removed.

1.4 Thesis Organization

Throughout this paper, a literature search to identify the problems caused by the non-effective removal of temporary marking removals, as well as current used techniques in Nebraska will be pointed out. Next, with a clear statement of objectives followed by a set of methodologies, tests results will be presented and appropriately analyzed to derive to a conclusions and recommendations. To derive to the most effective marking removal technique, an objective way to evaluate the state of the pavement after removal will be developed with the use of digital image processing. An economic analysis, along with results from a night drive on the pavement after removal will also contribute to the final method selected

1.5 Chapter Summary

The first chapter first identified the problems that are caused by the ineffective removal of markings. Goals and objectives of this study were stated, as well as methodologies to derive to conclusions. The data collected during testing will be evaluated by different criteria, all also discussed above.

CHAPTER 2 LITERATURE REVIEW

2.1 Current pavement marking removal methods

Among the pavement markings available to contractors, the most commonly used are the chemical removal method, grinding, high pressure water jet, hot compressed air burning, oxygen burning, hydro blasting, shot blasting, sand blasting, and temporary taping. Many pavement marking removal methods are available to contractors. Problems with these methods involve damage to the road that can create complications for motorists. Among those problems, scarring of the pavement is very important as “ghost stripes,” the image of the old marking, are created (FHWA 2006). These scars are confusing to motorists, especially under wet weather conditions at night. Figure 1 shows an example of a scar on highway I-80 west bound in Lincoln, NE. The sections that follow introduce some common methods used to remove pavement markings.

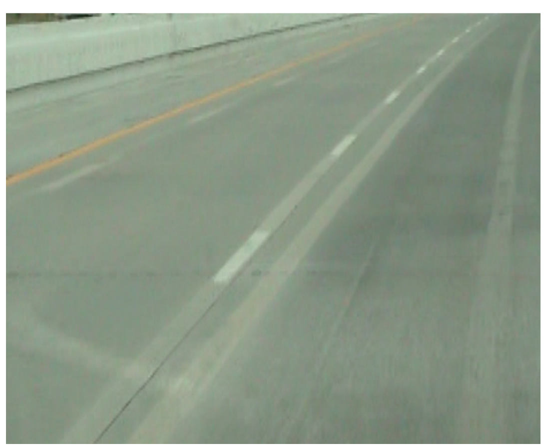

Figure 1: Scars on I-80 that can confuse drivers

2.1.1 Chemicals Method

Chemical paint strippers are applied to the marking lanes with a brush. During application of these strippers, workers are required to wear a face mask, as recommended by the paint manufacturers. The chemical, in the form of liquid or gel, is left on the marking to set for 20 to 30 minutes; the set time is dependent on the thickness of the markings and the temperature of the road surface. Afterwards, the chemical can be rinsed off the pavement with a simple water jet (400 to 1000 psi). Some chemical paint strippers are water rinsable, environmental friendly, non-flammable, non toxic, and contain no Methylene chloride (MCl). The Environmental Protection Agency (EPA) does not have specific or additional guidelines for paint strippers that do not contain MCl (EPA 2007). The Occupational Safety & Health Administration (OSHA) also has no standard or laws on common solvents or chemicals found in most chemical paint strippers (OSHA 2009). When removing long and multiple lanes the chemical methods process can be very fast and cost-effective.

2.1.2 Water Blasting

Water blasting is a process of using a high pressure water jet—usually greater than 10,000 psi depending on the thickness of the paint and/or type of pavement surface—to remove markings from pavements. This method is effective in removing the markings, but can also leave scars on the pavement and leave the site messy. Water blasting costs can be high depending on the amount of water needed to remove the markings. Removal speed might also be a disadvantage as it requires added time to completely remove the markings. Figure 2 below shows a high pressure water jet being used to blast paint on an asphalt surface.

Figure 2: High pressure water jet water blasting pavement marking

2.1.3 Grinding

Grinding method most commonly used, effectively removes markings. Depending on the cutting teeth applied on the grinder, it can be rapid by quickly cutting through the pavement. Interchangeable heads make grinding ideal for different pavement thicknesses and applications. The biggest disadvantage of grinding is scarring—affecting both the pavement texture and color— since a deep scar will confuse motorists and lead to accidents. Figure 3 is an example of a grinder being used to remove paint on concrete.

Figure 3: Grinder removing paint on asphalt pavement

2.1.4 Shot Blasting

This process consists of using small steel balls at high velocity to blast the pavement surface. The used shots can be recycled for reuse, which can reduce cost. Shot blasting works better on dry surfaces to allow the shots to be blasted and recycled easily. This method can be slow because of the recycling process, and it is not every effective for thicker lanes or application on tapes (Ellis et al., 1999).

2.1.5 Sand Blasting

Sand blasting is the process of propelling very fine materials at high velocity to blast the markings. In previous years, sand was the most commonly used material, but has been replaced as a result of lung diseases caused by dust inhalation. Although sand blasting can be effective on both concrete and asphalt pavements, it can leave scars on the pavement. Sand blasting is slow and the operator's skill and experience affect the effectiveness of the process.

2.1.6 Hydro Blasting

Just like water blasting, this method also uses a high-pressure water blast yet is combined with sand to blast markings. Hydro blasting is effective, though it can leave scars (Ellis and al. 1999). Hydro blasting is effective because of the ability to recapture and reuse the water, reducing waste and the impact on the environment.

2.1.7 Hot Compressed Air Burning

Here, a combination of propane heat (over 2400 degrees F) mixed with heated air is used to vaporize the marking. The process can be effective, but can also burn the surface and leave some marks. Hot compressed air burning can be time consuming as the operators have to move slowly to remove the markings. When burning temporary tapes, this process can be faster than others.

2.1.8 Excess Oxygen Burning

Just like hot compressed air burning, excess oxygen burning also uses a high temperature propane flame, oxygen in this case, to remove the marking. Excess oxygen burning usually takes more time especially for thicker markings; however, scars left on the pavement disappear quickly with weather and traffic wear.

2.1.9 Black Paint

To mask the marking, black paint has been used for temporary purposes. When the new applied paint dries off, however, the pre-existing paint can sometimes be visible enough to confuse motorists. Most state agencies do not allow its use for temporary marking removal purposes.

2.1.10 Dry Ice Blasting

Dry ice blasting is the process of applying pressure to the pavement using the solid form of carbon dioxide (CO_2) on the marking (Bernold et al. 2010). Several studies have shown that dry ice blasting can be very effective but costly.

2.2. Previous related research work

As the descriptions indicate, all the removal methods discussed above can either damage the road or create scars that confuse motorists. Many studies done by different departments of transportation and other research groups to test the effectiveness of marking removal have identified other methods as more effective than grinding. In 1999, the Florida DOT tested marking removals by using grinding, water blasting and a combination of both. The markings were tested on asphalt pavements and lanes were marked by water-based paint, thermoplastics, and pre-formed tape. Furthermore, water blasting was found to be more effective than grinding, as scarring was found to be minimal when compared to the other methods. However, water blasting was not recommended as a standard because the research concluded that operator skills and experience affected the results (Ellis and al. 1999).

In an earlier study done by the New York DOT, sand blasting, water blasting, and hydro blasting were the methods evaluated against grinding. Here, traffic paint, thermoplastic, epoxy and preformed tape were stripped. Sand blasting was concluded to be the most effective method. However, hydro blasting and water blasting also sometimes displayed similar results with sand blasting; nonetheless, results were not consistent with the markings' thicknesses and equipment used. Grinding left noticeable scarring, but removed thicker markings.

In 2001, the Oregon Department of Transportation (ODOT) conducted field trials to also evaluate different stripping methods on asphalt pavements (Haas 2001). In this study a soda blaster, scarifier, and grinder were used to remove the markings. Results showed that the soda blaster removed the majority of the markings with very minimal scarring. The grinder and scarifier also removed the markings while leaving some scarring. Operator skills and experience likewise affected the results.

In 2006, Ellis and Pyeon studied various pavement marking removal techniques, and concluded that no removal methods completely eliminate pavement markings without causing permanent scarring (Ellis and Pyeon 2006). As an alternative method, several seal coating methods were tested to obscure the existing unnecessary markings, and they concluded that the modified sand-seal covering method is most effective to completely cover temporary traffic paint markings. An additional draft specification was recommended in order to implement the alternate method.

2.3 Chapter Summary

Although the aforementioned studies all advised different removal methods, there were common agreements about their conclusions:

(1) There was no one method that was always better than the others;

(2) Operator skills and experience play a significant role in all the test methods; and

(3) Removal performance was also dependent on thickness of marking and type of equipment used.

The literature review presented in this chapter provided a brief introduction of the concepts that will be used in this research. Clear examples of the necessity to provide an environmental safe, cost effective, and result oriented method capable of integrating path planning navigation with indoor positioning for indoor construction applications were mentioned as well.

CHAPTER 3 Survey Results

3.1 Introduction

This chapter presents the survey's responses to generate an analysis that will show common trends among agencies. This chapter is divided into five sections, representing five of the questions that were asked on the questionnaire. For each section, the data gathered will be presented and interpreted.

3.2 Techniques used for Temporary Marking Removal

There were a total of 50 responses to the survey. Figure 4 and Table 1 break down the number of respondents per state. Out of the 50 responses, 24 different U.S. states and 1 province in Canada had representatives that used a total of 12 different removal methods. In addition, a variety of materials are used for temporary markings including epoxy, inlaid marking material, tape, paint, and thermoplastic. The marking removal methods that were mentioned at least once are grinding, heat torching, sand blasting, shot blasting, water blasting, black out tape, black thermoplastic/paint, flail milling, lift off, overlay, strip seals, and, finally, torch and scraper.

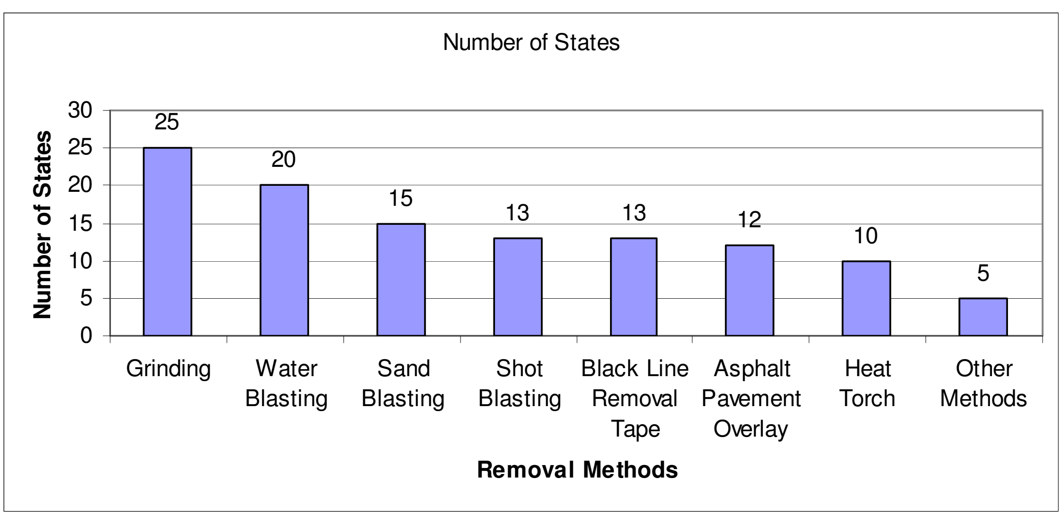

Figure 4: Removal methods usage frequency in 25 states

Table 1: Breakdown of removal techniques per state

Pavement Marking Removal Methods	**Number of States (Out of 25)**	**Percentage**
Grinding	25	100%
Water Blasting	20	80%
Sand Blasting	15	60%
Shot Blasting	13	52%
Black Line Removal Tape	13	52%
Asphalt Pavement Overlay	12	48%
Heat Torch	10	40%
Other Methods	5	20%

From Table 1, all 25 state respondents have used grinding to remove temporary markings. The next most common method is water blasting, followed by sand blasting; shot blasting; black line removal tape; and asphalt overlay. Less than half of the respondent states use heat torch and other methods not mentioned above to remove temporary stripes. These results confirm the need to find a single method that would effectively remove temporary markings because of the previously mentioned problems caused by grinding.

3.3 Most commonly used removal techniques

The next question sought to identify the most common techniques to remove markings. The responses to the most commonly used methods are summarized in Figure 5, and broken down by percentage in Table 2.

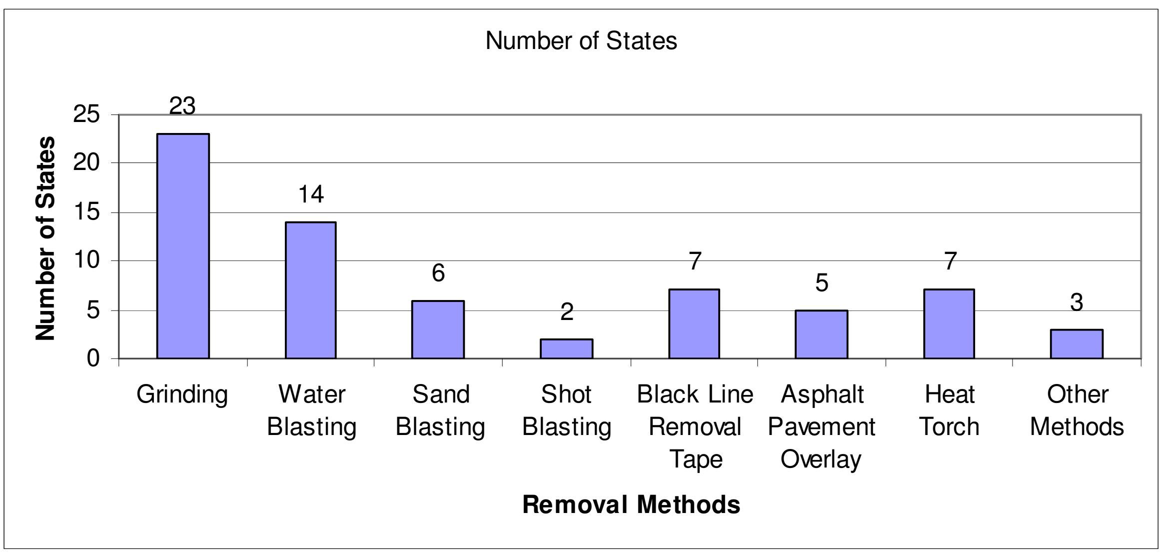

Figure 5: Most commonly used methods frequency graph

Table 2: Breakdown of most common techniques percentage

Pavement Marking Removal Methods	Number of states (Out of 25)	Percentage
Grinding	23	92%
Water Blasting	14	56%
Sand Blasting	6	24%
Shot Blasting	2	8%
Black Line Removal Tape	7	28%
Asphalt Pavement Overlay	5	20%
Heat Torch	7	28%
Other Methods	3	12%

Grinding is the most common removal method, and is followed at a distance by water blasting. All the other methods usage frequencies are less than 50%, and are therefore only popular in single states. Despite the fact that grinding is known to leave scars on pavements, agencies still prefer this method over others. The lack of a proven method that will effectively remove the markings may be a reason for agencies to continuously grind pavements.

3.4 Most Satisfactory Method(s)

Figure 6 and Table 3 summarize the answers received from question 5, which asked for the pavement marking removal(s) that has (have) been the most satisfactory to the agencies.

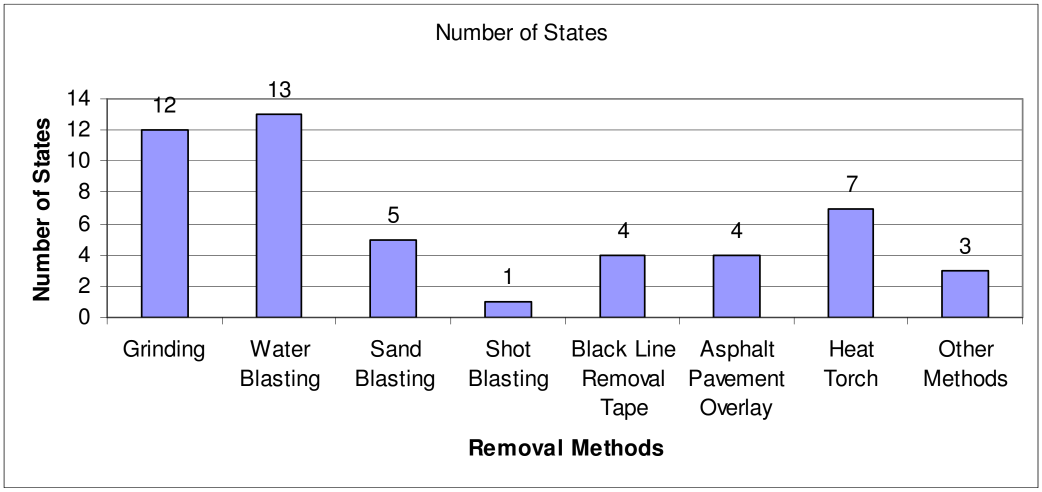

Figure 6: Most satisfactory used techniques frequency graph

Table 3: Percentage of most satisfactory methods breakdown per state

Pavement Marking Removal Methods	**Number of States (Out of 25)**	**Percentage**
Grinding	12	48%
Water Blasting	13	52%
Sand Blasting	5	20%

Shot Blasting	1	4%
Black Line Removal Tape	4	16%
Asphalt Pavement Overlay	4	16%
Heat Torch	7	28%
Other Methods	3	12%

From the previous graph and table, less than half of the respondents are dissatisfied with grinding and more than half like to water blast pavement markings. If grinding is less dissatisfied than water blasting, reasons such as costs; productivity; ease o application, etc. might explain why grinding would still be more common than water blasting.

3.5 Most common problems associated with each method

Next, when asked about the common problems associated with each marking removal, agency respondents provided detailed explanations that are reproduced exactly in the following list.

- Grinding
  - Damage to existing pavement leaving the appearance of a line
  - Scarring of pavement and residual amount of reflectivity
  - Doesn't always remove it and can still be seen where it was
  - Ghost stripe due to deep grinding scars and poor removal of existing paint.
  - Grinding grooves are forever present

  - Over grinding
  - Painted lines are difficult to fully remove by grinding as the paint penetrates the surface to lower layers.
  - Still see the ghost stripes due to exposed aggregate
  - Surface deterioration
  - The surface has a different appearance where marking was removed.
  - Visual issues surrounding the ground pavement

- Water Blasting
  - Complete removal without damaging pavement
  - Not cost effective , but does a good job
  - Removal of Surface Fines
  - Removes some of the asphalt as well, but still leaves discolorations sometimes viewed as markings
  - Scarring of pavement and residual amount of reflectivity
  - Small pieces of tape often remain behind which are still reflective at night.

- Shot Blasting
  - Old asphalt crumbles away
  - Scarring to the pavement
  - Shots remaining in removed line, then gets rusted when shot gets wet
  - Surface damage

- Sand Blasting
  - Leaves ghost image
  - Not complete removal
  - Sand blasting leaves permanent scars that accelerate the deterioration of the pavement surface

- Blasting
  - Embeds the paint and doesn't remove all of it
  - Still see the ghost stripes due to exposed aggregate

- Flail Milling
  - Too deep and can scar pavement which can simulate the stripe.
  - Too shallow and leaves traces of pavement markings which reflect from headlights at night or the from a low sun angle.

- Black Thermoplastic/Paint
  - Can wear off the underlying paint or thermoplastic which allows the stripe to show through.

- Black Out Tape
  - Black out tape moves

  - Color does not always match existing roadway, and can still show location of markings.
  - In high traffic areas, problems are performance and maintenance problems
  - Sometime after 10 months, the tape can become permanent.

- Lift off
  - Black out tape stuck to the permanent markings and parts of the roadway were left without markings
  - Left residue or glue creating the appearance of a lane change when one was not present
  - Tears/small pieces

- Heat Torching
  - Overheating
  - Time consuming

- Overlay
  - Cost is too much just to remove markings

- Strip Seals

  - Can wear away or flush under traffic which can simulate stripe during low light conditions especially when stripe is running diagonally across traffic during phased construction.

- Torch and Scraper
  - None (only one person responded in this section).

In summary, respondents identified more problems with the use of grinding as a technique to remove temporary markings. Some also felt that water blasting was not cost effective, and most of the other techniques left scars on the pavements. Cost is surely the reason why agencies still prefer grinding over water blasting despite grinding's many faults.

3.6 Most used types of pavement marking materials

To better understand the removal techniques 'problems, questions about the type of temporary pavement marking materials were asked. Figure 7 and Tables 4 and 5 summarize the answers to the types of pavement marking materials that are used often.

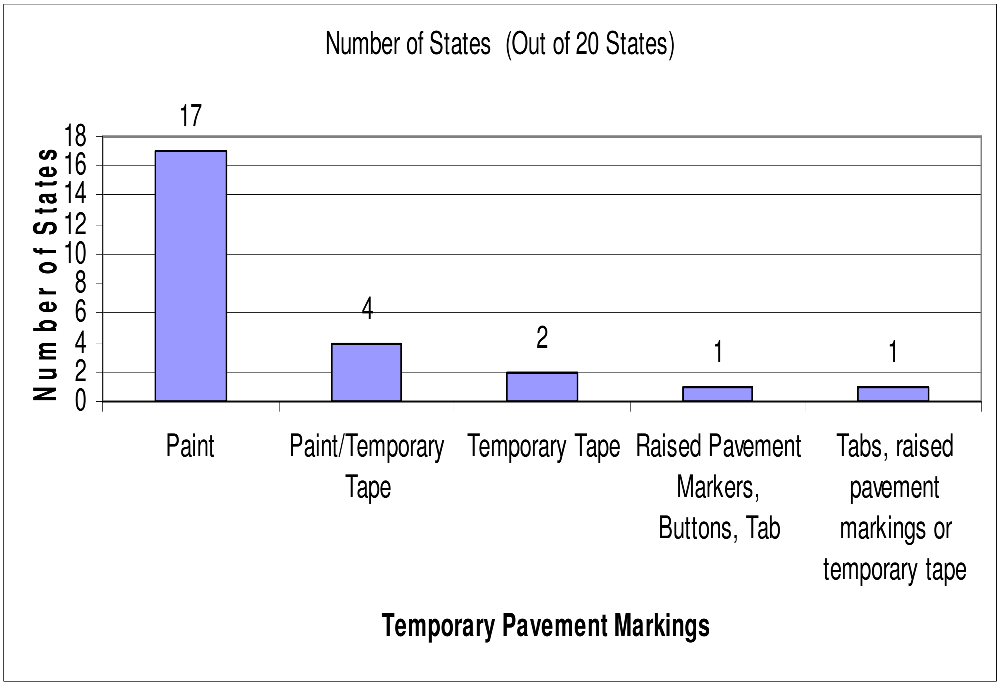

Figure 7: Most types of pavement markings frequency graph

Table 4: Most frequent temporary pavement markings used per state

State	Most Frequently Used Temporary Pavement Markings
Alaska	Paint
Georgia	Paint
Illinois	Paint
Iowa	Paint
Kentucky	Paint

Michigan	Paint
Mississippi	Paint/Temporary Tape
Nebraska	Paint/Temporary Tape
New Hampshire	Paint
North Carolina	Paint
Nova Scotia	Temporary Tape
Ohio	Paint
Oklahoma	Paint
Québec	Paint
South Dakota	Tabs, Raised Pavement Markers or Temporary Tape
Tennessee	Paint/Temporary Tape
Texas	Raised Pavement Markers, Buttons, Tab
Vermont	Paint
Washington	Paint/Temporary Tape
West Virginia	Paint

Table 5: Breakdown per state of most frequently used temporary pavement markings

Most Frequently Used Temporary Pavement Markings	**Number of States**	**Percentage**
Paint	17	85%
Paint/Temporary Tape	4	20%
Temporary Tape	2	10%
Raised Pavement Markers, Buttons, Tab	1	5%
Tabs, raised pavement markings or temporary tape	1	5%

Most agencies use only paints to temporally mark their pavements. Very few use tape and other materials for temporary markings. Therefore, the problems associated with removal techniques are most likely related to paints.

3.7 Chapter Summary

This chapter presented the responses received from the survey. In summary, grinding and water blasting are the two most commonly used techniques, but water blasting was the most satisfactory. When asked about problems associated with the removal techniques, grinding was the one that had the most faults, as shown in Figure 8. The same problems that were mentioned above in the literature review section were the same provided by the survey respondents. Scarring of the pavement, color, and texture discrepancies of the surface all can lead to motorists' confusion. Grinding was however the most commonly used removal technique, but users prefer it over water blasting for cost savings purposes.

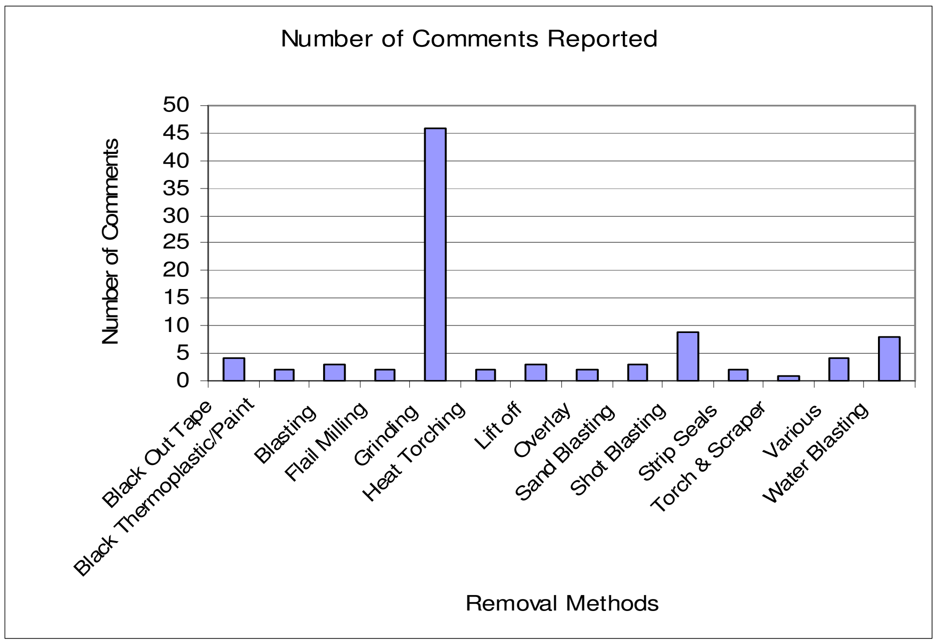

Figure 8: Problems and/or comments per removal technique

CHAPTER 4 Field Test and Data Analysis

4.1 Introduction

This chapter evaluates each method of removal with the criteria developed and mentioned above. The first section of this chapter will display and explain results found per technique. The following section will present evaluation results for the markings, and the last section will present cost information on the methods.

4.2 Test Data Analysis

Different removal techniques were tested on the concrete site (Figure 9) and asphalt site (Figure 10) all located at the NDOR District 1 office.

Figure 9: Concrete site used for testing

Figure 10: Asphalt yard used for tests

4.2.1 Markings removed by Water Blasting

Water blasting removed the marking on all surfaces, but left a scar that could lead to confusion. Water blasting worked the best on concrete while removing water based paint of 12 mils (Figure 11). Figures 12 and 13 show the results of water blasting on oil-based paint concrete and water-based paint on asphalt, respectively.

Figure 11: Concrete pavement condition before (on left) and after (on right) 12 mils water based paint has been removed by water blasting

Figure 12: Concrete pavement condition before (on left) and after (on right) 10 mils oil based paint has been removed by water blasting

Figure 13: Asphalt pavement condition before (on left) and after (on right) 10 mils water based paint has been removed by water blasting

The process of water blasting was much slower compared to the other methods, but was very fast and effective on tape (Figure 14). It was relatively easier to remove the tape by water blasting. The surface was free of scars as shown in Figure 14. It should be noted here that the tests were performed at non-favorable weather condition for the tape. The temperature outside may not have allowed the tape to have properly set down before testing.

Figure 14: Concrete pavement condition before (on left) and after (on right) tape has been removed by water blasting.

4.2.2 Markings removed by Dry Ice Blasting

Dry ice blasting did not entirely remove the paint markings on the concrete surface, as shown in Figures 17 and 1.8. On asphalt pavement, however, the removal was well completed, but left a scar on the pavement (Figure 19). Dry ice blasting was the slowest method of removal. Results improved as the operator spent longer times on the markings. Both pavement surfaces were left with scars and texture change after removal. As mentioned previously, a container of dry ice pellets (Figure 15) is attached to a hose that shoots the dry ice onto the pavement (Figure 16).

Figure 15: Container full of dry ice

Figure 16: Dry ice is shot onto the markings

Figure 17: Concrete pavement condition before (on left) and after (on right) 10 mils water based paint has been removed by dry ice blasting

Figure 18: Concrete pavement condition before (on left) and after (on right) 12 mils oil based paint has been removed by dry ice blasting

Figure 19: Asphalt pavement condition before (on left) and after (on right) paint has been removed by dry ice blasting

4.2.3 Markings removed by Grinder

To remain consistent throughout the whole test, the operator only made a single pass every time with the grinder. For the most part, the rate of removal with the grinder is higher than the other techniques. The pressure applied onto the machine increases as the depth of the scar on the pavement increases. The grinder did damage the pavement by causing minimal color and texture discrepancies. Regardless of the pavement type or marking material, the grinder did leave scars, as shown by Figure 20 on concrete, and Figure 21 on asphalt.

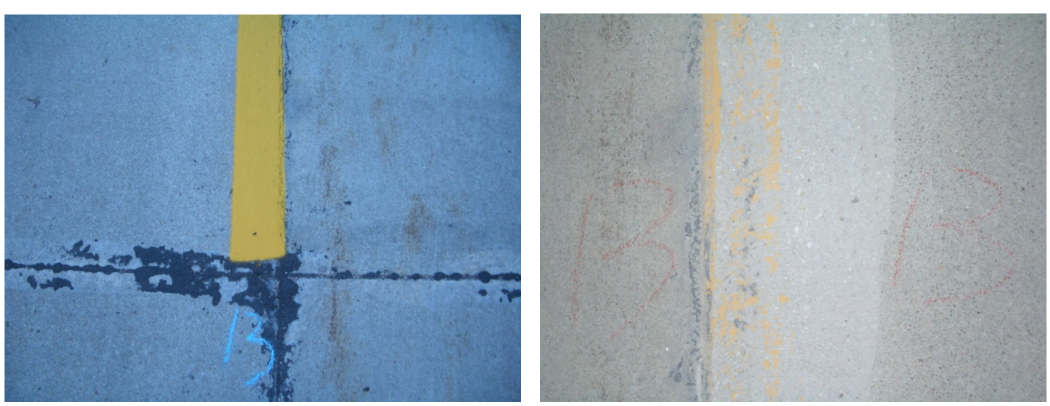

Figure 20: Concrete pavement condition before (on left) and after (on right) paint has been removed by grinding

Figure 21: Asphalt pavement condition before (on left) and after (on right) paint has been removed by grinding

4.2.4 Markings removed by Scarifier

The scarifier is just like a grinder except the cutting blade heads never leave the surface while cutting in forward and reverse directions. While the scarifier is a fast process, it damages the pavement and does not completely remove the paint markings. The scarifier also left scars on the pavements. Figures 22 and 23 show the results of using a scarifier on concrete and asphalt pavements, respectively.

Figure 22: Concrete pavement condition before (on left) and after (on right) paint has been removed with scarifier

Figure 23: Asphalt pavement condition before (on left) and after (on right) paint has been removed with scarifier

4.2.4 Markings removed by poly crystalline diamond cutter (PCD)

This method is also a form of grinding, but the only difference here is that the cutter is made of polycrystalline diamond material, which generates less heat during the cutting process and increases the grinding efficiency (Figure 24). The PCD scrapper allows the operators to decrease the intensity of labor while effectively removing the markings.

Figure 24: PCD plate cutter

For evaluative purposes, the PCD was only used to remove one marking, and it displayed similar results as the grinder. Figure 25 shows the concrete pavement condition before and after the PCD was used.

Figure 25: Concrete pavement condition before (on left) and after (on right) 12 mils paint has been removed by PCD grinder

4.2.5 Markings removed by Chemical

The use of an environmentally friendly chemical stripper—it did not contain Methylene Chloride (MeCl) and was biodegradable—was tested to remove paint markings. First, the operator or worker needs to apply one pass of the chemical solution (here liquid) on the paint marking with a brush or roller (Figure 6.16), and let it set for approximately half an hour. The set time depends on the chemical stripper and marking material types. The material safety data sheet will have more details on setting time. The next step consists of power washing the solution from the pavement with a sprayer hose under a pressure of 400 to 1000 psi.

The Environmental Protection Agency (EPA) only has specific and additional guidelines for paint strippers that contain MeCl in their solution (EPA 2007). According to the EPA, any paint stripping that does not contain MeCl is not a hazardous air pollutant and is therefore not risky to the public health. While applying and removing the chemical stripper, the operator should wear protective clothing, gloves, and a face shield (Figure 6.17) as recommended by the operation manual. There are no specific regulations on paint stripping by the Occupational Safety and Health Administration (OSHA 2009). For larger projects, chemicals could be dispensed from a paint truck equipped with an attached vacuum that operates concurrently with removal operations to clean any mess left from power washing. This would also allow the surface to be ready for stripping shortly after removal.

Figure 26: Applying the chemicals on the markings

Figure 27: Operator with proper protection while removing marking by chemical method

The chemical stripping method was the most effective during tests and left no or very little paint on both surfaces (Figure 28 and 29).

Figure 28: Concrete pavement condition before (on left) and after (on right) paint has been removed by chemicals.

Figure 29: Asphalt pavement condition before (on left) and after (on right) paint has been removed by chemicals

4.3 Evaluation of Marking Removal Methods

There was no visible scar on the pavement after the use of chemical strippers. Table 6 below is a summary of some data that were recorded during testing. The complete data is shown in Appendix 2. The completeness of removal rating shows whether or not there was paint left on the surface (5 was for little or no paint, and 1 was significant amount of paint left). The degree of scarring rating was used to classify how much damage and/or texture difference was/were left on the pavement (5 was for a lot of scar, and 1 for little or no scar). Please note that the set time of the chemicals was not used to calculate the rate of removal.

Table 6: Test data results

Removal Method	**Type**	**Marking**	**Marking size**	**Rate (Ft/min)**	**Completeness of Removal**	**Degree of Scarring**
Chemicals	Concrete	Water Based	12 mils	12.58	5	1
	Concrete	Solvent Based	20 mils	10.10	5	1
	Asphalt	Water Based	20 mils	5.00	5	1
	Asphalt	Solvent Based	12 mils	8.61	5	1
Water Blasting	Concrete	Water Based	20 mils	3.11	4	1
	Concrete	Solvent Based	12 mils	1.52	4	1
	Asphalt	Water Based	12 mils	11.58	5	5
	Asphalt	Solvent Based	20 mils	1.14	3	5
	Asphalt	Tape	4 inch	74.92	5	1
Dry Ice Blasting	Concrete	Water Based	12 mils	1.48	1	1
	Concrete	Solvent Based	20 mils	0.19	1	4
	Concrete	Tape	4 inch	87.05	5	1
	Asphalt	Water Based	20 mils	22.83	4	5
	Asphalt	Solvent Based	12 mils	6.83	3	5
Shot Blasting	Concrete	Water Based	20 mils	57.73	4	4
	Concrete	Solvent Based	12 mils	26.59	3	4
	Asphalt	Water Based	12 mils	45.92	5	1
	Asphalt	Solvent Based	20 mils	22.37	4	5
	Asphalt	Tape	4 inch	28.00	5	1
Scarifier	Concrete	Water Based	12 mils	36.01	3	5
Grinding	Concrete	Solvent Based	20 mils	44.49	3	5
Heat Torch	Concrete	Tape	4 inch	63.25	5	1
Grinding	Asphalt	Water Based	12 mils	116.09	5	5
PCD	Asphalt	Solvent Based	20 mils	1.34	5	5
Scarifier	Asphalt	Tape	4 inch	2.05	5	1

The chemical stripping method was the most efficient on both surfaces for paint, and was rather fast if one does not consider the setting time. There was also little or no scar left on the pavement after using chemical strippers. The outside temperature was about 20 °F when the tape was laid down on the pavements; therefore, most of the tape did not stick well to the surface, and some were not even entirely set. Almost every method used on tape was successful except for dry ice and heat torching which left some marks on the pavement. Figure 30 shows the result of the heat torch on concrete pavement.

Figure 30: Condition of concrete pavement after heat torch applied on tape

After determining the most efficient methods, the cost data to gauge the overall value of the different removal techniques was also referred to.

4.4 Cost Information

The lack of information available to individually estimate each technique per surface has made it difficult to obtain much comparable data. For the project, the contractors selected quoted the whole removal as a lump sum, and found it cumbersome to break down. Nevertheless, the contractor that was hired to remove the markings was able to provide a cost per linear foot estimate based on how much material, equipment, and labor was spent on each lane and technique. The contractor, from Kansas City, Missouri, also used other information like past projects, removal time to come up with an estimate. Table 7 highlights some costs that were provided. See Appendix 3 for the complete data with all the cost information.

Table 7: Cost data for pavement marking removal techniques

Removal	Type	Marking	Marking Size	Cost per Linear Foot
Chemicals	Concrete	Water Based	12 mils	$0.33
	Concrete	Solvent Based	20 mils	$0.41
	Asphalt	Water Based	20 mils	$0.83
	Asphalt	Solvent Based	12 mils	$0.48
Water Blasting	Concrete	Water Based	20 mils	$2.14
	Concrete	Solvent Based	12 mils	$4.39
	Asphalt	Water Based	12 mils	$0.58
	Asphalt	Solvent Based	20 mils	$5.86
	Asphalt	Tape	4 inch	$0.09
Dry Ice Blasting	Concrete	Water Based	12 mils	$3.37
	Concrete	Solvent Based	20 mils	$26.00
	Concrete	Tape	4 inch	$0.06
	Asphalt	Water Based	20 mils	$0.22
	Asphalt	Solvent Based	12 mils	$0.73
Shot Blasting	Concrete	Water Based	20 mils	$0.12
	Concrete	Solvent Based	12 mils	$15.95
	Asphalt	Water Based	12 mils	$3.47
	Asphalt	Solvent Based	20 mils	$0.55
	Asphalt	Tape	4 inch	$0.02

Scarifier	Concrete	Water Based	12 mils	$0.19
Grinding	Concrete	Solvent Based	20 mils	$0.15
Heat Torch	Concrete	Tape	4 inch	$0.11
Grinding	Asphalt	Water Based	12 mils	$0.58
PCD	Asphalt	Solvent Based	20 mils	$0.80
Scarifier	Asphalt	Tape	4 inch	$3.25

Water blasting and dry ice blasting are the most expensive methods among the ones tested for paint removal. Shot blasting and chemical are the other non-grinding techniques for paint removal. For tape removal, dry ice blasting is the cheapest non-grinding method, while heat torch and water blasting are both the most expensive. Removal of paint by chemical is therefore both result-oriented and economically effective.

In order to evaluate the effectiveness of all removal methods including those tested in this research, a software program was developed using a digital imaging processing technology.

4.5 Driving Visibility Test

For this test, pictures of the removed markings were taken on both types of pavements during unfavorable driving conditions. Motorists are more likely to be confused by scars left on pavements at night and/or when it is raining. Snapshots of the pavements were taken at night to see how the scars left from the methods would affect motorists. Figure 31 is a picture taken right after sunset.

Figure 31: Night picture of concrete pavement site taken after tests

In summary, the markings removed by chemical methods were unrecognizable, as they were not visible on both types of pavement. The grinder, scarifier, PCD and the dry ice blasting marks were the most visible. The waterblasted markings were only visible on the asphalt pavement.

4.6 Chapter Summary

This chapter presented the results of the tests and evaluated the removal techniques. It was concluded that chemical was the most result and cost oriented way to remove temporary markings. A test drive was also done at night to identify the lines that would confuse drivers. The lines removed by chemical method were the most unidentifiable. The validity of these conclusions is presented in the following chapter.

CHAPTER 5 Image Processing Technology

5.1 Introduction

The objective of this chapter is to develop a baseline of measurement that can be used to objectively determine the effectiveness of a marking removal. In the process, a validation of conclusions made in the previous chapter will also be made. This chapter presents image processing technology used, then analyzes the data found with the same technology, and concludes by setting numerical and objective ways to gauge the effectiveness of marking removal methods.

5.2 Image Processing

Road marking properties have been assessed in the past by the use of digital image analysis (Burrows et al., 2000). Image processing was selected because of its simplicity in quantifying and analyzing the removed marking area. In order to do so, a background image must be compared with an image of the removed marking. The pixels of these digital images were then analyzed by their grayscale and saturation properties.

5.2.1 Grayscale

By definition, grayscale is an image in which the value of each pixel is a single sample. Grayscale images contain a range of gray tones, from white to black, for a better representation of pictures. Figure 32 is an example of a grayscale image of a pavement marking that was ground away. A computer program that would calculate the average grayscale difference of a picture to find a baseline of measurement was then developed.

The first step to determine the gray scale difference (GD) is to take a picture of the pavement with a digital camera showing the area where the marking has been removed, as well as a background image (or undisturbed pavement with no marking). The second step is to upload the picture on a computer and open it with the developed program. Next, manually select an area of removed marking from the image. The user has to be careful not include much of the background picture in the first area selection. The next step is to select an area that will be used as a comparison section against the first area selected. Click on the "Select Background Area" function to select an area next to the first area selected. The background area must contain an undisturbed and clean section of pavement, or, in other words, the pavement area that contains no markings. Figure 33 is an example showing the marking and background areas selected. The program will then automatically calculate a grayscale difference percentage by using the following formula:

$$\text{Gray Scale Difference \% (GD)} = [(G1 - G2) / G1] \times 100$$

Where,

G1: Average grayscale of removed marking area

G2: Average grayscale of background area

Figure 32: Actual picture (on left) and grayscale image (on right) of pavement after marking has been removed.

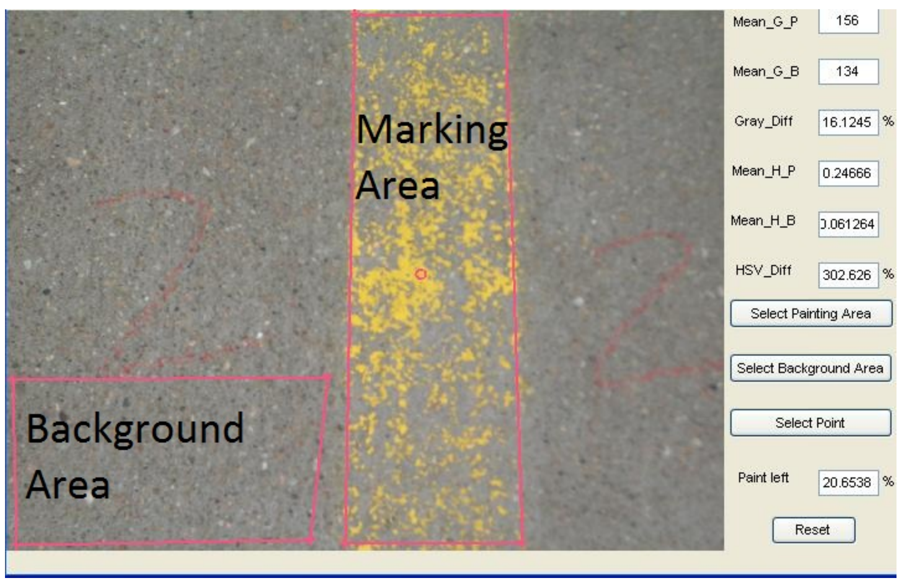

Figure 33: Marking and background areas of picture to be analyzed

Other conditions used to evaluate the pavement after marking removal in this computer analysis were image saturation and the percentage of marking remaining.

5.2.2 Saturation and Marking Left

A standard image is usually analyzed by the red, green, and blue (RGB) model in which the previously mentioned colors are added together in various ways to interpret the other surrounding colors. However, for this research, the hue, saturation, and value (HSV) color space was used because of its capability to rearrange colors and better read bright colors. All the markings on the pavements were bright and reflective yellow, so HSV was a better color model. Saturation is typically used to describe the intensity of the color of an image and works better on bright colors. Similar to the grayscale analysis method, the saturation difference (%) formula below was programmed to be calculated by selecting the area of the marking removed as well as its background. Figure 34 is an example of a saturation image.

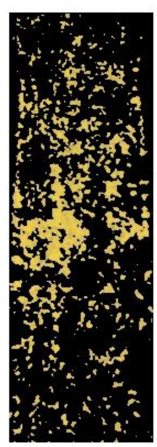

Figure 34: Saturation image of the marking removed on Figure 27.

Saturation Difference % (SD) = [(S1 – S2) / S1] x 100

Where,

S1: Average saturation of removed marking area

S2: Average saturation of background area

Additionally, the marking remaining, representing the amount of marking color left after the marking was removed, was also quantified by this computer program. To do so, the user would have to select the removed marking area and then click on the original color of the marking to allow the program to identify how much color is still present in the selected area.

5.2.3 Image processing Analysis

To achieve the goals set by objectives No. 3 of this research, saturation and grayscale differences were computed, as well as the percentage of the markings left. Some of the results are shown in Table 8.

Table 8: Image Processing analyses results

Marking	**Type**	**Marking**	**Marking Size**	**Grayscale Difference (%)**	**Saturation Difference (%)**	**Paint Left (%)**
Water Blasting	Concrete	Water-Based	12 mils	3.88	17.60	1.55
Dry Ice	Concrete	Water-Based	12 mils	16.07	302.53	20.73

Grinding	Concrete	Water-Based	12 mils	20.12	0.02	4.85
Chemicals	Concrete	Water-Based	12 mils	5.64	3.60	0.74
Chemicals	Concrete	Water-Based	20 mils	7.69	22.57	0.00
Dry Ice	Concrete	Water-Based	20 mils	55.37	15.55	9.78
Scarifier	Concrete	Water-Based	20 mils	15.28	8.47	15.93
Water Blasting	Concrete	Water-Based	20 mils	1.63	38.15	0.11
Dry Ice	Concrete	Solvent-Based	12 mils	11.93	373.09	91.15
Chemicals	Concrete	Solvent-Based	12 mils	6.37	28.00	0.23
Chemicals	Concrete	Solvent-Based	20 mils	8.49	25.58	1.25
Dry Ice	Concrete	Solvent-Based	20 mils	5.84	477.44	30.23
Shot Blasting	Concrete	Solvent-Based	20 mils	8.27	61.33	20.24
Chemicals	Asphalt	Water-Based	12 mils	6.92	16.07	0.07
Shot Blasting	Asphalt	Water-Based	12 mils	7.93	0.25	0.00
Water Blasting	Asphalt	Water-Based	20 mils	13.97	34.38	0.05
Chemicals	Asphalt	Water-Based	20 mils	9.54	59.54	0.00
Grinding	Asphalt	Water-Based	20 mils	11.52	22.47	0.00
Shot Blasting	Asphalt	Water-Based	20 mils	0.13	29.25	0.00
Dry Ice	Asphalt	Water-Based	20 mils	24.06	193.81	2.35
Scarifier	Asphalt	Water-Based	20 mils	16.14	48.66	1.68
Water Blasting	Asphalt	Solvent-Based	12 mils	24.20	96.38	0.25
Chemicals	Asphalt	Solvent-Based	12 mils	7.82	8.32	0.00
Chemicals	Asphalt	Solvent-Based	20 mils	2.29	70.30	0.00
PCD	Asphalt	Solvent-Based	20 mils	8.66	44.91	0.00
Heat Torch	Asphalt	Tape	4 inch	21.88	98.79	0.00
Heat Torch	Concrete	Tape	4 inch	23.74	136.94	0.00

5.3 Guidelines

The GD and SD values calculated were compared against the pictures taken from the sites to find a baseline that would objectively determine whether or not a method was deemed effective. With the aid of image digital processing technology, the

NDOR could develop specific guidelines in their standards instead of the passage that currently says "removed markings shall no longer be visible on the final surface" (Nebraska 2002). For this study, the baseline for this set of data analyzed would be as followed:

(1) If the grayscale difference is below 10% or less, the marking removal is considered effective.

(2) If the grayscale difference is over 10%, then the saturation difference needs to be examined. If the saturation difference is 25% or less, then the marking removal method is effective. If the saturation difference is over 25%, the removal method is not effective. This means that if the GD is greater than 10% and the SD is over 25%, scars from the removal and/or color texture, or marking residues are still apparent on the pavement.

This baseline was used to validate the site tests that were done. It should also be noted that for the baseline would not be applicable to some of the techniques that would leave a very noticeable visible scar. Most grinding techniques, although showing a grayscale and saturation differences that could pass the baseline, would leave scars that will not require the need of image processing to identify. The percentage left could also be used to determine how much paint is left on the pavement. According to the baseline, the chemical method of removal was validated to be the most effective among all of those tested.

5.4 Chapter Summary

This chapter uses the aid of digital image processing technology to develop guidelines and standards that can be used to objectively evaluate the effectiveness of a temporary marking removal method. The recommended baseline of measurement was also used to analyze the data results to validate that chemical removal was the most effective marking removal method.

Chapter 6 Conclusions and Recommendations

Pavement markings are one of the most important items on road for guidance to motorists. Effectively managing temporary markings is of even greater importance because their removal can create ghost striping—leading to driver confusion and potential accidents. Several removal techniques were carefully analyzed through developed evaluation methods. The removal by chemicals was concluded to be the most effective way as both asphalt and concrete pavements had no scars or marking material residues after removal. The process of removal by chemicals is environmentally safe and also cost effective. The state of Tennessee, for example, allows the use of chemicals or/and solvents for temporary marking removal. In section 712.05 of Tennessee Department of Transportation's Standard specifications for road and bridge construction, "Temporary Traffic Control, Pavement Marking Removal," the methods listed as acceptable for marking removal are "solvents and chemicals" (Tennessee 2006). It should be also pointed out that the standard did not however say that the removal by chemical was the most effective among all used.

On the other hand, one of chemical usage disadvantages is that operators have to wait for the chemicals to set before rinsing them off. However, on lengthy projects, operators can apply the chemicals on the markings to be removed, and come back later to wash the chemicals applied earlier. This is feasible because the chemicals would have already set by the time water is applied on all markings to be removed. A truck mounted stripper could be used where the chemicals could be first sprayed and brushed on the markings. After drying, a vacuum recovery system that would concurrently power wash and clean the surface could also be mounted on a truck and allow the surface to be ready to stripe shortly after removal. By saving time, this method increases productivity while yielding better results.

Finally, the feasibility of using digital image processing was recommended. Digital image processing would provide an objective approach that produces easy to understand results when in doubt of a removal technique. For example, for this study, when the grayscale difference of the removed markings is 10% or less, the marking removal would be effective. When the grayscale difference is over 10%, the marking removal method would only be acceptable if the saturation difference is 25% or less.

REFERENCES

Bernold, L. E., Lee, T. S., Koo, J. K., & Moon, D. S. (2010). Automated eco-friendly road stripe removal system. *Automation in Construction, 19,* 6, 694-701

Burrow, M. P. N., Evdorides, H. T., and Snaith, M. S. (2000). Road marking assessment using digital image analysis. *Proceedings of the Institution of Civil Engineers. Transport, 141.*

Ellis, R. and Pyeon, J. (2006). "Development of Improved Procedures for Removing Temporary Pavement Markings during Highway Construction," Proceedings of the Transportation Research Board 85th Annual Meeting, Washington, D.C., January 22-26.

Ellis, R. D., B. Ruth, and P. Carola. (1999). Development of Improved Procedures for the Removal of Pavement Markings during FDOT Construction Projects. Final Report, Florida Department of Transportation, Tallahassee, FL.

Haas,K. (2001). *Methods for traffic stripe removal*, Research notes, Oregon Department of Transportation, OR.

Nebraska Department of Roads. (2002). *Construction manual*. Nebraska Department of Roads, Lincoln, NE.

Oregon DOT Research Notes. (2001). " Methods or Traffic Stripe Removal." RSN02-05, Oregon Department of Transportation, OR.

Tennessee Department of Transportation. (2006). *Standard specifications for road and bridge construction*. Nashville: Tennessee Department of Transportation, TN

Environmental Protection Agency. (2007). *National emission standards for hazardous air pollutants: Paint stripping and miscellaneous surface coating operations at area sources*. Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency, Washington, D.C.

Federal Highway Administration. (2009). *Manual on uniform traffic control devices for streets and highways*. U.S. Dept. of Transportation and the Federal Highway Administration, Washington, D.C.

OSHA. (2009). *OSHA standards for the construction industry (29 CFR part 1926): With amendments as of January 2009*. CCH Incorporated, Chicago, IL.

Appendix A: Survey Questionnaire

IRB # 20101111321 EX

Problem Statement

Proper pavement markings help motorists navigate the roads safely. However, such markings have a finite lifespan due to normal wear and tear of the road. They must be eventually removed and subsequently replaced. Currently, many roads are operating near or beyond capacity, and there is a growing demand for frequent road maintenance or repair. During such activities, highway construction operations often require that traffic be shifted to alternate vehicle paths. When this occurs, the original permanent markings must be removed, and temporary markings must be applied. When the traffic pattern is shifted back after completion of the application of new markings, the temporary markings must be removed. To avoid confusing or misguiding the motorist, removed markings should not be visible under any driving conditions.

Questions
Please complete the following:

Name:
Address:
Company or Agency:
Phone Number:

What criteria/guidance is used by your agency in removal of temporary pavement markings? Please explain or provide a specification reference if different from the ***Manual on Uniform Traffic Control Devices*** (MUTCD).

What pavement marking removal techniques have been used in your state?
☐ Grinding

☐ Chemical
☐ Water Blasting
☐ Sand Blasting
☐ Heat Torching
☐ Shot Blasting
☐ Hot Compress-Air Burning
☐ Oxygen Burning
☐ Black Line Removable Tapes
☐ Asphalt pavement over lays
☐ Other methods: ______________________________

Which pavement marking removal methods have been most commonly used?
☐ Grinding
☐ Chemical
☐ Water Blasting
☐ Sand Blasting
☐ Heat Torching
☐ Shot Blasting
☐ Hot Compress-Air Burning
☐ Oxygen Burning
☐ Black Line Removable Tapes
☐ Asphalt pavement over lays
☐ Other methods: ______________________________

Which pavement marking removal method has been most satisfactory?
☐ Grinding
☐ Chemical
☐ Water Blasting
☐ Sand Blasting
☐ Heat Torching
☐ Shot Blasting
☐ Hot Compress-Air Burning
☐ Oxygen Burning
☐ Black Line Removable Tapes
☐ Asphalt pavement over lays
☐ Other methods: ______________________________

What are the most common problems that you have experienced with pavement marking removal practice? (If any, please specify Removal method, Pavement Type, Marking Type, and Problems)

Pavement Type	***Marking Type***	***Problem***

What type(s) of temporary pavement markings do you use the most? Why?

Appendix B: Complete Marking Results (without cost information)

Type	Removal	Marking	Marking size	Rate (Ft/min)	Completeness of removal	Degree of scarring
Concrete	Water Blasting	Water-Based	12 mils	5.017	4	1
Concrete	Dry Ice	Water-Based	12 mils	1.485294118	1	1
Concrete	Scarifier	Water-Based	12 mils	36.01428571	3	5
Concrete	Grinding	Water-Based	12 mils	63.125	3	5
Concrete	Chemicals	Water-Based	12 mils	12.5825	5	1
Concrete	Chemicals	Water-Based	20 mils	12.605	5	1
Concrete	Dry Ice	Water-Based	20 mils	1.732758621	1	5
Concrete	Shot Blasting	Water-Based	20 mils	57.73563218	4	4
Concrete	Scarifier	Water-Based	20 mils	47.93333333	3	5
Concrete	Grinding	Water-Based	20 mils	45.3	3	5
Concrete	Water Blasting	Water-Based	20 mils	3.114375	4	1
Concrete	Water Blasting	Solvent-Based	12 mils	1.517666667	4	1
Concrete	Dry Ice	Solvent-Based	12 mils	0.313479624	1	1
Concrete	Shot Blasting	Solvent-Based	12 mils	26.59235669	3	4
Concrete	Grinding	Solvent-Based	12 mils	47.85714286	4	5
Concrete	Scarifier	Solvent-Based	12 mils	33.93796359	3	5
Concrete	Chemicals	Solvent-Based	12 mils	10.05	5	1
Concrete	Chemicals	Solvent-Based	20 mils	10.1	5	1
Concrete	Dry Ice	Solvent-Based	20 mils	0.192307692	1	4
Concrete	Shot Blasting	Solvent-Based	20 mils	27.72727273	4	2
Concrete	Scarifier	Solvent-Based	20 mils	36.55	3	5
Concrete	Grinding	Solvent-Based	20 mils	44.49565217	3	5
Concrete	Water Blasting	Solvent-Based	20 mils	1.708333333	5	4
Asphalt	Grinding	Water-Based	12 mils	116.0930233	5	5
Asphalt	Dry Ice	Water-Based	12 mils	24.415	4	5
Asphalt	Scarifier	Water-Based	12 mils	103.893617	5	2
Asphalt	Chemicals	Water-Based	12 mils	15.52666667	5	1
Asphalt	Shot Blasting	Water-Based	12 mils	45.92	5	1
Asphalt	Water Blasting	Water-Based	12 mils	11.5825	5	5

Asphalt	Water Blasting	Water-Based	20 mils	3.84	5	4
Asphalt	Chemicals	Water-Based	20 mils	5	5	1
Asphalt	Grinding	Water-Based	20 mils	45.45454545	5	5
Asphalt	Shot Blasting	Water-Based	20 mils	23.35023041	5	4
Asphalt	Dry Ice	Water-Based	20 mils	22.835	4	5
Asphalt	Scarifier	Water-Based	20 mils	5.452562704	4	5
Asphalt	Water Blasting	Solvent-Based	12 mils	1.923076923	4	5
Asphalt	Dry Ice	Solvent-Based	12 mils	6.832857143	3	5
Asphalt	Scarifier	Solvent-Based	12 mils	3.410641201	3	5
Asphalt	Shot Blasting	Solvent-Based	12 mils	14.33333333	5	5
Asphalt	Grinding	Solvent-Based	12 mils	102.84	4	5
Asphalt	Chemicals	Solvent-Based	12 mils	8.611666667	5	1
Asphalt	Chemicals	Solvent-Based	20 mils	10.166	5	1
Asphalt	Dry Ice	Solvent-Based	20 mils	9.166	3	1
Asphalt	Scarifier	Solvent-Based	20 mils	7.142857143	4	4
Asphalt	Grinding	Solvent-Based	20 mils	77.21666667	5	5
Asphalt	PCD	Solvent-Based	20 mils	1.340694006	5	5
Asphalt	Shot Blasting	Solvent-Based	20 mils	22.36888889	4	5
Asphalt	Water Blas	Solvent-Based	20 mils	1.13825	3	5
Asphalt	Dry Ice	Tape	4 inch	282.3529412	5	5
Asphalt	Heat Torch	Tape	4 inch	27.90697674	5	5
Asphalt	Water Blasting	Tape	4 inch	54.50574713	5	1
Asphalt	Water Blasting	Tape	4 inch	74.91947291	5	1
Concrete	Dry Ice	Tape	4 inch	87.04974271	5	1
Concrete	Scarifier	Tape	4 inch	70.58823529	5	1
Concrete	Grinding	Tape	4 inch	196.25	5	1
Concrete	Heat Torch	Tape	4 inch	63.25301205	5	1
Concrete	PCD	Tape	4 inch	42.2	5	1
Asphalt	Scarifier	Tape	4 inch	2.054187192	5	1
Asphalt	Shot blasting	Tape	4 inch	28	5	1

Appendix C: Complete Cost Information of Removal Techniques

Type	Removal	Marking	Marking size	Cost per Linear FT
Concrete	Water Blasting	Water-Based	12 mils	$1.33
Concrete	Dry Ice	Water-Based	12 mils	$3.37
Concrete	Scarifier	Water-Based	12 mils	$0.19
Concrete	Grinding	Water-Based	12 mils	$0.11
Concrete	Chemicals	Water-Based	12 mils	$0.33
Concrete	Chemicals	Water-Based	20 mils	$0.33
Concrete	Dry Ice	Water-Based	20 mils	$2.89
Concrete	Shot Blasting	Water-Based	20 mils	$0.12
Concrete	Scarifier	Water-Based	20 mils	$0.14
Concrete	Grinding	Water-Based	20 mils	$0.15
Concrete	Water Blasting	Water-Based	20 mils	$2.14
Concrete	Water Blasting	Solvent-Based	12 mils	$4.39
Concrete	Dry Ice	Solvent-Based	12 mils	$15.95
Concrete	Shot Blasting	Solvent-Based	12 mils	$0.19
Concrete	Grinding	Solvent-Based	12 mils	$0.14
Concrete	Scarifier	Solvent-Based	12 mils	$0.20
Concrete	Chemicals	Solvent-Based	12 mils	$0.41
Concrete	Chemicals	Solvent-Based	20 mils	$0.41
Concrete	Dry Ice	Solvent-Based	20 mils	$26.00
Concrete	Shot Blasting	Solvent-Based	20 mils	$0.18
Concrete	Scarifier	Solvent-Based	20 mils	$0.18
Concrete	Grinding	Solvent-Based	20 mils	$0.15
Concrete	Water Blasting	Solvent-Based	20 mils	$3.90
Asphalt	Grinding	Water-Based	12 mils	$0.06
Asphalt	Dry Ice	Water-Based	12 mils	$0.20
Asphalt	Scarifier	Water-Based	12 mils	$0.06
Asphalt	Chemicals	Water-Based	12 mils	$0.27
Asphalt	Shot Blasting	Water-Based	12 mils	$0.15
Asphalt	Water Blasting	Water-Based	12 mils	$0.58
Asphalt	Water Blas	Water-Based	20 mils	$1.74

Asphalt	Chemicals	Water-Based	20 mils	$0.83
Asphalt	Grinding	Water-Based	20 mils	$0.15
Asphalt	Shot Blasting	Water-Based	20 mils	$0.29
Asphalt	Dry Ice	Water-Based	20 mils	$0.22
Asphalt	Scarifier	Water-Based	20 mils	$1.22
Asphalt	Water Blasting	Solvent-Based	12 mils	$3.47
Asphalt	Dry Ice	Solvent-Based	12 mils	$0.73
Asphalt	Scarifier	Solvent-Based	12 mils	$1.95
Asphalt	Shot Blasting	Solvent-Based	12 mils	$0.47
Asphalt	Grinding	Solvent-Based	12 mils	$0.06
Asphalt	Chemicals	Solvent-Based	12 mils	$0.48
Asphalt	Chemicals	Solvent-Based	20 mils	$0.41
Asphalt	Dry Ice	Solvent-Based	20 mils	$0.55
Asphalt	Scarifier	Solvent-Based	20 mils	$0.93
Asphalt	Grinding	Solvent-Based	20 mils	$0.09
Asphalt	PCD	Solvent-Based	20 mils	
Asphalt	Shot Blasting	Solvent-Based	20 mils	$0.30
Asphalt	Water Blasting	Solvent-Based	20 mils	$5.86
Asphalt	Dry Ice	Tape	4 inch	$0.02
Asphalt	Heat Torch	Tape	4 inch	$0.12
Asphalt	Water Blasting	Tape	4 inch	$0.12
Asphalt	Water Blasting	Tape	4 inch	$0.09
Concrete	Dry Ice	Tape	4 inch	$0.06
Concrete	Scarifier	Tape	4 inch	$0.09
Concrete	Grinding	Tape	4 inch	$0.03
Concrete	Heat Torch	Tape	4 inch	$0.11
Concrete	PCD	Tape	4 inch	$0.08
Asphalt	Scarifier	Tape	4 inch	$3.25
Asphalt	Shot blasting	Tape	4 inch	$0.24