DETERMINATION OF THE PRESENCE CONDITIONS OF PAVEMENT MARKINGS USING IMAGE PROCESSING

A Thesis

by

HANCHENG GE

Submitted to the Office of Graduates Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2010

Major Subject: Civil Engineering

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Approved by:

Chair of Committee,	Yunlong Zhang
Committee Members,	Gene Hawkins
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	Paul Carlson
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ABSTRACT

Determination of the Presence Conditions of Pavement Markings

Using Image Processing. (August 2010)

Hancheng Ge, B.E., Beijing Jiaotong University

Chair of Advisory Committee: Dr. Yunlong Zhang

Pavement markings, as a form of traffic control devices, play a crucial role in safely guiding drivers. Restriping pavement markings is an important task in the maintenance of traffic control devices. Every year state agencies spend a lot of money in maintaining pavement markings as the retroreflectivity or durability values of the markings fall below a minimum level. Currently, the most widely adopted method used to determine the presence conditions of pavement markings is by expert observation, a subjective technique that may not provide consistent and convinced results for agencies. Hence, a fast and accurate way to determine the presence conditions of pavement markings can lead to significant cost savings while ensuring driving safety.

In this study, a systematic approach that can automatically determine the presence conditions of pavement markings using digital image processing techniques is presented. These techniques are used to correct the geometric deformity, detect colors of pavement markings, segment images, enhance images, detect edge lines of ideal pavement markings, and recognize the features of pavement markings appearing in the photographs. To better implement the aforementioned techniques, a software package has been developed by Graphic User Interface (GUI) as a platform to simultaneously evaluate the presence conditions of single or multiple pavement markings. The developed software package is able to do operations such as open files, calibrate camera calibration, clip, rotation, histogram display, and detection of edge lines of ideal pavement markings. The above system was tested and evaluated with the photograph datasets provided by the NTPEP Mississippi test deck. The empirical results (when compared with the manual method and expert observation) show that the developed system in this study is accurate and reliable. Additionally, the interactivity of the developed software package is satisfactory due to the feedback from ten volunteers. It is also concluded that the developed system, as an important reference, potentially helps agencies make a better decision in the maintenance of pavement markings with more accurate and speedy evaluation of the presence conditions of pavement markings.

DEDICATION

Dedicated to

My father, Yutong Ge, and

My mother, Qiang Huang

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Firstly, I would like to thank my committee chair, Dr. Zhang, for his great assistance in helping me with my thesis. I could have never finished it without the instruction, advice and help from Dr. Zhang. Also, I appreciate my committee members, Dr. Hawkins, Dr. Carlson, Dr. Cui and former member Dr. Ji, for their continuous guidance and helpful recommendations along the full course of this thesis.

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NOMENCLATURE

MUTCD	Manual on Uniform Traffic Control Devices
FHWA	Federal Highway Administration
NTPEP	National Transportation Product Evaluation Program
PCC	Portland Cement Concrete
MMA	Methyl Methacrylate
VOC	Volatile Organic Compound
ATSSA	American Traffic Safety Services Association
TRC/UAF	Transportation Research Center/University of Alaska Fairbanks
TxDOT	Texas Department of Transportation
MRU	Mobile Retroreflectometer Unit
AADT	Annual Average Daily Traffic
TTI	Texas Transportation Institute
BPNN	Back-Propagation Neural Network
HSV	Hue-Saturation-Value
RGB	Red-Green-Blue
ROI	Region of Interests
GUI	Graphic User Interface
FFT	Fast Fourier Transformation
AASHTO	American Association of State Highway and Transportation Officials

ASTM	American Society for Testing and Materials
JPEG	Joint Photographic Experts Group
GIS	Geographic Information System

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1. INTRODUCTION

1.1 Background

Pavement markings are a very important part of the communication system for road users, playing a critical role in maintaining a safe driving environment, especially at nighttime. Pavement markings help road users maintain proper vehicle position, guide them through different geometric roadway conditions such as curves, and give notification of where passing is allowed. There are four basic types of pavement markings: longitudinal lines, transverse lines, arrows, words and symbol markings, and special markings. The Manual on Uniform Traffic Control Devices (MUTCD) (*1*) defines that pavement markings are commonly placed using paint or thermoplastic materials, although other suitable marking materials can also be used (Federal Highway Administration [FHWA], 2003) (*2*).

Research shows that pavement markings usually have a shorter lifespan than markings applied directly to pavement. Every year, agencies around the world spend a lot of money to maintain pavement markings that need to be restriped when their retroreflectivity or their durability values fall below a minimum level. There are various factors that can account for failures of pavement markings, such as high traffic volume, weather conditions, markings types, roadway surface and environmental factors like ultraviolet radiation. It is very crucial to maintain and preserve the effectiveness of pavement markings for operational safety. In order to ensure the quality function of

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This thesis follows the style of *Transportation Research Record.*

pavement markings, the agencies replace old ones regularly. Therefore, fast and accurate determination of the presence conditions and retroreflectivity of pavement markings can lead to significant cost savings, while ensuring safety at the same time. While there are standard measurement devices for determining retroreflectivity, the determination of the presence condition of a pavement marking is entirely subjective at this time.

1.2 Problem Statement

National Transportation Product Evaluation Program (NTPEP) defined that the durability, or presence, of pavement markings is evaluated based on the overall percentage of marking material remaining, as well as the retained retroreflectivity. Currently, most agencies have replaced markings annually or at slightly longer intervals. However, it is very difficult to make a cost-effective determination of marking conditions while keeping the road safe and guiding drivers effectively. However, there is a need to develop a method to determine the presence conditions of pavement markings accurately and effectively. Expert observation is currently the most widely-used method in estimating the presence conditions of pavement markings. In the NTPEP evaluation program, experts rate the markings on a subjective scale of 1-10, representing the percentage of the marking that remains after the initial application. The final score is conducted by averaging the scores of all the experts. Although visual inspection is an easy and direct way to determine the presence conditions of pavement markings, it is undeniable that the method is subjective, and may not provide a consistent and accurate result. In addition, this evaluation process is labor-intensive, lacking a numerical criterion to determine durability. There is a need to develop a new method as the criteria to determine the presence conditions of pavement markings with higher accuracy and consistency, which could significantly reduce labor costs and supply a more accurate time to repaint pavement markings.

Image processing, a form of signal processing where the input is an image, such as photographs and frames of video, has been widely used in transportation research. While previous studies mainly focused on researching presence conditions of pavement markings based on the expert experience, researchers rarely applied the technique to determining the presence conditions of pavement markings. This research is designed to apply the image processing techniques for determining the presence conditions of pavement markings with a higher accuracy, speed, and consistency. The method, as a theoretical system foundation, has the potential to replace the NTPEP rating procedure and can also be expanded to assess the condition of any pavement markings.

1.3 Research Objectives

The goal of this research is to develop a new method to determine the presence conditions of pavement markings with digital image processing techniques. The research objectives are:

- To develop a camera calibration method that will correct the oblique distortion of images provided by NTPEP;
- To develop a method that can detect the edges of pavement markings in the images;

- To determine the presence conditions of pavement markings in test NTPEP images accurately, developing a method that will be used to judge the correlation between actual images and criteria ones;
- To develop a software package to interface with users; and
- To provide recommendations to implement the core logic for use in assessing any pavement markings in the field.

1.4 Research Benefits

This research develops a new method to determine the presence conditions of pavement markings via digital image processing techniques. The results of this research provide insight into fast and accurate determination of the presence conditions of pavement markings and help agencies make a cost-effective decision for maintaining pavement markings. This method, as a theoretical foundation, has the potential to be applied to evaluate the presence conditions in mobile pavement marking retrereflectometer van associated with the measurement of retroreflectivity by applying one more camera. Agencies could collect both retroreflectivity and presence condition data simultaneously with lower cost and better service. Additionally, this method could be used to control pavement marking quality, a process which usually requires that pavement markings applied by contractors should cover pavement surface within the area of markings with certain percentage.

1.5 Thesis Organization

This thesis is composed of six sections. In Section 1, background information on the presence conditions of pavement markings is presented, followed by research problems, objectives, and benefits. In Section 2, literature related to pavement marking issues such as types, performance evaluation, and durability are reviewed and the applications of image processing techniques in pavement markings are described. In Section 3, image processing methods developed in this study are presented. In Section 4, the introduction of Matlab, Graphic User Interface (GUI), and the developed software package as a platform to determine the presence conditions of pavement markings are described. In Section 5, the photograph datasets used to test the developed system are introduced. The comparisons with the manual method and the expert observations in the determination of presence conditions of pavement markings are also summarized and analyzed by using criteria photographs and test deck photographs from NTPEP's Mississippi Test Deck. The evaluation of interactivity for the developed system from 10 volunteers is presented as well. In Section 6, a summary of the main contents of this study, followed by the findings and limitations, is presented. Finally, future works in the automatic determination of presence conditions of pavement markings using image processing techniques are suggested.

2. LITERATURE REVIEW

2.1 Introduction

In this section, literature related to the basic information of the pavement markings and previous studies on the determination of the durability/presence conditions of pavement markings is presented. The first part provides an introduction to the basic concept of pavement markings, while the second part provides a general idea of the durability/presence conditions of pavement markings and previous research related to the determination of their durability/presence conditions. The last part includes applications of image processing techniques used in the field.

2.2 Pavement Markings

According to the Manual on Uniform Traffic Control Devices (MUTCD) (*1*), pavement markings on highways provide guidance and information for the road user. They give drivers directional information associated with road signs and signals, ensuring that drivers remain in an acceptable part of the lane and also give drivers effective information with respect to the course of the road (such as the no-entering, overtaking zones, etc). For markings to be visible at night, they should be retroreflective unless ambient illumination ensures adequate visibility (*3*).

Every year transportation agencies spend a lot of money in applying and maintaining pavement markings. In 2000, the estimated cost in application and maintenance of pavement markings by state transportation agencies, as well as 13

Canadian provinces and territories, U.S. counties, and U.S. cities was $1,548,616,821 on 3,818,688 centerline-miles of highways (*3*). Transportation agencies found that it was difficult to maintain good retroreflectivity over a long period of time. The total cost is influenced by direct or indirect factors, such as the utilization of new and diverse materials with new technologies, a shortage of skilled labor, the increased number of older drivers, and increases in traffic. The large variety of new products, combined with the lack of a widely-accepted standard test for pavement marking performance, further complicates the evaluation of these products.

2.2.1 Different Types of Pavement Markings and Their Characteristics

Pavement markings consist of longitudinal lines, transverse lines, words, numbers and symbols. Water-borne paint is most commonly used for markings, followed by thermoplastic, tapes and epoxies (*3*). Traffic paints, as the most commonly used marking type in US, encompass roadway, zone and airport markings with spray or extrusion application. However, traffic paints often discolor or do not bond well initially, and also have the shortest life-span and poor nighttime visibility (*4*). Most agencies say that water-borne markings more cost-effective than other material types. Thermoplastics markings, which often perform poorly on Portland Cement Concrete (PCC) surfaces, generally have better retroreflectivity ratings and longer service times with faster drying times and good durability when compared to similar traits of the traffic paints, especially under night and wet conditions (*5*). The high initial retroreflectivity of the thermoplastics exists because they are manufactured at factories with better quality standards. The best way to apply thermoplastics markings and assess their bonding strengths on PCC surface was developed by Ahmed et al. (*6*). ASTM: D 4541-95 (Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers) was used to evaluate the pull-off strength of the coating. The weak tensile forces between markings and pavement surfaces lead to the failure of adhesion. The two types of adhesion failures on PCC surfaces are between epoxy glue and thermoplastic coating, and the separation of thermoplastics from pavement surface. In terms of treatment methods, sandblasting, wire-brushing, grinding or scarifying, and water blasting can be used on four different strips. It was discovered that the grinding or scarifying treatment was the best technique to use on asphalt and PCC surfaces. For preformed tapes, the major problem is that retroreflectivity levels deteriorated drastically with a fast rate, despite being easily installable with good initial retroreflectivity values and good adhesion (*5*). Epoxy is generally applied on PCC pavement surfaces for better visibility and durability. However, it is occasionally difficult to apply, and also needs a long drying time as compared to others (*7*). As the study of Holzschuher et al. showed (*8*), Polyester has a better performance than that of paints with an average service life of two to three years, but also has a longer drying time. Methyl Methacrylate (MMA) markings are more suitable to be applied at low temperatures, as they can provide services for a longer time with better retroreflectivity values than other types of markings under cold climatic conditions (*5*).

2.2.2 Material Selection Criteria

Materials used in pavement marking application have to be evaluated on certain factors, such as retroreflectivity, durability, life-cycle cost, type of line, pavement surface, climatic conditions, traffic volume and type of street and highway. Recently, the level of volatile organic compound (VOC) has also been taken into account to meet environmental regulations.

2.2.3 Pavement Marking Performance Evaluation

Transportation agencies and organizations such as the American Traffic Safety Services Association (ATSSA) (which gives training courses and seminars at the transportation agencies) usually take a rigorous and disciplined approach to conducting performance evaluations for pavement markings in order to reduce the maintenance costs while meeting specifications and guidelines. Such evaluations take place both before and after the installations. Materials are evaluated using standardized evaluations, in-house evaluations, or a combination of both to ensure their compliance with the requirements before placement and during scheduled maintenance service after the placement [9]. In the procedure of performance evaluations, the line quality, including line thickness, bead distribution, quantity of material, and measurement of the initial retroreflectivity is inspected by agencies. For most American agencies, the general practice is to evaluate new markings from 3 days or less to more than 1 month after installation (*3*). Transportation Research Center of University of Alaska Fairbanks (TRC/UAF) researchers evaluated markings based on an average of the performance factors for expected service life, visibility, durability and overall costs (*5*). Researchers and staff from TxDOT (at a conference for pavement marking performance) recommended that a single statewide retroreflectivity performance specification be established, using threshold values of 250 mcd/m2/lux for white colored markings and 175 mcd/m2/lux for yellow colored markings (*9*). Through these recommendations, evaluations can use either objective or subjective techniques.

Objective Evaluation

Pavement markings can be objectively evaluated by using retroreflectometers, which measure the retroreflectivity of markings. Conventional 30-m hand-held retroreflectometers used to be widely used as conventional measuring instruments, but transportation agencies have recently preferred to use 30-m mobile retroreflectometer units (MRU). MRUs provide multiple advantages, among them a smaller number of person-hours, faster data acquisition, reduced risk to the workers, lesser traffic control (for examining longer section of roads) and lower cost for data collection (*8*). On the other hand, errors in measurement and a lack of experienced personnel were identified as some of the disadvantages of the MRUs. Florida DOT produced a study of MRU characteristics, among them safety and economic benefits, functional issues, etc. (*8*).

As an important issue, the wet performance evaluation for pavement markings has been carried out by several agencies compared to the dry performance evaluation frequently adopted by most of the agencies. A special technique developed for the wet pavement evaluations was introduced in the report made by Migletz et al. (*3*). The retroreflectivity is measured for dry sections of 1.22 meters (4 ft.) and then these sections are wetted by application of five back-and-forth passes of a paint roller saturated with water. Wet retroreflectivity was then measured after allowing the water to drain off from the sections for 1 minute (*10*). To measure retroreflectivity at least one month after striping in order to obtain a more accurate representation of long-term pavement marking performance and to measure retroreflectivity for centerlines of undivided two-way roadways in both directions for obtaining adequate data are concluded and recommended for objective evaluations in the study (*9*). However, in the objective evaluation, the variability as a serious problem should be overcome by taking necessary actions. Significant variability was observed in the retroreflectivity data that was collected even though the AADT and environmental conditions were similar between different roadways (*10*). Differences in the application and installation methods of markings by different striping crews, the threshold values for retroreflectivity measurements set during the device calibration, the misalignment of the Laserlux® device, the orientation of the laser reflection off the beads, , , percentage and depth of the glass beads in the paint, dirt on the markings and background color of the pavement are potential to cause such inconsistency (*11*).

Subjective Evaluation

As its name implies, subjective evaluation depends upon the observation experience of staff and researchers involved in the evaluation. It is more widely adopted by agencies than objective evaluation. With this kind of evaluation, pavement markings are first rated on a subjective scale of 1-10, and then judged with the standards and guidelines. Subjective evaluations include the evaluation of the markings' durability, bead retention, color scale, wet performance pocket microscope test, and color chart. In most pavement marking studies, subjective evaluation is used to indicate the minimum retroreflectivity and visibility (daytime and night time) (*5*). Previous studies have been criticized for a minimum reflectance of 100mcd/m2/lx as a threshold for determining the subjective ratings which were given from one indicating very poor or not adequate reflectance to more than adequate or superior reflectance. Lower threshold values were considered for yellow in some studies, as compared to threshold values in white colored markings (*10*). NTPEP test deck has been developed to evaluate the general performance and bead retention based on retroreflectivity and durability (*3*). Studies sponsored by Minnesota DOT (MnDOT) and New Jersey DOT (NJDOT) applied subjective evaluations to derive reasonable retroreflectivity threshold values for pavement markings, depending on actual driving evaluations. Both studies involved a large sampling of the public (from different age groups) to values of retroreflectivity that drivers were comfortable with. Some results from these studies were concluded and summarized as follows (*12*) :

- Driver satisfaction increased significantly with the increase in the level of retroreflectivity from 0 to 120 mcd/m2/lux in the MnDOT study and from 0 to 125 mcd/m2/lux in the NJDOT study.
- Driver satisfaction increased slightly as the retroreflectivity increased from about 120 mcd/m2/lux to 200 mcd/m2/lux.
- Driver satisfaction remained constant as the retroreflectivity rose above 200 mcd/m2/lux.

Photometric-Based Evaluation

A study co-sponsored by Virginia DOT and the FHWA attempted to find the minimum retroreflectivity levels for pavement markings. Since these measurements depend on visibility distances, it was an objective evaluation. In this study, the dosage factor, calculated as the product of the apparent marking size and the retroreflectivity at threshold, was used to produce minimum retroreflectivity levels by a measure of the total light energy from the individual markings on the road. Recommended minimum retroreflectivity values were derived as shown in Table 1 based on the dosage factor and driver preview need time of 2.0 and 3.65 seconds.

Table 1 Recommended Minimum Retroreflectivity

Speed (mph)	**Preview Time = 2.0 sec**	**Preview Time = 3.65 sec**
65	117.0	711.5
55	70.9	431.0
45	38.8	236.1
35	18.3	111.1
25	6.6	40.5

2.3 Previous Studies on the Durability of Pavement Markings

In general, pavement marking performance is judged based on two criteria: retroreflectivity and durability. Durability is defined as the percentage of pavement marking remaining on a surface and the ability to retain retroreflectivity over time.

The study made by Montebello and Schroeder (*13*) in 2000 focused on providing guidelines for pavement markings in county and city highways. It found that for roadways with high AADT, a more durable product may be a better alternative than paint, because it can reduce worker exposure to traffic while also maintaining a visible line for at least one to four years. Bead application plays an important role in the retroreflectivity of all pavement markings materials. Proper application can lead to increased nighttime visibility and greater line durability. Additionally, Montebello and Schroeder estimated the service life of pavement marking products during their study. For example, they found that Epoxy could be used for 4 years, and Tape could be used more than 6 years.

In the study of Virginia Department of Transportation (VDOT) (*14*), the effectiveness of pavement markings was investigated. They examined the durability and the cost-effectiveness of nineteen of Virginia's pavement materials, taking paint contract sizes into consideration. The durability (service life) was estimated by VDOT's district staff responsible for maintaining the various kinds of markings on VDOT maintained roads. They used the retroreflectivity value of 150mcd/m_2/lux as the criteria to determine the end of service life of pavement markings. The conclusion they made was that the large paint contract was the most cost-effective for two lane roads under most traffic volume conditions and for four- and six-lanes low-volume roads. For the durability of pavement markings, the order from most to least cost-effective is polyurea, thermoplastic, epoxy, and waffle tape for the low-volume roads.

In 2001, Migletz et al. (*5*) evaluated the service life of durable, longer lasting pavement markings sponsored by the Federal Highway Administration (FHWA). This study used the cumulative passages and the number of months required for the retroreflectivity to drop below a minimum threshold value as the durability criteria to determine when the pavement markings needed to be repainted. Six different kinds of markings were evaluated for the durable performance in this study. They established criteria for the minimum retroreflectivity value used to define the end of a pavement markings service life. Finally, statistical modeling was used to determine the relationship between decreasing retroreflectivity with time (in months) and cumulative traffic passages in freeway and non-freeway.

Hawkins et al. (*9*) studied the determination of the durability of various pavement materials on concrete pavements in Texas. For NTPEP testing, the authors invited Texas Transportation Institute (TTI) research staff to rate each of the 313 total materials as “good,” “marginal,” or “poor” based on a combination of the retroreflectivity and durability performance on concrete pavements. They concluded that epoxy materials and preformed tapes should be used on PCC roadways and thermoplastic only should be used for short-term applications with low to medium traffic. In 2003, they also conducted a study to determine the durability of various pavement materials on concrete pavements in Texas and made the final recommendations, as shown in Table 2.

Table 2 Recommended Pavement Marking Materials for Concrete Pavements

Traffic Characteristic[s]	**Pavement Remaining Service Life**		
	0-2 Years	**2-4Years**	**>4 Years**
AADT<10,000	TxDOT Thermo[b]	Epoxy	Epoxy
10,000<AADT<50,000	TxDOT Thermo[b]	Epoxy	Epoxy
AADT>50,000	Epoxy	Epoxy	Performed Tape
Commercial Vehicles or Heavy Wearing/Turning	Epoxy	Performed Tape	Performed Tape

Note: Contrast makings or profiled markings may be used to improve visibility and safety as needed.

[a] AADT Average Annual Daily Traffic.

[b] Primer/sealer required prior to application of current TxDOT spec. thermoplastic on bare concrete.

Abu Lebdeh Ghassan et al. (*15*) studied the change in retained retroreflectivity of waterborne paint and spray thermoplastic pavement markings, before and after winter maintenance. They concluded that if the pertinent initial conditions are known, such as fall retroreflectivity, marking material, and line type, it is possible to predict future performance for a given variable such as annual winter maintenance. The fall retroreflectivity and product type are predictors of spring retroreflectivity. In general, as fall retroreflectivity increases, the percent retroreflectivity retained in the spring decreases in a predictable fashion for both waterborne and spray thermoplastic pavement markings.

2.4 Applications of Image Processing in the Pavement Marking Field

The measurement of the performance of pavement markings is very important for agencies around the world to guarantee the effectiveness of markings and determine when the old pavement markings need to be replaced or restored. A visual rating system has been widely used to measure the performance of pavement markings. More recently, advances in image processing techniques have provided an opportunity for the use of this technology in the measurement of pavement markings.

M. P. N. Burrow et al. (*16*) developed a method to automatically measure the road marking erosion via digital video image analysis techniques. Techniques such as image digitization and image segmentation were used to analyze the image to ascertain whether the picture elements are clearly road markings or not. Furthermore, the authors used the technique of image enhancement to remove misclassified picture elements. Finally, the determination of road marking erosion can be produced via comparing the ‘ideal’ road markings based on the feature description. The test results demonstrated that the method developed in this paper was more accurate and reliable than manual method in the determination of the road marking erosion.

A paper written by Joel C. McCall and Mohan M. Trivedi (*17*) presented a solution to road lanes detection problem using the steerable filter, which can provide robustness to various environment such as lighting changes, shadows and road markings variation. According to the test results for a 9000-frame image sequence that includes various road conditions, the method they developed has been shown to have a strong ability of robustness and high accuracy for the detection.

In 2006, Collado et al. (*18*) studied road detection and classification for Driver Assistance Systems, which tracks several road lanes and identifies the type of lane boundaries. From the study, an algorithm was developed that used an edge filter to extract the longitudinal road markings to which a straight line model could be fitted. Based on this, the position, orientation and type of road lanes can be automatically detected from that the camera can be seen.

Jin Huang et al. (*19*) focused on the study of the automatic extraction of road lane markings from high resolution arterial image. Multi-resolution image analysis-based methods and Anisotropic Gauss filtering have been used in their study. In the paper, road centerline, road surface and pavement markings could be extracted from the high resolution arterial image. The experimental result using the stereo digital arterial image dataset supported the conclusion that the method the authors developed has a satisfied performance of the extraction of road lane markings.

In 2009, Masafumi Noda et al. (*20*) developed a method for the recognition of pavement markings on the generated road surface from in-vehicle camera images. The method combined the techniques of projection transformation, image blurring, image clipping and a pattern learning algorithm. According to the experimental results, the method had a good performance in the recognition of pavement markings and overcame the effect of various real environments.

3. METHODOLOGY

3.1 Introduction

This section, which consists of six sections, is organized to present methodology proposed in this study. The first part provides an introduction to the basic concepts of Hough transformation for edge detection. The second part briefly discusses the geometric deformity that occurs in NTPEP photographs, and how to correct such oblique distortion through camera calibration. The third part gives a general idea of the statistical pavement marking color model proposed for extracting colors of pavement markings. In the fourth and fifth parts, image segmentation used to identify pavement markings in the image and image enhancement applied to improve the quality of image after segmentation are discussed, respectively. Finally, a method to determine the final presence conditions of pavement markings is developed and described in the last part.

3.2 Hough Transformation for Edge Detection

The Hough transformation (first introduced by Paul Hough (*21*) and expanded to the field of computer vision by Dana H. Ballard (*22*)) is a powerful technique used to extract features of a particular shape from an image. Commonly, it is used to detect regular shapes, such as lines, circles, ellipses, and so on. In order to accomplish this purpose, there is a need to detect pixels located at boundaries of desired shapes within an image. The main advantage of Hough transformation is a good tolerance of image noise.

In this study, Hough transformation is only applied in the detection of lines such as edge lines of pavement markings. In fact, the simplest Hough transformation is the linear transformation for detecting straight lines. It can be assumed that there is a straight line described as $y = k * x + b$ and plotted for each pair of image points (x, y), as illustrated in Figure 1. The most expressed characteristics of this straight line are its parameters (the slope parameter k and the intercept parameter b), not image points x or y. Therefore, this straight line can be described in the $k - b$ coordinate system based on a dual relationship with the $x - y$ coordinate system, as shown in Figure 1.

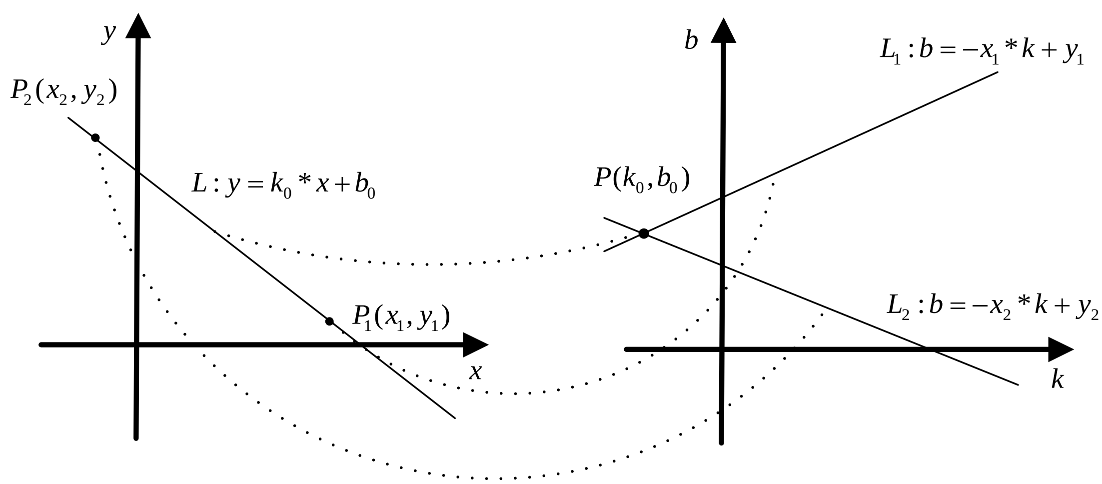

Figure 1 A Dual Relationship between the $x - y$ and $k - b$ Coordinates Systems

Each point of the straight line in the $x - y$ coordinate system is connected with a straight line in the $k - b$ coordinate system. Correspondingly, the intersection point of straight lines in the $k - b$ coordinate system respect lines in the $x - y$ coordinate system. Therefore, the straight lines in an image can be estimated via the investigation of intersection points in the $k - b$ coordinate system. However, it should be noted that the slope will approach infinity when a straight line is vertical to the X-axis. In order to overcome this problem, the formula of a straight line can be re-expressed as $r = x * \cos\theta + y * \sin\theta$ in the polar coordinate system, where r is the distance from the origin to the straight line, and $\theta \in [0, \pi]$ is the orientation of r with respect to X-axis, as shown in Figure 2. Similarly, points (x_i, y_i) of the straight line in the $x - y$ coordinate system correspond with sinusoidal curves that have an intersect point in the polar coordinate system, as seen in Figure 2.

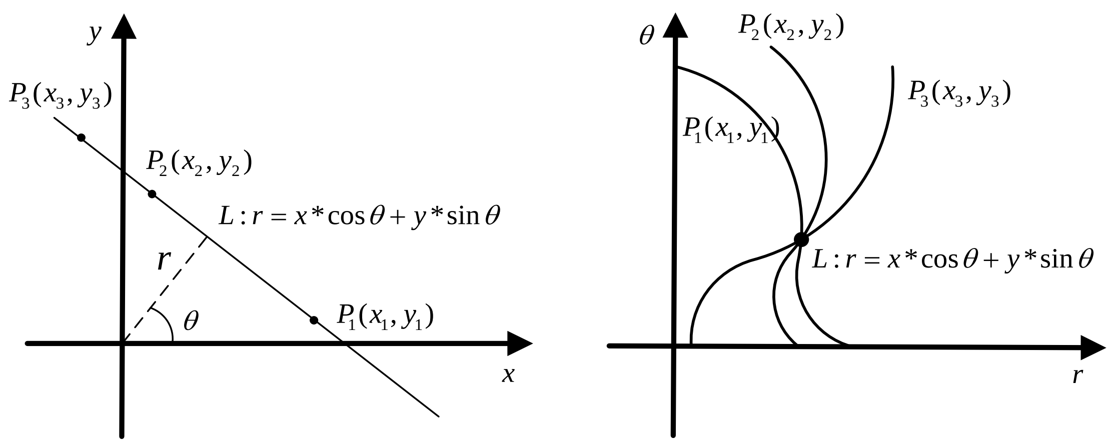

Figure 2 The Straight Line in Polar Coordinates System

Therefore, the detection of straight lines in an image strongly relies on the estimation of corresponding intersection points in the polar coordinate system. The general steps are as follows:

1. Find all edge points in the image using edge detection techniques.
2. Quantize the polar space with cells.
3. Each cell will be incremented by 1 if it corresponds to an edge point within an image.

4. The result is a histogram as a vote matrix showing the frequency of the correspondence to edge points.
5. The large valued cells, selected based on the threshold value, are considered as intersection points corresponding to lines in the image.

The test implementation finds that Hough transformation is capable of detecting edge lines of pavement markings, as shown in Figure 3. After the process of edge detection in the original image (Figure 3 (a)), all intersection points (the number of edges that the system has detected) are found and marked by rectangular boxes in the polar space as shown in Figure 3 (b) and (c). In 3-D view (Figure 3 (c)), intersection points are represented by peaks. Figure 3 (d) demonstrates all detected edges with green lines.

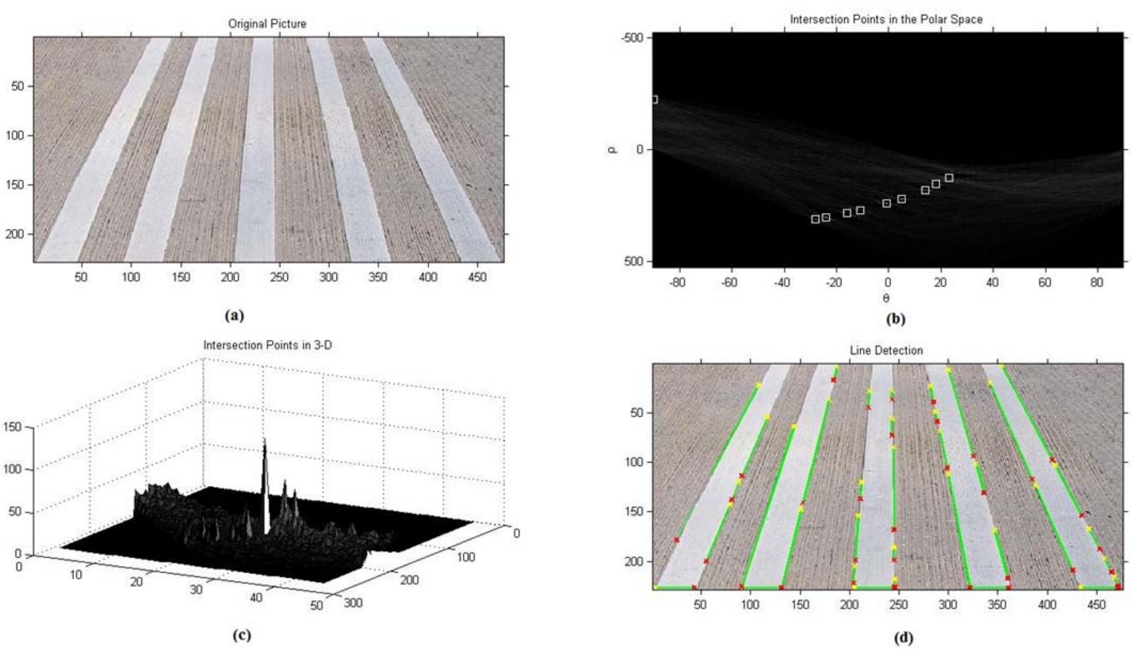

Figure 3 Test Implementation of Hough Transformation

3.3 Camera Calibration

In the field of pavement markings, a camera is frequently used to record the presence situation of pavement markings in both real-world and experimental decks. However, geometric deformity would occur when transferring between the 3-D real-world coordinates and the responding 2-D image coordinates when taking an image with a camera (*23*).

Since all images adopted in this study are from NTPEP test deck photo logs such as the one shown in Figure 4, it is apparent that such images have oblique distortion due to the angle between the camera and the road plane. Without the correction of geometric deformity, it would be difficult to detect the exact edges of each pavement marking to segment them in images, as a part of one marking could overlap with another one in the vertical direction, as the red line illustrates in Figure 4. Therefore, before the further analysis, in order to make such image markings parallel, camera calibration is an essential process for such geometric deformity as a crucial pre-processing for the whole work, which could significantly affect the following image processing steps and the accuracy of the presence determination for pavement markings.

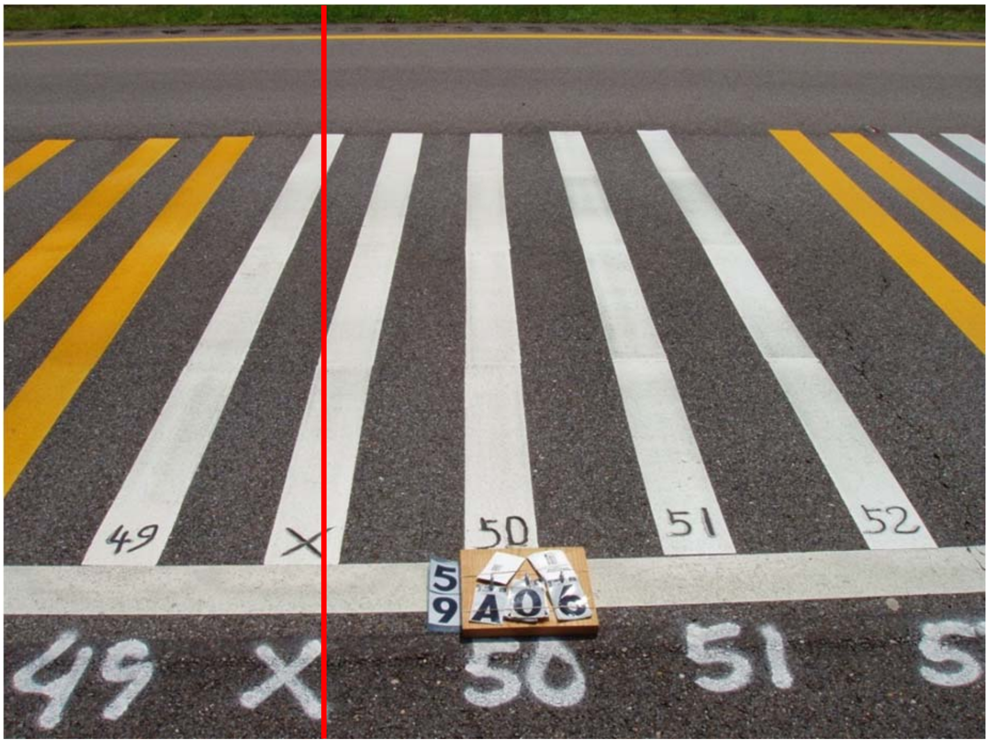

Figure 4 A Sample Image from NTPEP

3.3.1 Camera Model

A camera's calibration model recovers the intrinsic and extrinsic camera parameters such as camera height, focus length, angle between camera and the ground, the aspect ratio, the position of the camera center, camera’s heading in world coordinates, etc. The camera model widely used by researchers is the one firstly proposed by Schoepflin et al. (*24*), and an example model, generic enough to suit different camera settings and orientations, is demonstrated in Figure 5. In order to simplify the calibration process and enhance the efficiency, it is assumed that that the intrinsic camera parameters are fixed (except for focus length).

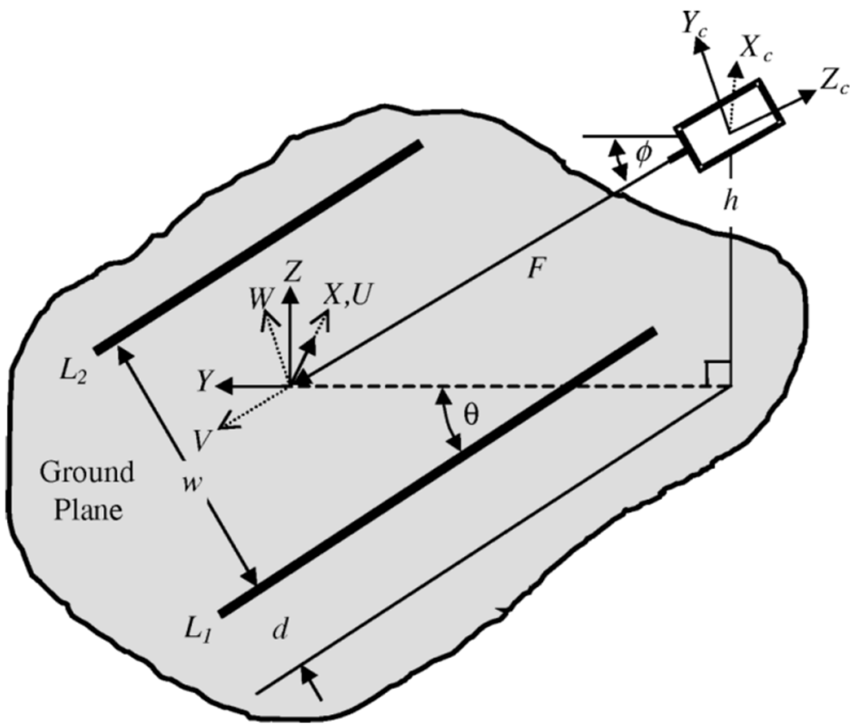

Figure 5 Employed Camera Model (*25*)

Before establishing a camera model, three coordinate systems (*25*) need to be defined: the world coordinate system $O - XYZ$, the camera coordinate system $C - X_cY_cZ_c$, and the camera-shift coordinate system $O - UVW$. The model is conducted as a set of parallel edges of pavement markings denoted as L_1, L_2 through a digital camera, with the assumption that the digital camera is utilized at a height h (as shown in Figure 6). C is the optical center of a camera with the projection from 3-D to 2-D. The angle between Y axis and the edge of pavement markings is defined as the pan angle θ, and the width of pavement markings at test decks is defined as w.

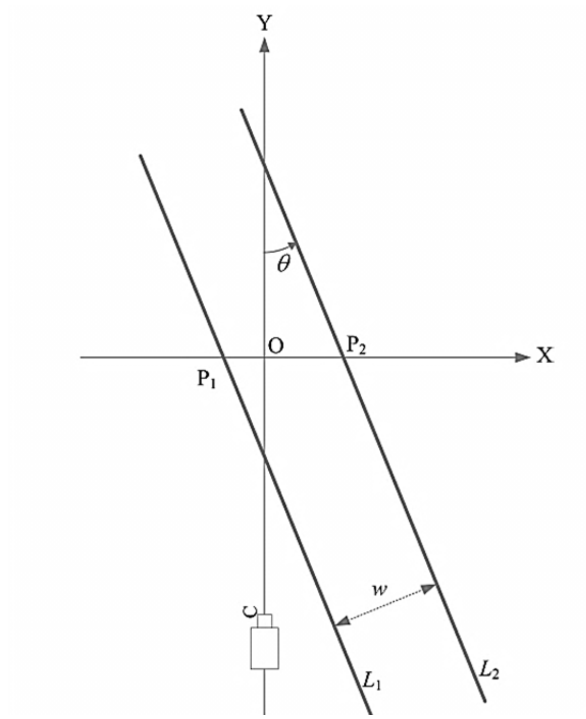

Figure 6 Bird's View of the World Coordinate System

On the other hand, as shown in Figure 7, the camera can be tilted at an angle $\emptyset$ with respect to the road from the side view of the world coordinate system. Point O is located on the ground as the objective, and the distance between a camera and the objective on the ground is denoted as $F = h * \csc \emptyset$, which is perpendicular to the image plane. It should be noticed that there is a basic assumption that the road is planar and the rotation of the ground plane about Z_c axis is negligible based on the analysis (*24, 25*). They pointed out that there is theoretically less than a 10% bias in distance measurements for road grades of 2% or less when using the reduced (two-angle) camera model, as the one adopted in this study.

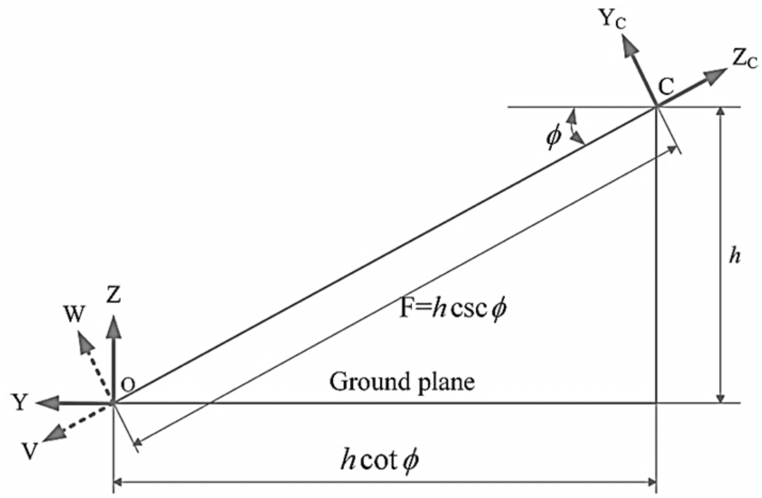

Figure 7 Side View of the World Coordinate System

Based on the proposed camera model, the projection of an image in the camera coordinate system can be viewed, as illustrated in Figure 8.

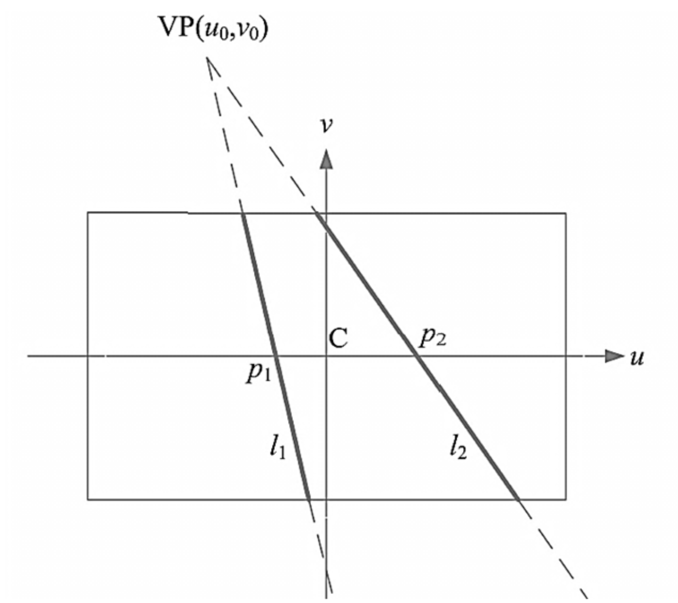

Figure 8 The Geometry in an Image with a Vanishing Point

There are two equations used to describe the relationship between the image coordinate system and camera's coordinate system with focus length f as following:

$$u = -f\frac{X_c}{Z_c} \quad (1)$$

$$v = -f\frac{Y_c}{Z_c} \quad (2)$$

As shown in Figure 7, it is obvious that the camera-shift coordinate system $O - UVW$ can be obtained from the world coordinate system $O - XYZ$ by rotating an angle $\emptyset$ around X axis. It can be expressed with the following equation (3).

$$U = X$$

$$V = Y * \cos\emptyset - Z * \sin\emptyset$$

$$W = Y * \sin\emptyset + Z * \cos\emptyset \quad (3)$$

Since the pavement markings are on the ground, the height of objectives can be considered as $Z = 0$. Therefore, the equation (3) can be further simplified with the following set of equations:

$$U = X$$

$$V = Y * \cos\emptyset$$

$$W = Y * \sin\emptyset \quad (4)$$

As the same way, the relationship between the camera coordinate system $C - X_cY_cZ_c$ and the camera-shift coordinate system $O - UVW$ can be described as following equations:

$$X_c = U = X$$

$$Y_c = W = Y * \cos\emptyset$$

$$Z_c = -V - F = -Y * \sin\emptyset \; - F \tag{5}$$

Next, putting equation (5) into (1) by replacing parameters $X_c,\ Y_c,\ Z_c$ produces:

$$u = -f\frac{X_c}{Z_c} = -f\frac{X}{-Y * cos\emptyset - F} \tag{6}$$

$$v = -f\frac{Y_c}{Z_c} = -f\frac{Y * \sin\emptyset}{-Y * \cos\emptyset - F} \tag{7}$$

A vanishing point $VP(u_0, v_0)$, a prerequisite of camera calibration, is formed by intersecting a pair of parallel edge lines of pavement markings in the image coordinate system shown in Figure 8. The rectangular region represents the image from a camera where C is the center of image as the center of camera, l_1 and l_1 are denoted as edge lines of pavement markings in the image, p_1 and p_2 are denoted as two intersection points of edge lines l_1 and l_1 with the u axis.The vanishing point $VP(u_0, v_0)$ is located at a position where $Y \to \infty$ and $X = Y * tan\theta$ in the world coordinate system. Based on the statement above, the position of the vanishing points can be evaluated with the equation (6) and (7) as following:

$$u_0 = \lim_{Y\to\infty} f\frac{X}{Y * cos\emptyset + F} \; = f * \tan\theta * \sec\emptyset \tag{8}$$

$$v_0 = \lim_{Y\to\infty} f\frac{Y * \sin\emptyset}{Y * \cos\emptyset + F} = f * \tan\emptyset \tag{9}$$

Additionally, the distance between two intersection points p_1 and p_2 in Figure 5 can be described in the u-coordinate as following:

$$\Delta u = u_2 - u_1 = \frac{fX_1}{F} - \frac{fX_2}{F} = \frac{f * w * \sec\theta}{F} = \frac{f * w * \sec\theta}{h * \csc\emptyset} \tag{10}$$

3.3.2 Camera Parameters Estimation

In terms of the camera model proposed above, parameters including focus length f, the pan angle θ, and the tilt angle $\emptyset$ need to be estimated after acquiring the vanishing point $VP(u_0, v_0)$ based on equations (8) and (9). After squaring equation (8) and applying equation (9), it can be got that:

$$u_0{}^2 = (f * \tan\theta * \sec\emptyset)^{\,2} = (f^2 + v_0{}^2) * (sec^{\,2}\theta - 1) \tag{11}$$

$$u_0{}^2 + (f^2 + v_0{}^2) = (f^2 + v_0{}^2) * sec^{\,2}\theta \tag{12}$$

From equations (9) and (11) above, the following can be arranged:

$$f^2 = v_0{}^2 * cot^{\,2}\emptyset = v_0{}^2 * (csc^{\,2}\emptyset - 1) \tag{13}$$

Furthermore, by rearranging the above equation (13),

$$f^2 + v_0{}^2 = v_0{}^2 * csc^{\,2}\emptyset \tag{14}$$

Applying equation (14) into equation (12),:

$$\frac{u_0{}^2 + (f^2 + v_0{}^2)}{f^2 + v_0{}^2} = \frac{(f^2 + v_0{}^2) * sec^{\,2}\theta}{v_0{}^2 * csc^{\,2}\emptyset} \tag{15}$$

From equation (10), equation (15) can be further expanded to:

$$\frac{u_0{}^2 + (f^2 + v_0{}^2)}{f^2 + v_0{}^2} = \frac{(f^2 + v_0{}^2) * \Delta u^2 * h^2}{v_0{}^2 * f^2 * w^2} = \frac{f^2 + v_0{}^2}{(\frac{v_0 * w}{\Delta u * h})^2 * f^2} \tag{16}$$

Considering f^2 as a variable X, then:

$$\left[\left(\frac{v_0 * w}{\Delta u * h}\right) - 1\right] * X^2 + \left\{\left(\frac{v_0 * w}{\Delta u * h}\right) * u_0{}^2 + v_0{}^2 * \left[\left(\frac{v_0 * w}{\Delta u * h}\right) - 2\right]\right\} * X - v_0{}^4 = 0 \tag{17}$$

In order to solve equation (17) as a quadratic equation, parameters such as the position of the vanishing point $VP(u_0, v_0)$, the width of pavement markings w, the distance between two intersection pointes of edge lines with the u-coordinate in an image Δu, and the camera height h need be calculated and given as prerequisites (based off of the statements in previous parts). It should be noted that the correct solution of equation (17) must be unique and positive. The correct solution should be satisfied by equation (10), especially if there are two positive solutions.

After solving equation (17), the parameters used for calibrating the camera are as following:

$$f = \sqrt{X} \quad (18)$$

$$\emptyset = tan^{-1} \frac{v_0}{f} \quad (19)$$

$$\theta = tan^{-1} \frac{u_0}{f * \sec \emptyset} \quad (20)$$

3.3.3 Transformation between Two Coordinate Systems

After the camera parameters have been investigated in previous sections, there is a need to construct the transformation between the world coordinate system and the image coordinate system in order to eliminate the geometric deformity in the image. In the world coordinate system, the distance between two intersection points P_1 and P_2 in $X -$ coordinates can be expressed so that:

$$\Delta P = w * \sec \theta \quad (21)$$

Meanwhile, the projection of these two intersection points is located at the image as points p_3 and p_4 shown in Figure 9, and the distance between them in the $u -$coordinates can be expressed and denoted as $\Delta u'$. Since Δu is the distance between points p_1 and p_2, it can be easily inferred that:

$$\frac{X}{u} = \frac{w * \sec\theta}{\Delta u'} \tag{22}$$

$$\frac{\Delta u}{\Delta u'} = \frac{v_0}{v_0 - v} \tag{23}$$

After equations (22) and (23) are combined to eliminate $\Delta u'$, it can be determined that:

$$X = \frac{v_0 * w * u * \sec\theta}{\Delta u * (v_0 - v)} \tag{24}$$

Based on the equations (6) and (7), it can be seen that:

$$\frac{u}{v} = \frac{X}{Y * \sin\emptyset} \tag{25}$$

Similarly, by applying equation (24) into (25), Y can be expressed as:

$$Y = \frac{v * X}{u * \sin\emptyset} = \frac{v * v_0 * w}{\Delta u * (v_0 - v) * \sin\emptyset * \cos\theta} \tag{26}$$

Therefore, 3-D positions from 2-D images can be reconstructed based on the equations (24) and (26) as shown in Figure 10.

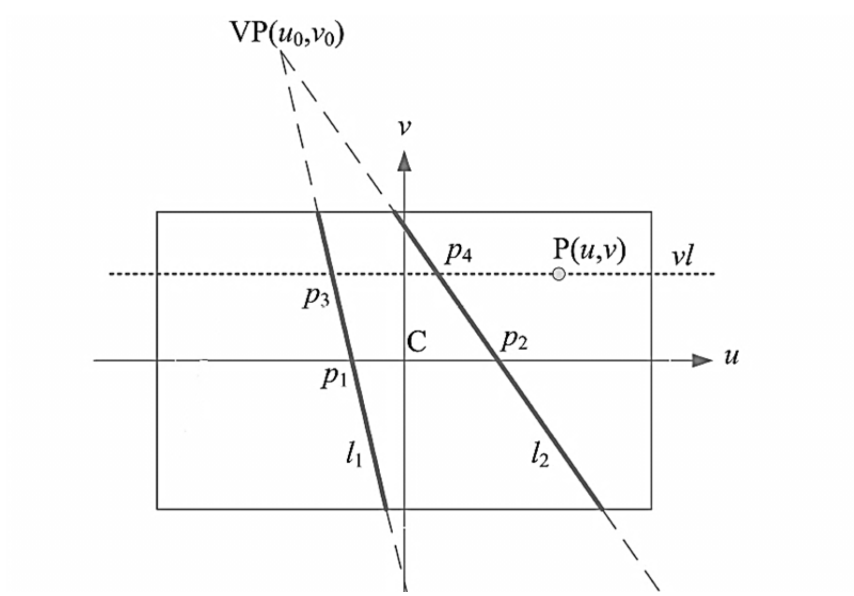

Figure 9 The Demonstration for the Transformation between 3-D and the Image

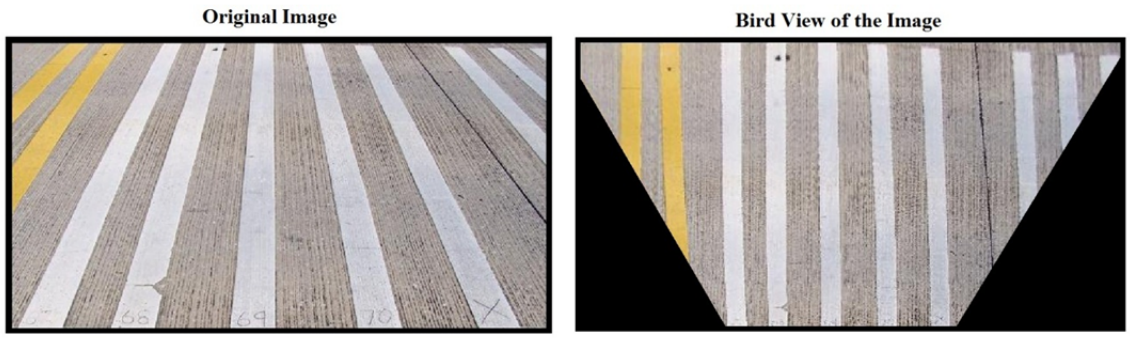

Figure 10 Camera Calibration Sample Test

However, it must be acknowledged that there is a limitation of images provided by NTPEP, which is the unknown camera height indispensable in camera calibration. Therefore, a reasonable value will be assumed to be used as the camera height in this study. In future work, the system will be expanded for field implementation, standardizing camera height, camera angle with the ground, and other settings in order to acquire better accuracy.

3.4 Statistical Pavement Marking Color Model

Color is considered as a visual perceptual property that is very crucial in attracting driver's attention. Since the colors of pavement markings (center and edge lines) are mainly from yellow and white based on the specification in MUTCD, color filtering plays an important role in the determination of presence conditions of pavement markings as an effective way to differentiate pavement markings from NTPEP images from other background objectives based on their special color characteristics. However, it is challenging to predict which color value belongs to the color class of pavement markings, since the color values of pavement markings in images can be widely dispersed under different outdoor conditions.

In order to overcome various outdoor conditions, the color model will be developed to detect pavement marking colors using a Back-Propagation Neural Network (BPNN) with a higher accurate and robust detection for pavement markings using labeled pavement markings' color samples from NTPEP images. For the basic concept of neural networks, Murino (*26*) and Zhang (*27*) have authored good introductions that can be referenced. The general main structure of BPNN employed in this work is shown in Figure 11, in which one hidden-layer is adopted with 30 neural nodes.

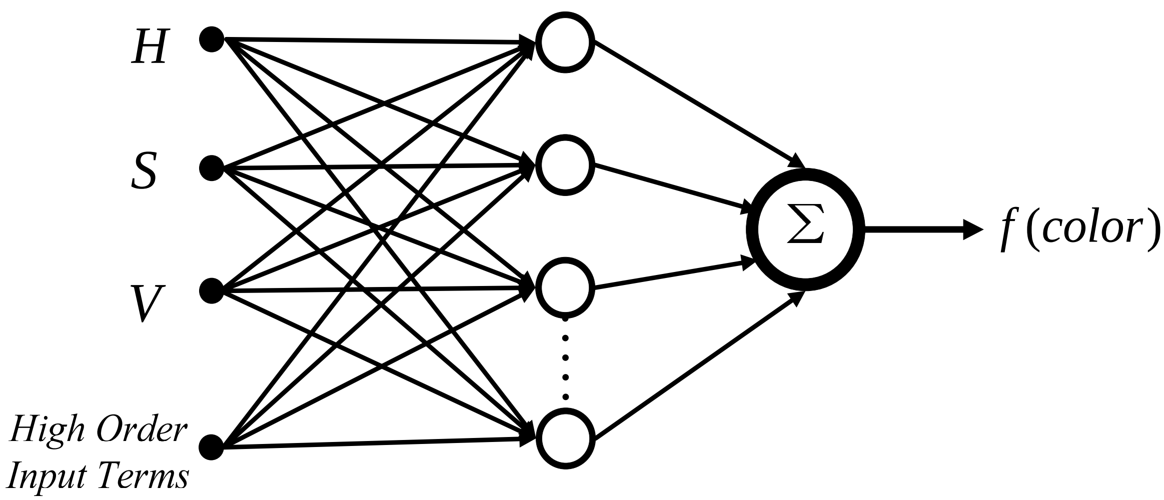

Figure 11 BPNN for Color Model Training

The hue-saturation-value (HSV) color space was adopted as the input for the color detection, as it was more perceptual than other color spaces and more appropriate to be used in linear color segmentation. Additionally, it should be noted that the inputs were expanded with the high-order terms in order to simply the structure and acquire the higher accuracy since multilayer neural networks can be substituted by one-layer networks by using the expanded inputs (*28*). However, the appropriate selection of high-order terms is very important as it strongly affects the performance of the developed network in the color detection. After testing various types of high-order input terms, the high-order polynomials were finally chosen as the expended inputs with a higher accuracy as following:

$$High - Order\ Polynomials = \begin{bmatrix} H & 2H^2 - 1 & H^3 \\ S & 2S^2 - 1 & S^3 \\ V & 2V^2 - 1 & V^3 \end{bmatrix} \qquad (27)$$

Its format is derived from the Fourier decomposition. Though trigonometric composition inputs could improve the discriminatory power of the color detection (*29*), it would significantly decrease the processing speed and make the network more complicated, such that the number of inputs would be enlarged to 30, or more if also considering cotrigonometric composition inputs. Therefore, the total count of the inputs used in practice was 12 including three inputs H, S, V and nine inputs of high-order polynomials as shown in the equation (27). The output of BPNN is a switch value which represents whether a pixel belongs to the color of pavement markings in the image (1 means YES, 0 means NO). For instance, if the RGB value of a sampled pixel is (233, 231, 232), tagged by humans as the color of pavement markings, the inputs of BPNN is based on the transformed HSV value (0.917, 0.00858, 0.914) with Matlab scales, and the output produced by BPNN is 1, indicating that this pixel belongs to the color of pavement markings. Figure 12 demonstrated such color detection, subtracting the background of the images.

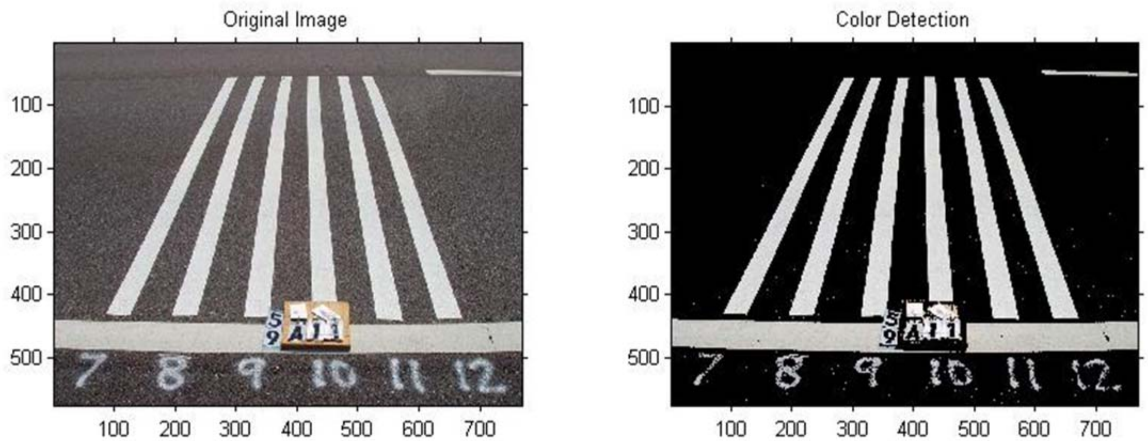

Figure 12 An Example of Color Detection

3.5 Image Segmentation

After color detection, pixels of pavement markings in the image need to be identified and separated from the road surface as the prerequisite for determining the presence conditions of pavement markings. In the image segmentation, the general process is demonstrated as follows:

- Convert color images to gray ones
- Apply adaptive threshold method to find an optimized threshold value
- Perform image binarization based on the optimized threshold
- Apply filtering techniques to reduce noises in binarized image
- Apply Hough transformation to find the edge of pavement markings

The step of image segmentation is very crucial for the whole system, and makes the further analysis of the image only focus on the separated road marking pixels and hence measures the performance characteristics of the pavement marking itself. For pavement marking images, pixels of pavement markings are usually located in the lighter area of an image with similar characteristics, and correspondingly, pixels of the background are usually located in the darker area. Because of such contrast of the brightness between pavement markings and the background in an image, a gray-level value is expected to distinguish these two regions as a threshold value. This indicates that pixels are considered as pavement markings if their gray values are higher than the threshold value, and pixels of the background should have lower gray values when compared with the threshold value. Therefore, selecting an appropriate gray value as the threshold could be the key for the image segmentation. This can be done by calculating the histogram of gray values of the image, as shown in Figure 13. The x-axis of the histogram is the gray levels of all pixels in the gray image, and the y-axis is the number of pixels at a certain gray value as a distribution within this image. The histogram is commonly considered as the combined distributions of objective and background, which belong to two distinct regions (called bimodal). Such bimodal images could be accurately segmented by selecting an appropriate threshold value within the entire image (*30*).

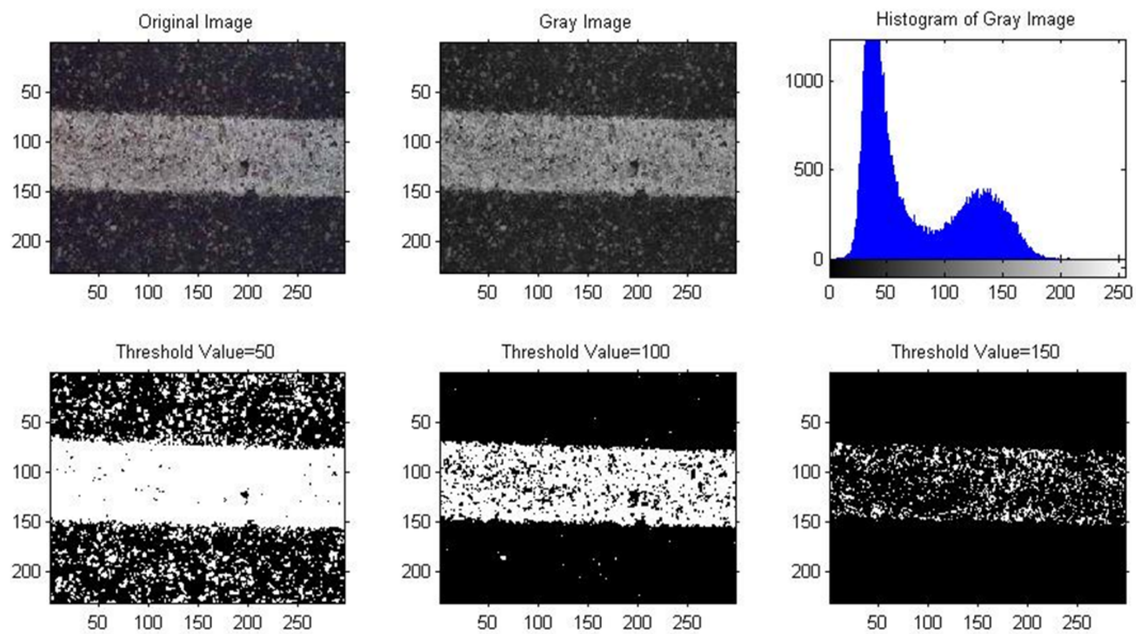

Figure 13 The Example of Image Segmentation based on Histogram of Gray Values

From Figure 13, it can be seen that a threshold value floating around 100 performs well. Otherwise, it could lead to the failure of the image segmentation, as the entire objective was not well-extracted from the image. Therefore, the results of image segmentation strongly depended on the threshold value, which significantly affects the accuracy of separating pavement markings from the background.

3.5.1 Segmentation Method Selection

A variety of techniques have been successfully implemented to segment the images, such as the Average Method, Variance Method, and Minimum Error Thresholding Method. All methods mentioned above are investigated in order to select an appropriate method to segment the images.

Average Thresholding Method

As the name suggests, the average thresholding method calculates the average grey level of the region of interests (ROI), and then sets that average as the threshold value for segmenting the image. The whole process can be illustrated by the equation (28).

$$t = \frac{\sum_{i=1}^{n_1} \sum_{j=1}^{n_2} z_{i,j}}{n_1 * n_2} \tag{28}$$

where $n_1 * n_2$ is the dimension of the image and $z_{i,j}$ is the gray level of a pixel in the image.

Variance Method

The variance method is an automated thresholding method developed by Otsu (*31*), which is capable of determining the threshold value in different images with robustness. Since it is simple and computationally inexpensive, this method has been widely used in image segmentation. The aim of Otsu's method is to make segmented objective and background with the most homogeneity as possible as it can. This homogeneity is determined by a weighted sum of the variation of grey levels within each group of objects and backgrounds. The objective (or background) will have high variance with low homogeneity. Therefore, a gray level achieving the highest homogeneity of the groups (objective or background) is considered as the optimized threshold value when a weighted sum of the variation of grey levels is minimized. According to the statement in Otsu's paper, the optimum threshold value is t^*, which maximizes the statistical parameter σ_B^2, as shown in the equations (29) and (30).

$$\sigma_B^2(t) = \frac{[\mu_T \omega(t) - \mu(t)]^2}{\omega(t)[1 - \omega(t)]} \tag{29}$$

$$\sigma_B^2(t^*) = \max_{1 \le t < L} \sigma_B^2(t) \tag{30}$$

where:

$$\mu_T = \sum_{z=1}^{L} z * p_z \tag{31}$$

$$\mu(t) = \sum_{z=1}^{t} z * p_z \tag{32}$$

$$\omega(t) = \sum_{z=1}^{t} p_z \tag{33}$$

$$p_z = \frac{n_z}{N} \tag{33}$$

where n_z is the number of pixels at the gray level z, N is the total number of pixels in the image, and L is the maximum gray level in the image. However, it should be noted that the variance method cannot easily handle images where histograms are unimodal distributions.

Minimum Error Thresholding Method

The minimum error thresholding method was first introduced by Kittler and Illingworth (*32*). The gray-level histogram of the image is modeled by standard statistical distributions. It is assumed that the histogram is represented by Gaussian distribution for the objective and the background. A criterion function J is introduced to examine the overlap between Gaussian distributions of the objective and the background.

The optimized threshold value is the gray level which minimizes the criterion function. The combined distribution of two Gaussians is defined as following:

$$f(z) = \frac{\omega_0}{\sqrt{2\pi\sigma_0}} e^{\frac{-1}{2[(z-\mu_0)/\sigma_0]^2}} + \frac{\omega_1}{\sqrt{2\pi\sigma_1}} e^{\frac{-1}{2[(z-\mu_1)/\sigma_1]^2}} \tag{34}$$

The criterion function is given by:

$$J(t) = 1 + 2[\omega_0 \ln \sigma_0(t) + \omega_1 \ln \sigma_1(t)] - 2[\omega_0 \ln \omega_0(t) + \omega_1 \ln \omega_1(t)] \tag{35}$$

$$J(t^*) = \min_{1 \le t < L} J(t) \tag{36}$$

where ω_0 is the probability of a pixel belonging to the background as given by:

$$\omega_0(t) = \sum_{z=1}^{t} p_z \tag{33}$$

Correspondingly, $\omega_1(t) = 1 - \omega_0(t)$ is the probability of a pixel belonging to the objective, and

$$\mu_0 = \left(\sum_{z=1}^{L} z * p_z \right) / \omega_0 \tag{37}$$

$$\mu_1 = \left(\sum_{z=1}^{L} z * p_z \right) / \omega_1 \tag{38}$$

$$\sigma_0^2(t) = \left\{ \sum_{z=1}^{t} [z - \mu_0(t)]^2 p_0 \right\} / \omega_0(t) \tag{39}$$

$$\sigma_1^2(t) = \left\{ \sum_{z=t+1}^{L} [z - \mu_1(t)]^2 p_1 \right\} / \omega_1(t) \qquad (39)$$

In order to test the fitness of methods introduced above for the segmentation in pavement markings images, fifty images with different types of the histogram were used.

Three classic types of the histogram are illustrated in Figure 14, Figure 15 and Figure 16. The first one depicts histograms of object and background without overlap. In the second, histograms have an overlap, which remains distinguishable due to two obvious peaks. The third diagram's histograms have been integrated into one, where the object and background are indistinguishable.

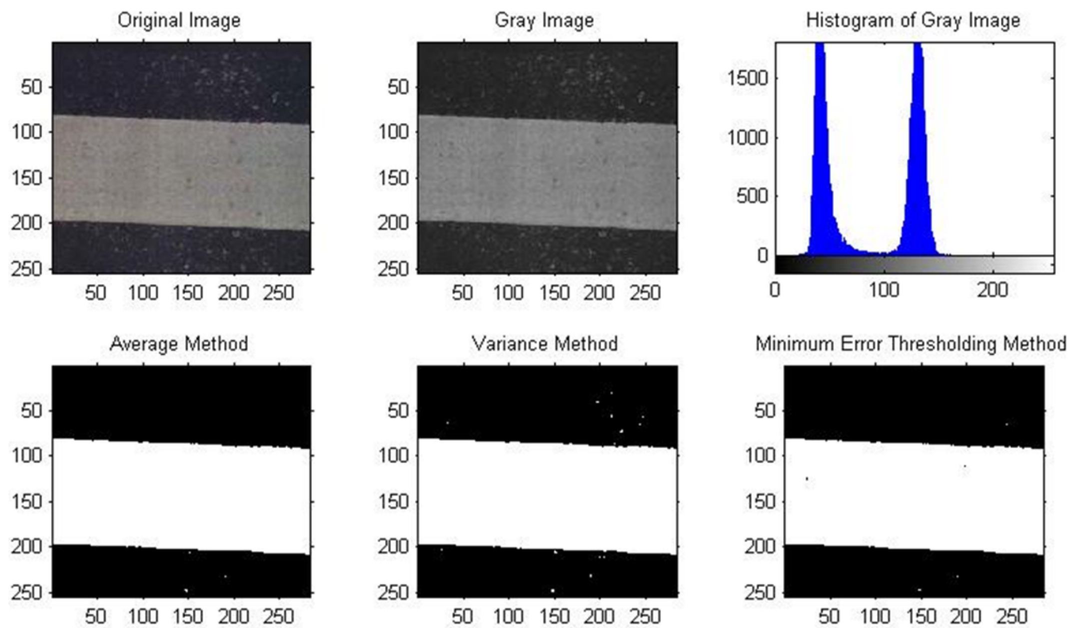

Figure 14 Image Segmentation Test 1

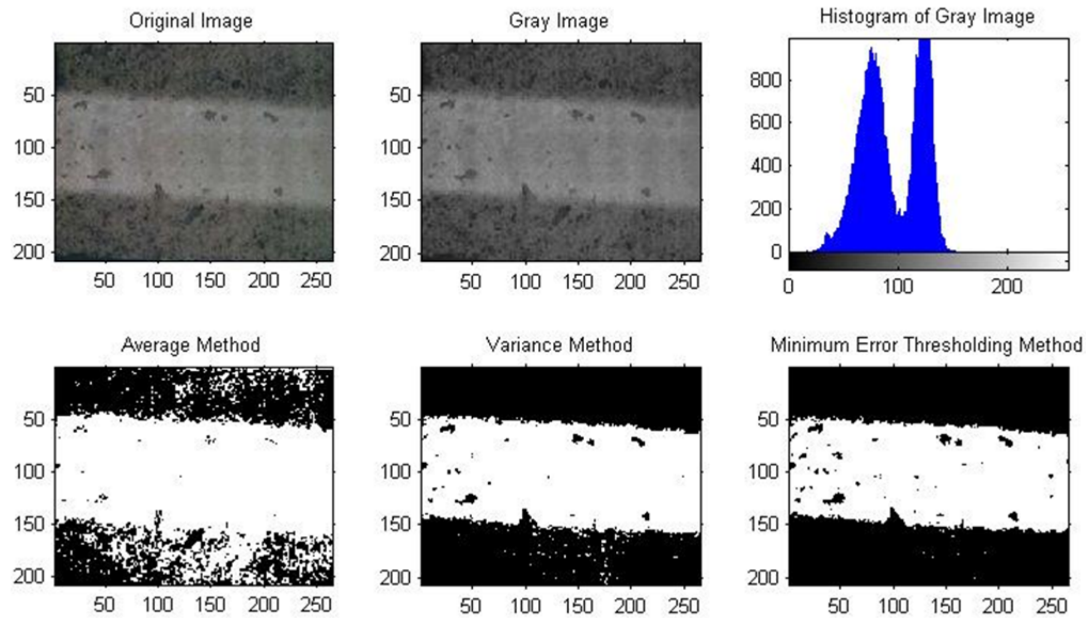

Figure 15 Image Segmentation Test 2

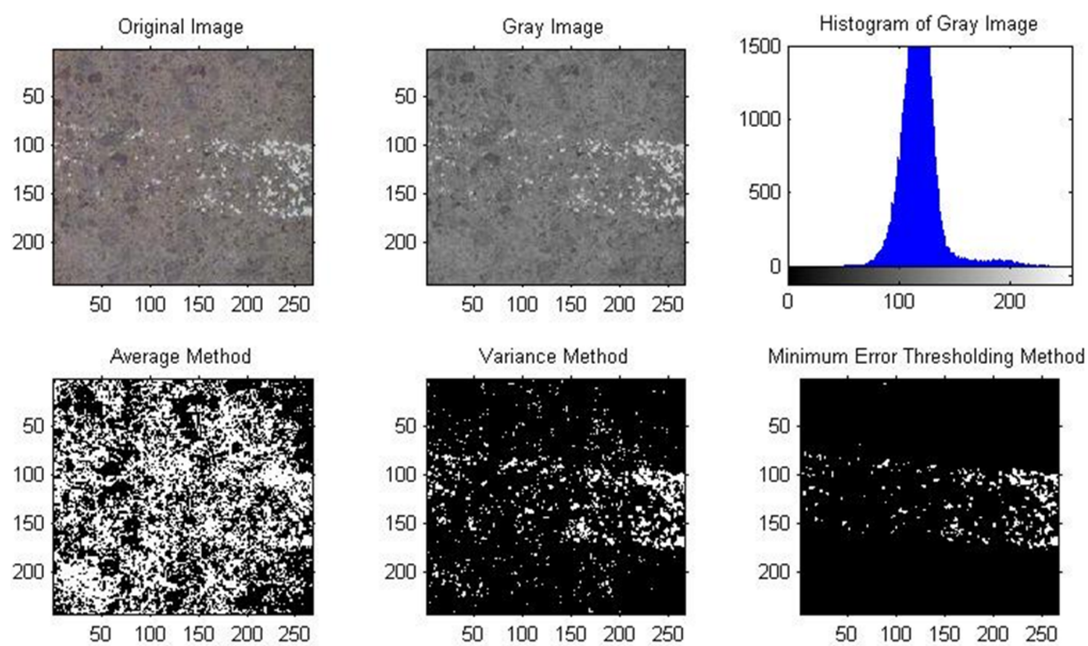

Figure 16 Image Segmentation Test 3

The testing results of three segmentation methods applied to three classic pavement marking images are presented in Figure 14, Figure 15 and Figure 16. It is obvious that the minimum error thresholding method performed better than the average method and the variance method in image segmentation, even though they have a similar perforation in the image which has two obviously distinct peaks (composed of objective and background) in the histogram. Consequently, the minimum error thresholding method is used in this study, since it is more suited for separate pavement markings from the background.

3.6 Image Enhancement

After color detection, the image is converted to gray, indicating that the dimension of 3-D data is changed to a single one. Then, through image segmentation, the gray-level image is binarized to separate pavement markings from the background based on the optimized threshold value. During the process of segmentation, some pixels outside of the region of pavement markings may be incorrectly classified into those of pavement markings. Such incorrectly segmented pixels are known as noise, and could significantly affect the further analysis of the presence conditions of pavement markings. This noise is usually located outside the region of pavement markings because there are pixels that commonly have similar colors as pavement markings within the region outside markings such as pavements, followers, etc. Due to this, there is a need to apply filtering techniques to eliminate this noise. The filtering techniques improve the quality of the image using such techniques as Low-Pass Filter, Histogram Modification, Median Filter, Frequency Domain Processing, etc., which can further reduce noise and increase the accuracy for further analysis. After testing, the modified median filter was employed to enhance the image with removing noise.

As its name implies, the median filter, the best-known filter in nonlinear spatial filters, replaces the value of a pixel by the median of values in its neighborhood. In this case, the number of white pixels in the neighborhood of a colored pixel will determine whether this pixel belongs to pavement markings or the noise. If the number of white pixels within a neighborhood is lower than a threshold value, this pixel will be considered as a noise and then removed. The opposite holds true, as a pixel will remain if its number of neighboring white pixels is higher than a threshold value. Based on Burrow's research, the optimized size of neighborhood is 8*8 pixels as a window, and the threshold number of white pixels for the determination of noise pixels is set as 20 to acquire maximum efficiency. The test result is demonstrated in Figure 17.

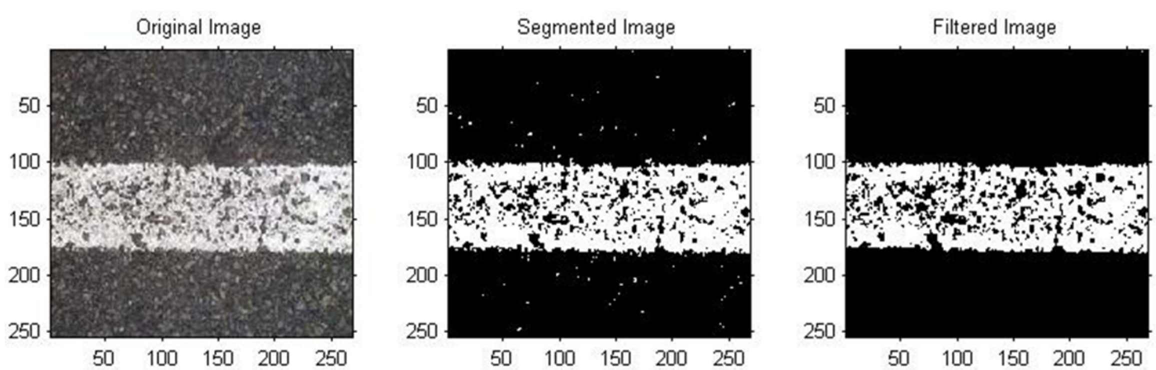

Figure 17 Test for Image Enhancement

3.7 Feature Recognition

The feature recognition in which the quantification of pavement markings erosion will be involved is based on two results: the computation of the number of remaining white pixels within the area between the ideal edge lines of pavement markings in a segmented and enhanced image, and the correlation of histographic data with criteria photographs provided by NTPEP as the supplementation.

A method is developed to detect ideal edge lines of pavement markings in an image according to the properties of the remaining pavement marking pixels in the image. The key of feature recognition is to estimate the likely position and size of the ideal pavement markings, which are commonly shown as parallelograms in images. As previously stated, Hough transformation is capable of detecting the edge lines of pavement markings. However, the resulting transformation is usually composed of discontinuous lines which are difficult to distinguish between and unsuitable to directly determine the likely position and size of ideal pavement markings. Fortunately, the slopes of detected edge lines can be provided for through Hough transformation, which is useful in correcting parallelogram-shaped pavement markings to rectangular-shaped ones capable of easily determining the ideal edge lines of pavement marking with higher accuracy, as the rectification of geometric deformity. Figure 18 demonstrates the spatial relationship between the parallelogram-shaped pavement markings and the transformed rectangular-shaped ones with two different coordinates.

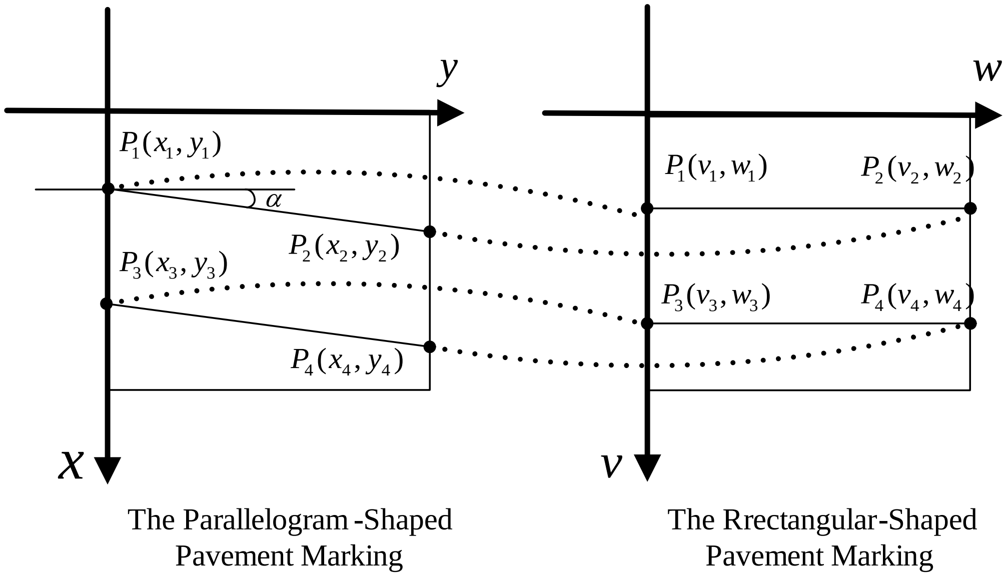

Figure 18 The Spatial Relationship between Parallelogram and Rectangle

Each pixel in a segmented and enhanced image with the $x - y$ coordinate has a corresponding point with the $v - w$coordinate under a spatial relationship. Such a spatial relationship can be mathematically described in the following equations (40) and (41), and a test is conducted and illustrated in Figure 19.

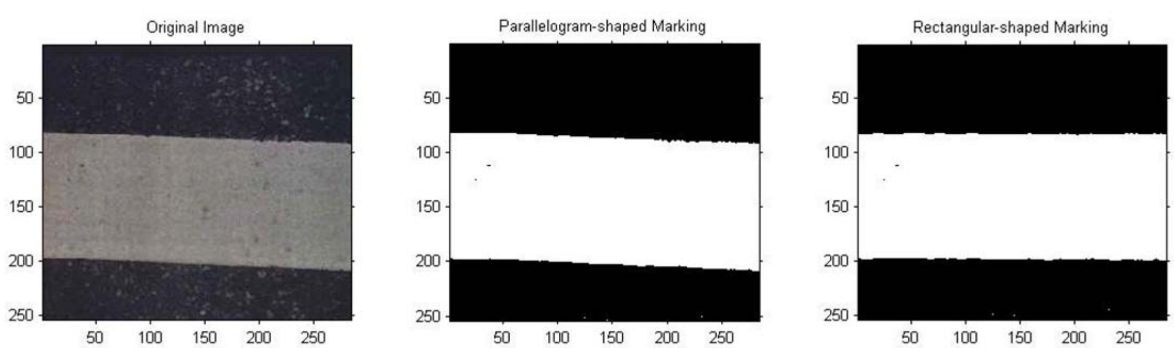

Figure 19 Test Results of the Conversion to a Rectangular-Shaped Pavement Marking

$$v = x - y * tan\,\alpha \tag{40}$$

$$w = y \tag{41}$$

In order to further investigate the ideal edge lines of pavement markings, it is necessary to calculate the centroid (known as the barycenter of a plane figure) of left pavement marking pixels by using the following equations, which could be used to estimate the center-line of the ideal pavement marking.

$$C_x = \frac{\int xD_y(x)dx}{A} \tag{42}$$

$$C_y = \frac{\int yD_x(y)dy}{A} \tag{43}$$

where (C_x, C_y) represents the position of the centroid, A is the area of remaining pavement marking pixels (the total number of white pixels in the image), $D_y(x)$ is he distance between the original point O and a pavement marking pixel of a segmented and enhanced image in the x-axis, and $D_x(y)$, correspondingly, is the distance in the y-axis. Hence, the center-line can be located as a horizontal line going through the centroid of the remaining pavement marking pixels in the image.

After locating the center-line, the ideal edge lines of pavement markings as boundaries can be estimated with the basis of the position of the detected center-line. Two ideal edge lines of the pavement marking are considered to be parallel and equidistant from the center-line. Since the pavement marking is separated by the center line into two symmetric parts, the center-line of each part can be calculated by the same method stated above. The double distance between the center-line of each part and that of the whole image can be calculated and considered as the distance between the ideal edge lines and the center line of the whole image because of the symmetry. Therefore, two ideal edge lines, as the ideal width of the pavement marking, can be finally determined at an equivalent distance apart from the center-line of the whole pavement marking. The percentage of remaining pavement markings could be deduced from the ratio of the number of remaining white pixels and the total pixels between the two ideal edge lines of the pavement marking. The percentage corresponds to the level based on Table 3.

Table 3 Correspondence between the Percentage and the Level

Percentage (%)	***0~15***	***15~25***	***25~35***	***35~45***	***45~55***	***55~65***	***65~75***	***75~85***	***85~95***	***95~100***
Level	1	2	3	4	5	6	7	8	9	10

On the other hand, before producing the final determination of the presence condition of pavement markings, the correlation of histograms between test and criteria photographs provided by NTPEP should be accounted for. In statistics, a correlation means a departure from independence between two random variables. Correlation is useful because it can indicate a predictive relationship that can be used in practice. The Pearson correlation coefficient is most widely used, as it is mainly sensitive to a linear relationship between two variables. It is obtained by dividing the covariance of the two variables by the product of their standard deviations, as shown in the equation below.

$$r_{XY} = corr(X,Y) = \frac{cov(X,Y)}{\sigma_X \sigma_Y} = \frac{E[(X-\mu_X)(Y-\mu_Y)]}{\sigma_X \sigma_Y}$$

$$= \frac{\mathrm{n}\sum \mathrm{x_i y_i} - \sum \mathrm{x_i} \sum \mathrm{y_i}}{\sqrt{\mathrm{n}\sum \mathrm{x_i}^2 - (\sum \mathrm{x_i})^2}\sqrt{\mathrm{n}\sum \mathrm{y_i}^2 - (\sum \mathrm{y_i})^2}} \tag{44}$$

where X and Y are the histograms of test and criteria images, E is the expected value, cov is covariance, μ_X and μ_Y are representative of the mean of the histograms X and Y, respectively, σ_X and σ_Y are standard deviation of the histograms X and Y. The correlation coefficient may take any value between -1.0 and +1.0. A positive one value coefficient means a perfect increasing linear relationship, while a negative one value depicts a perfect decreasing linear relationship. The value between -1.0 and +1.0 represents the degree of linear dependence between two variables. The closer the coefficient is to either -1.0 or 1.0, the stronger the correlation between two variables. Each test image will be evaluated by the correlation analysis with all criteria photographs from level 1 to 10. The level of the test image will correspond to the criteria photograph with the highest correlation value.

Thereafter, the final determination of the presence conditions of pavement markings will be conducted by taking into account both the results of the percentage and the correlation analysis. If the highest correlation value is below 0.6, the percentage is only considered as the determination of the presence conditions without the correlation result. Correspondingly, if the highest correlation value is more than 0.6, the final presence conditions of pavement markings will be determined by a linear regression equation as follows:

$$L = 0.9 * P + 0.1 * C \tag{45}$$

where P is the level corresponding to the percentage of remaining white pixels within the ideal pavement marking and C is the level corresponding to the criteria photograph with the highest correlation. L will round to an integer value as the final determination of the presence conditions of pavement markings. A preliminary result can be found in Figure 20.

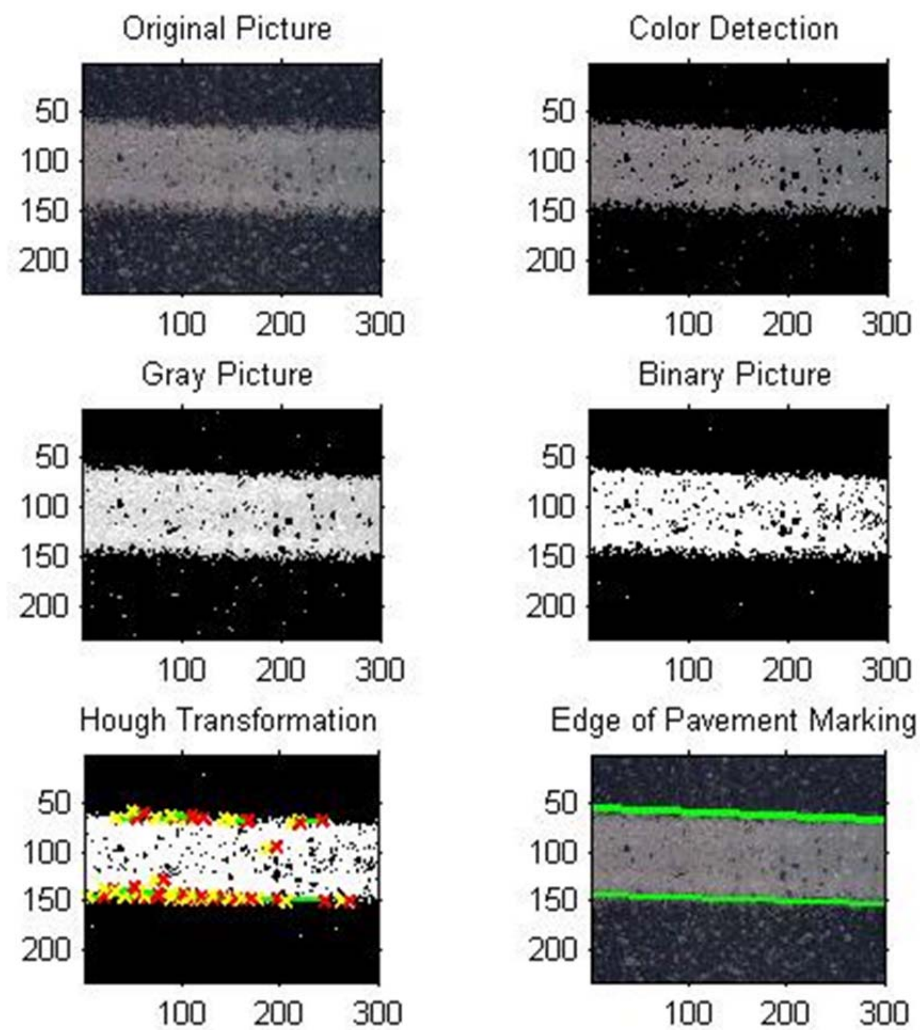

Figure 20 The Preliminary Result of Feature Recognition

4. SYSTEM DEVELOPMENT

4.1 Introduction

This section first introduces the basics of mathematical software Matlab and Graphic User Interface (GUI) (used to develop the interface software as a component of Matlab). Then, the interface system as a platform to implement all functions proposed in the section of methodology is developed, and all its components are described.

4.2 Mathematical Software Matlab

Matlab, composed of the first three letters of MATrix and LABoratory, respectively, is a numerical computing software tool which integrates the functions of visualization, words processing, simulation, real-time control, and so on. It is developed by MathWorks© and widely used in academic and research institutions, as well as industrial enterprises. The biggest feature of Matlab is its simplicity and directness as the fourth-generation programming language. The main functions Matlab can complete are as following:

- Data Analysis
- Numerical and Symbolic Computation
- Engineering and Academic Drawing
- Control System Design and Simulation
- Signal Processing
- Digital Image Processing

- Communication System Design and Simulation
- Graphic User Interface (GUI) Design

Similar to C and FORTRAN, third-generation programming languages, Matlab sets people free from cumbersome codes by discarding the computer hardware. It is easy to call plenty of functions and implement them in Matlab.

According to the classification of its functions, Matlab consists of Development Environment, Math Library, Programming and Data Types, File I/O, Graphic Display, 3-D Visualization, Graphic User Interface, and External Interface.

4.2.1 Development Environment

The development environment of Matlab is a friendly interface window as shown in Figure 21. Adequate functions are provided, which can be easily applied to manage variables, input/output data, M-files, etc. Moreover, Matlab is an integrated program editor, debugger and execution controller as a whole that brings a lot of benefits such as simple and direct programming, convenient debugging, quick launching, and visual result display. Additionally, the complete on-line inquiry and help system are also integrated into the development environment of Matlab.

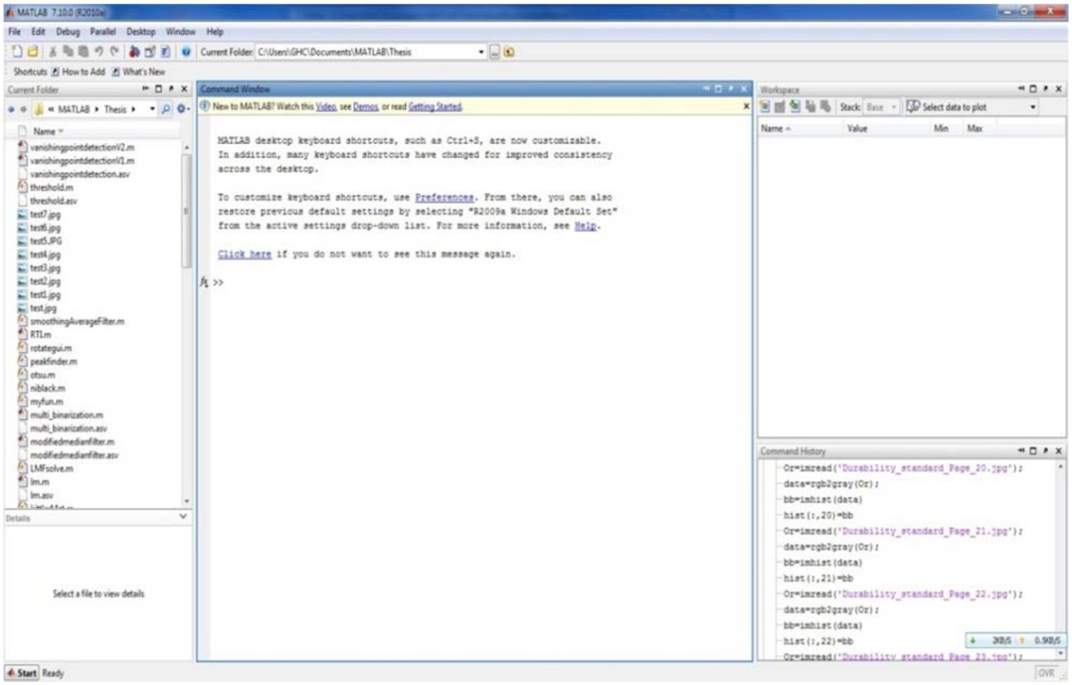

Figure 21 Matlab R2010a Screenshot

4.2.2 Math Library

Matlab provides a lot of mathematic functions to engineers. For example, there are simple functions such as Summation, Sine, Cosine, Tangent, and so on, but complicated functions such as Matrix inversion, Fast Fourier Transformation (FFT), 3-D drawing, and so on, are also provided.

4.2.3 Programming and Data Types

Different data types such as integer, double precision, chart, etc. are available in Matlab for the convenience of users. Additionally, learning and applying Matlab language is a straightforward process.

4.2.4 File I/O

Matlab uses common file types such as .m, .mdl, .mat, .pdf, .html and text files, even for most image files.

4.2.5 Graphic Display

Since Matlab's origins, its strong ability to visualize Matrix and Vector has been praised as one of its biggest features. Various graphs and image data can be expressed through mathematic functions.

4.2.6 3-D Visualization

Matlab provides a group of functions that can draw 3-D graphs for bivariate functions, including high-level and low-level functions. High-level functions are mainly for drawing graphs with simple and compact commands, low-level functions focus on the adjustment of 3-D graphs such as rotation, zoom, etc.

4.2.7 Graphic User Interface (GUI)

In order to bring the convenience to users in the design of GUI, Matlab also provides functions used in windows settings, properties adjustment, etc.

4.2.8 External Interface

External interface functions could allow users to access C and FORTRAN programs in Matlab. For people familiar with C and FORTRAN, programs developed using C and FORTRAN could be conveniently transplanted into Matlab for wide use.

4.3 Graphic User Interface (GUI)

As the name suggests, the graphic user interface (GUI) is a type of user interface that allows users to interact with actions and information through graphic icons and visual indicators rather than text commands. A GUI is a good tool that can be used repeatedly and conveniently, and a good choice to represent techniques and methods. Without a GUI, people would be limited to text-based interfaces, which can be extremely difficult and frustrating, especially for new users. A good GUI can make programs simpler and easier to use through common windows, buttons, combo boxes, menus, etc. A GUI consists of three basic parts: components, windows, and responses.

4.3.1 Components

In Matlab's GUI, each item is a graphic component. All components can be classified into four categories: graphic controls (buttons, edit boxes, scroll bar, etc.), static components (windows, texts and strings), menus, and coordinate systems. The function *uicontrol* is used to create graphic controls and static components. Menus can be created by the functions *uimenu* and *uicontextmenu*. Coordinate systems are usually used to demonstrate the graphic data via the function *axes*.

4.3.2 Windows

Each component of GUI must be arranged in graphical windows which are usually automatically created when drawing graphic data. Windows are platforms used to place various types of GUI components.

4.3.3 Responses

If users click the mouse or input information, GUI will respond accordingly. For example, if users click a button with the mouse in a window, the corresponding event, called responses, will be triggered to react.

4.4 System Configuration

Since Matlab is capable of computing with a friendly interface, the whole system is used to determine the presence conditions of pavement markings is developed by Matlab's GUI in this study. Figure 22 demonstrates the system organization of the developed system. One main consideration to develop the system on the Matlab platform is keeping the training and maintaining requirements on a minimal level. The whole system is developed to incorporate related agencies to evaluate the presence condition of pavement markings. Additionally, the functions will enter image data and automatically analyze the degree of erosion for single or multiple pavement markings, as shown in Figure 23. In the developed software package, it could evaluate the presence conditions of single, multiple, or even a part of pavement markings. The following parts explain the basic components and their functions of the developed system.

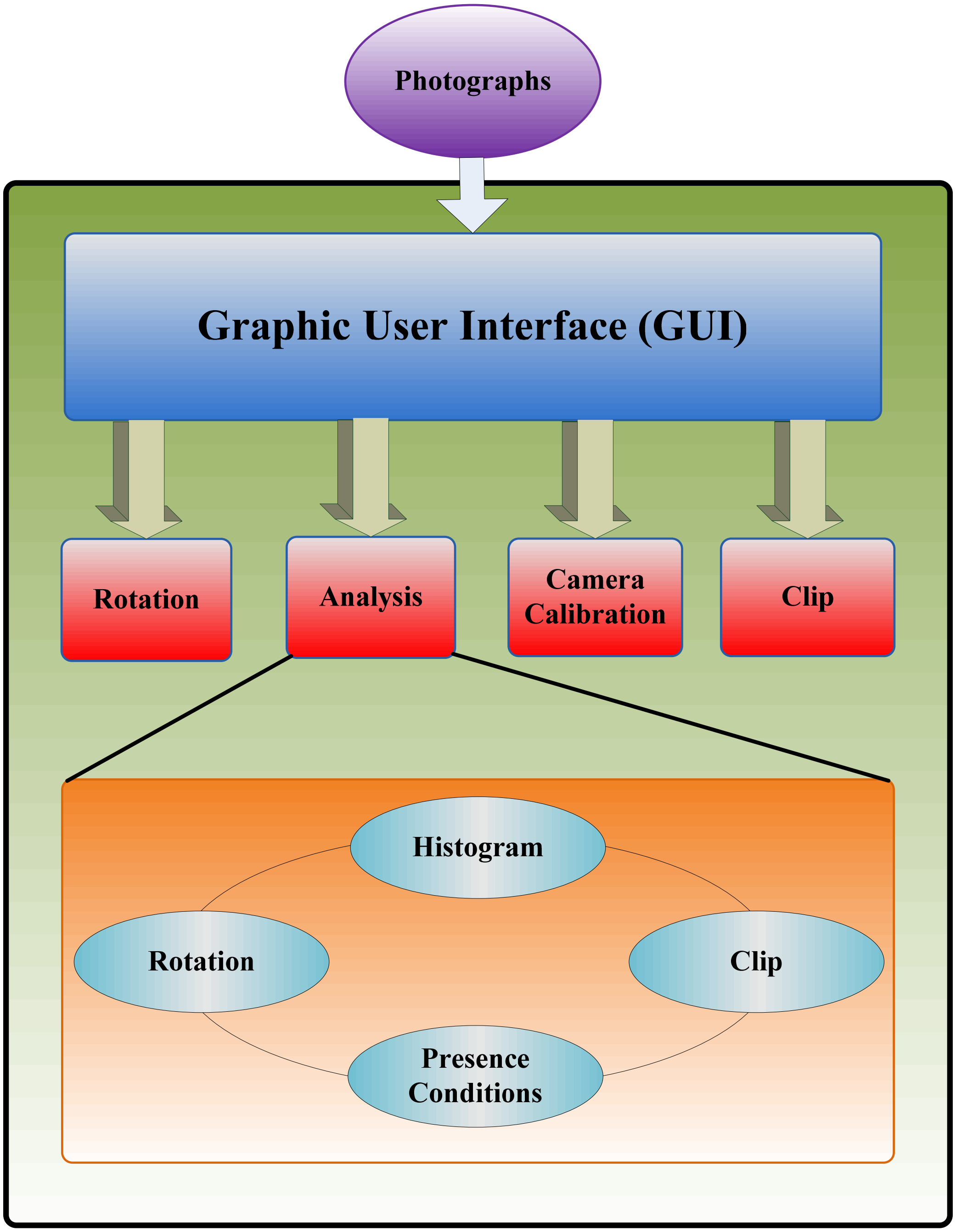

Figure 22 System Organization of the Developed System

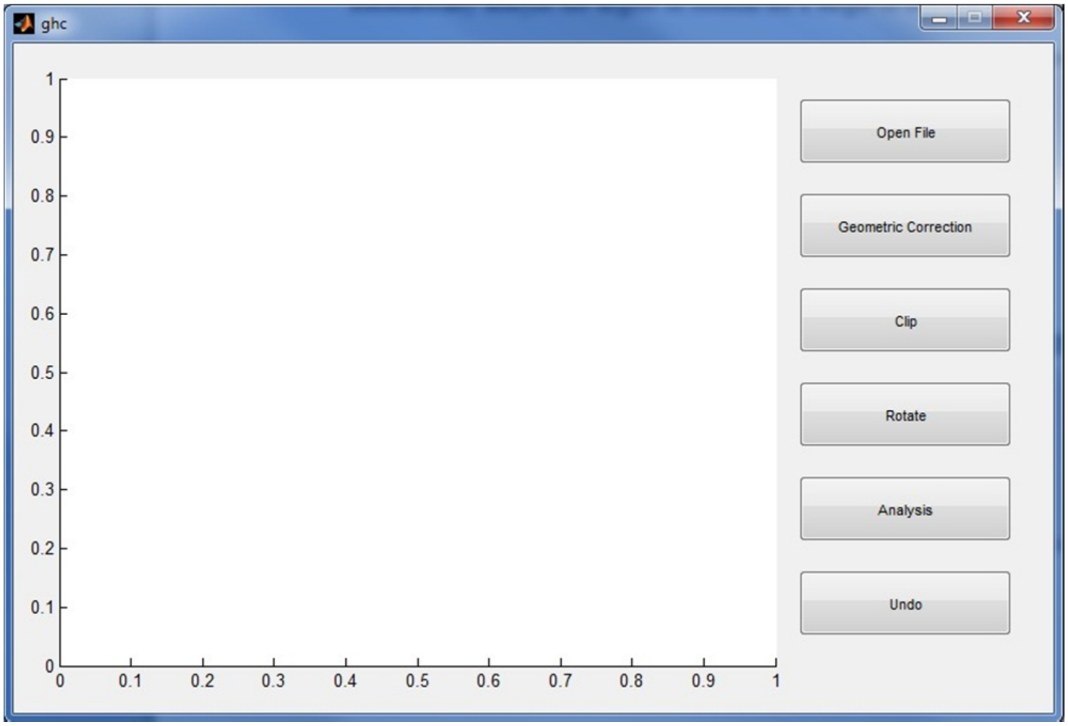

Figure 23 The Main Interface

4.4.1 Open Files

In the first step, it is necessary to input the image in which the presence conditions of pavement markings would be analyzed. The button Open provides an effective way to make users select the image they would like to analyze. By clicking Open, a sub-window, as demonstrated in Figure 24, will pop-up to let users examine all files saved in the computer and select a satisfied image, similar to using Windows operation systems. As we can see in Figure 25, after the selection, the chosen image is displayed on the left of the main interface, ready for further analysis.

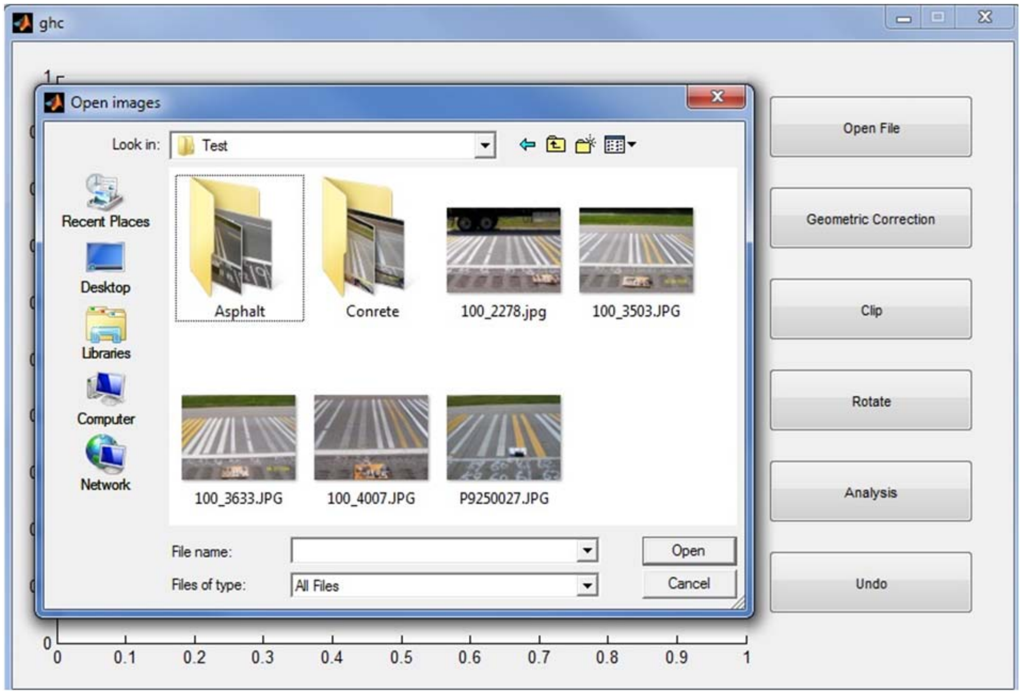

Figure 24 The Sub-window for Opening the Image

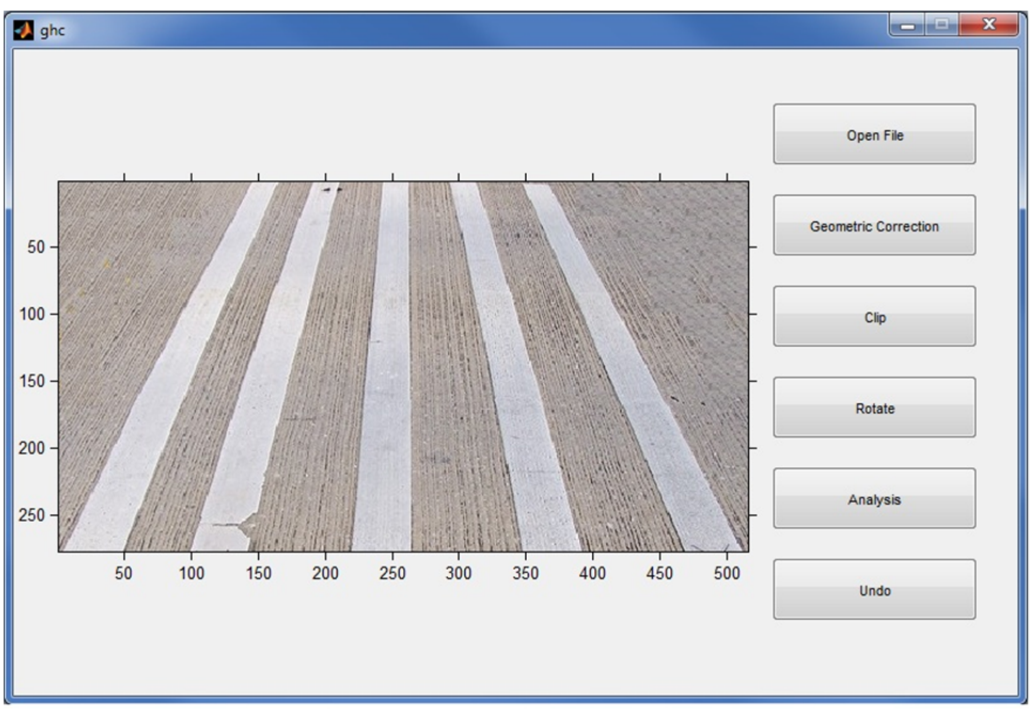

Figure 25 The Main Interface after the Image Selection

4.4.2 Geometric Rectification

As stated previously, since NTPEP images have oblique distortion because the camera projection, there is a need to correct such geometric deformity via camera calibration. Otherwise, it is very difficult to get the exact edges of pavement markings in the image. After loading the selected image, a subprogram can be enabled to correct the geometric deformity in the image by hitting the button Geometric Correction on the right hand of the main interface. After a wait (if the loaded image is very large, the waiting time is probably more than 30 seconds), the corrected image is displayed on the right of the main interface, replacing the original one, as shown in Figure 26.

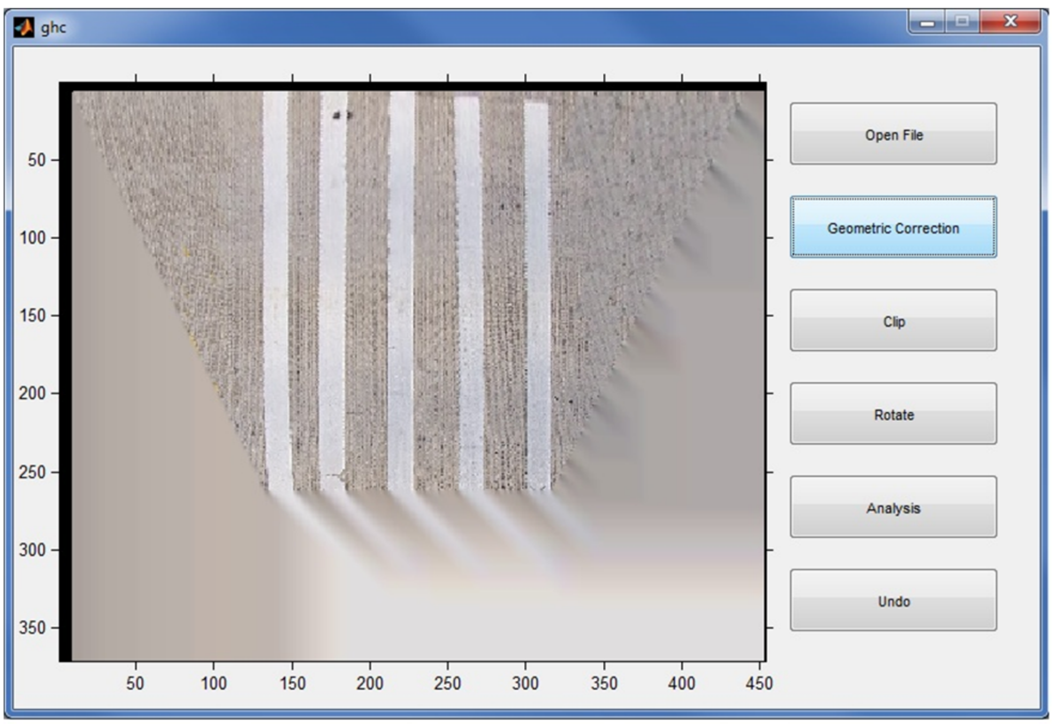

Figure 26 Camera Calibrations for Geometric Deformity

4.4.3 Clip

As its name suggests, Clip enables users to select and cut the region of interest (ROI) of the image with square or rectangular box for further analysis. After hitting the button Clip, a pop-up window (shown in Figure 27) serves as a platform of selecting areas. In order to select objects, users need double-click at each corners of the selection area, respectively. At the bottom of this window, there are two shapes used to select the region of interest for users to use. Additionally, there are two modes used to determine how to locate the selection area,; one to locate from the center of the selection area, the other to locate from two corners of the selection area. Users can also zoom in on the image for a better view of the selection by clicking the arrow icon to choose the appropriate percentage, as shown in Figure 28. Users can change their selections by clicking Start Over on the left bottom of the window. Moreover, it should be noted that the information related to the size of selection area, such as the width and length, is displayed on the left top of the window. When all selections have been done, the window used to select and cut ROI is automatically closed and the selected part is showed back to the main interface after clicking the button Done on the right hand.

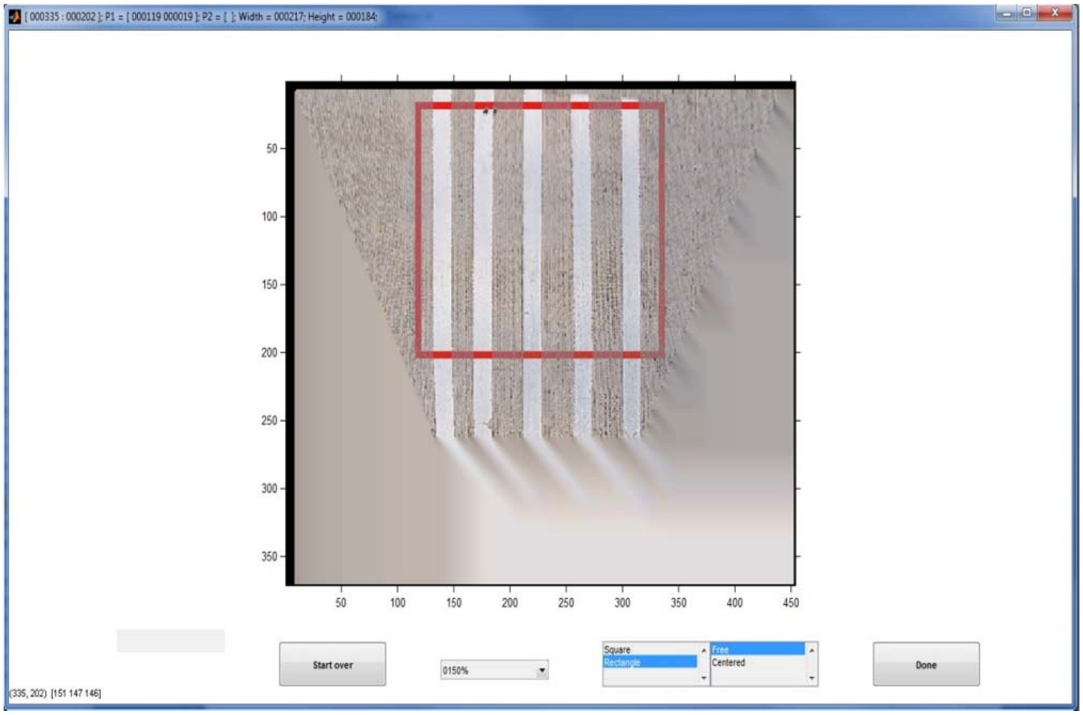

Figure 27 The Pop-up Window of Clip

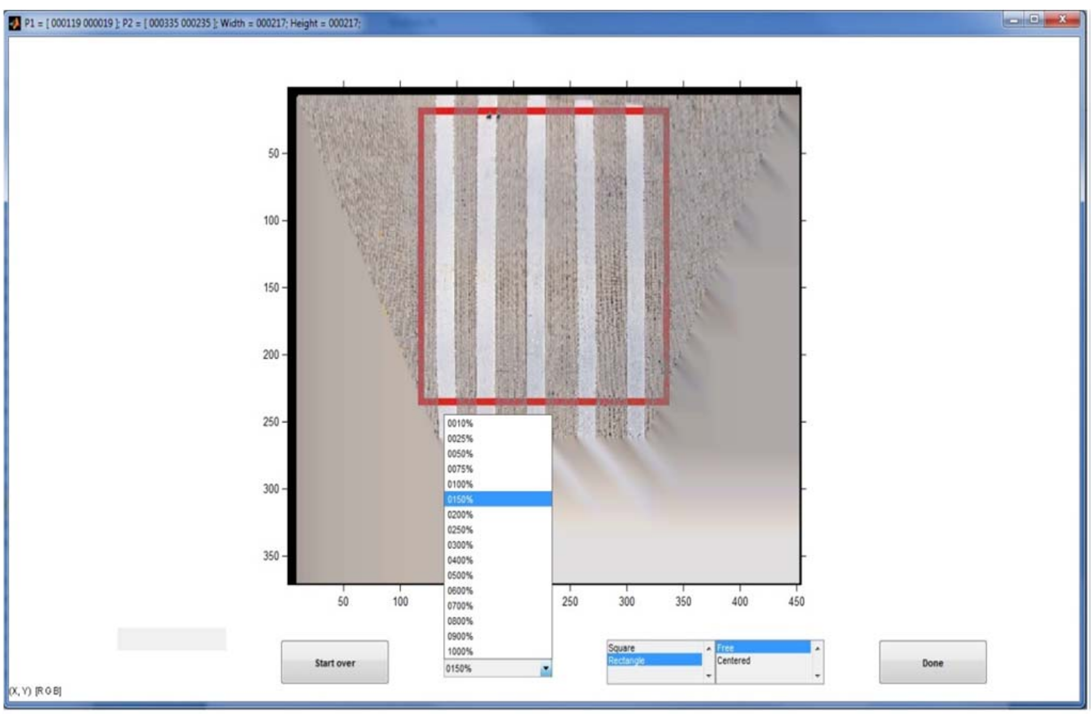

Figure 28 Zoom Images in the Clip Window

4.4.4 Rotate

Rotate allows users to turn a single image around a central fixed point through a window interface. By clicking the button Rotate, a window interface pops up, as illustrated in Figure 29. This window interface consists of four parts: Display, Direct Rotation Control, Advanced Rotation Control, and Confirm/Cancel. The area of Display is used to preview changes of the image with the rotation made by users. In the Direct Rotation Control panel, users can directly rotate the loaded image clockwise and counterclockwise, and flip it horizontally or vertically by pushing corresponding buttons. In the Advanced Rotation Control, users can rotate the image with a certain angle from -180^o to 180^o by moving the scroll bar, and the exact degree of the rotation angle is demonstrated in the white box located next to the scroll bar. Additionally, there are two more advanced options related to the size of output image and the method of interpolation. By using the drop down box, the output image can either have a size the same as the loaded image, or expanded to fit the rotated image. It is also available for users to choose the desired interpolation method such as Nearest-Neighborhood, Bilinear and Bicubic. When all desired rotations and options are selected, three buttons located below the Advanced Rotation Control panel will be enabled, allowing users to confirm all changes in the image by pushing the button Apply. After clicking Ok, the rotation interface is automatically closed and the main interface reappears. If users do not make any change on the image, they can close the window by clicking the button Cancel.

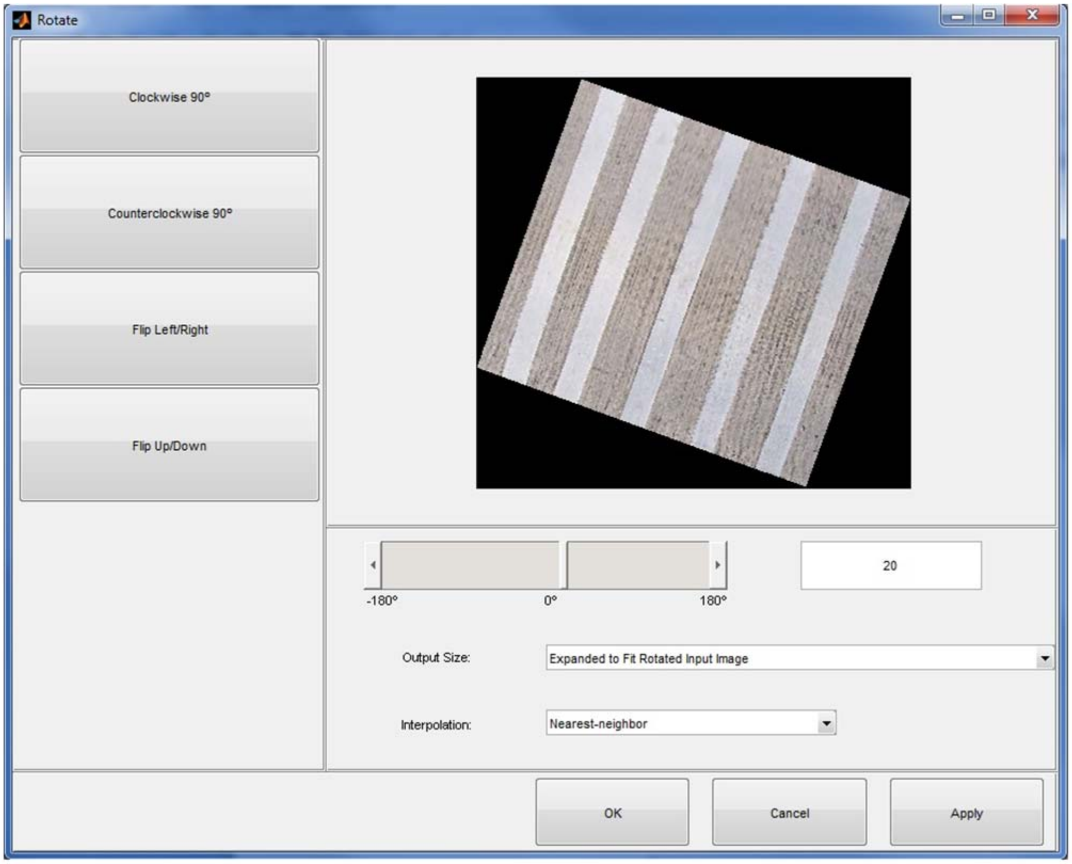

Figure 29 The Window Interface of Rotation

4.4.5 Analysis Function

Analysis is the most important part of the whole system, as it is where the evaluation of presence conditions of pavement markings with image processing techniques is made. When the Analysis button is clicked (Figure 23), the image used to be analyzed, the options of processing techniques and the level of presence conditions are displayed on a pop-up window as illustrated in Figure 30. The Analysis consists of two image display boxes and five buttons (Histogram, Rotate, Clip, Presence Condition and Undo). By clicking the button, Histogram users can examine the gray-level histogram of the loaded image with intensity levels in a certain range as shown in Figure 31. Histogram, showing a visual impression of the distribution of image data, is a graphical representation which can provide useful image statistics for users, such as brightness and contrast. Meanwhile, if users want to further investigate the presence conditions of a part of pavement markings, the image can still be rotated and clipped by hitting the buttons Rotate and Clip, which function as stated previously. The button Undo enables users to re-operate the original image which is showed back to the left display box if they do not satisfy the changes made in the original image or expect to do more other evaluations. After clicking the button Presence Condition, the edge lines of ideal pavement markings colored as green lines are showed in the right display box, comparing with the original one on the left hand, as demonstrated in Figure 32. At the same time, the evaluation results (including the correlation with the histograms of criteria photographs, the percentage of remaining pavement markings and the final level of presence conditions conducted by previous two results) are displayed at the bottom of the window interface. Additionally, by clicking the button Process on the left top of the window interface, a drop down box appears (as in Figure 33). Users can also examine each technique applied into the determination of presence conditions of pavement markings in the image, for instance, converting the image to gray one, filtering the gray image, Hough transformation, detecting edge lines of ideal pavement markings, etc. through this drop down box. If users want to close the window interface of Analysis, they can click the button Close located next to the button Process on the left top of the window.

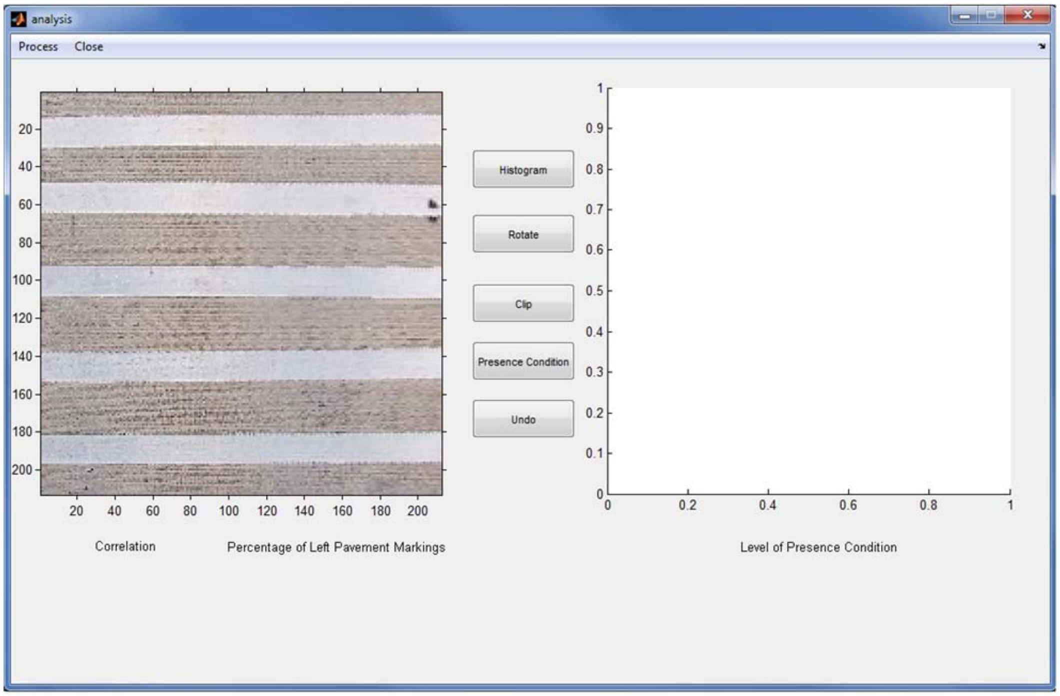

Figure 30 The Window Interface of Analysis

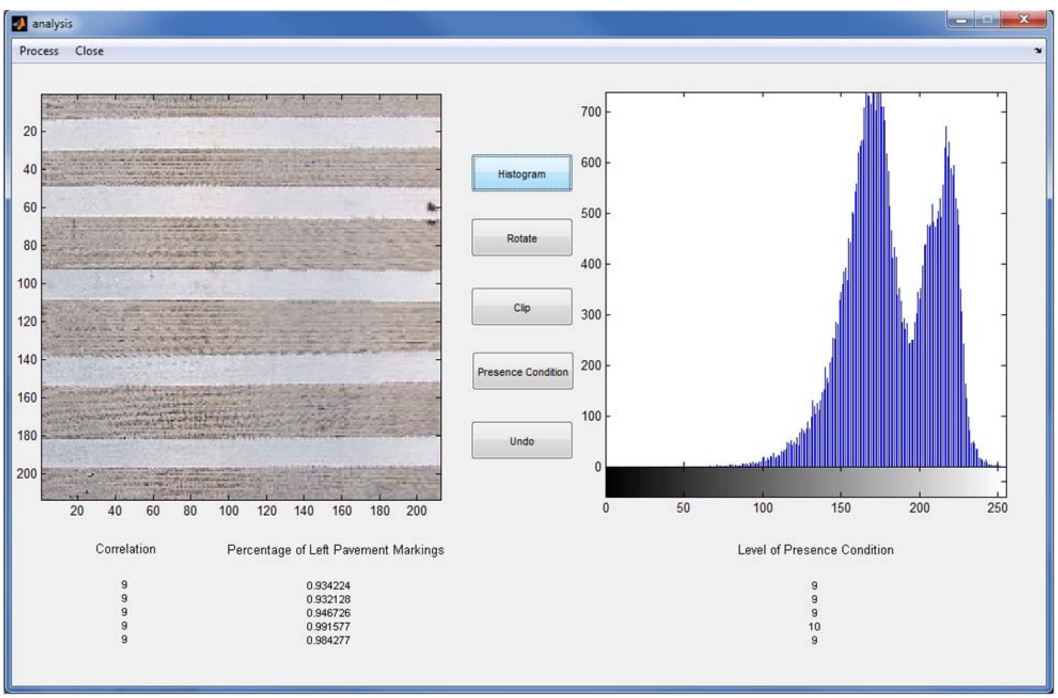

Figure 31 Histogram showed in the Window Interface of Analysis

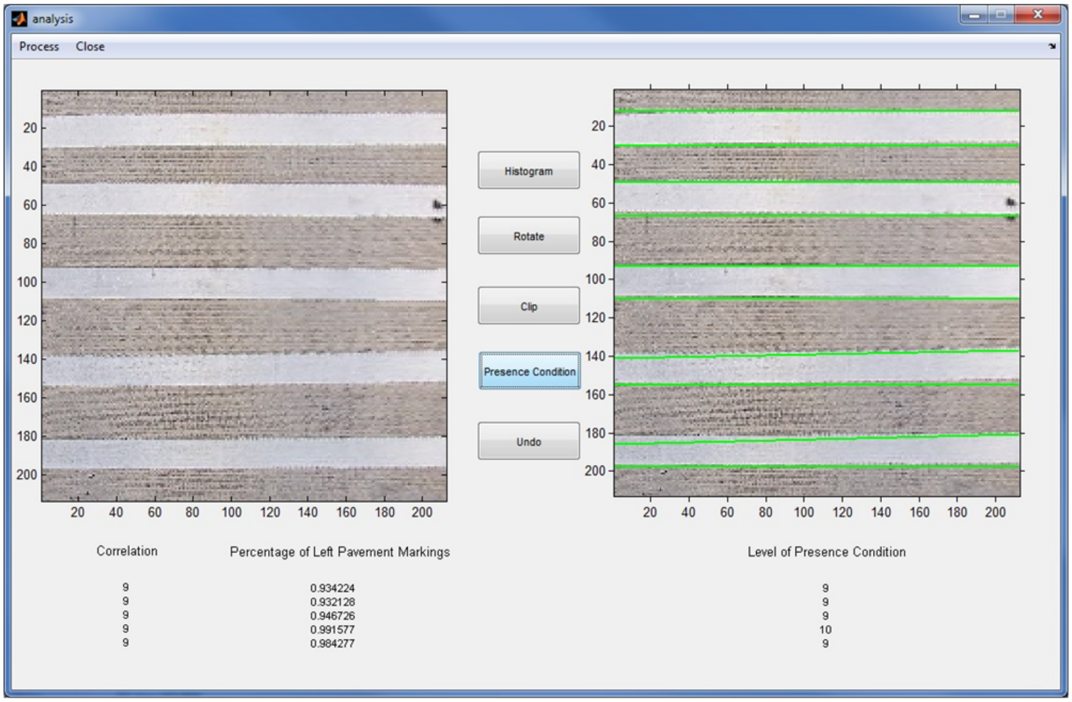

Figure 32 Determination of Presence Condition in the Window of Analysis

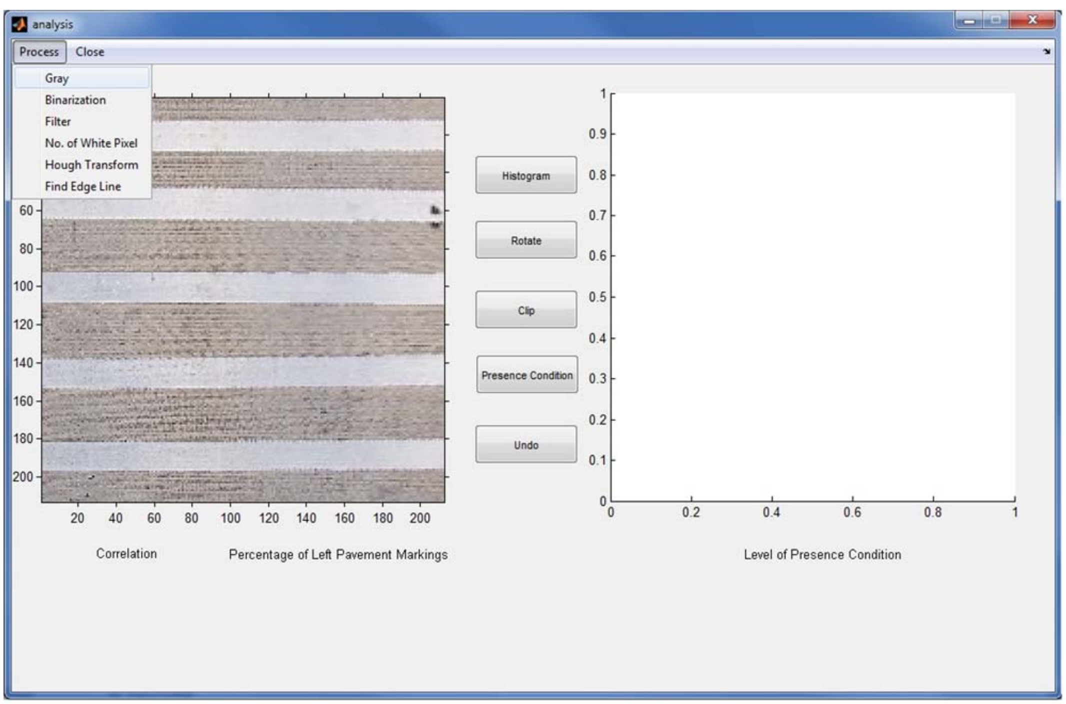

Figure 33 Process Menus in the Window of Analysis

5. CASE STUDY

5.1 Introduction

This section presents a case study of the proposed system on determining the presence conditions of pavement markings. Based on proper setups of the experiment, two different kinds of photograph datasets provided by the NTPEP Mississippi test deck program are used to evaluate the whole system developed in this thesis study. One is the criteria photographs used to test the reliability of calculating the percentage of remaining pavement markings manually. The other one is the test deck photographs used to investigate all functions of the developed system in terms of camera calibration, rotation, clip, etc. Finally, ten volunteers are invited to evaluate the interactivity as well as the usability of the developed system.

5.2 Data Description

The National Transportation Product Evaluation Program (NTPEP) was founded in 1994 as a Technical Services Program whose mission was to prequalify and test products, materials, and devices that are commonly used in transportation with comprehensive reduced duplication of efforts by state DOT's and industry participants. NTPEP mainly reports to American Association of State Highway and Transportation Officials (AASHTO), generating 12 to 15 reports yearly. These reports are distributed to end users and policy makers of AASHTO who have the opportunity to use the test data for future decision-making. Three main categories of transportation products are evaluated by NTPEP: traffic safety products, construction materials and maintenance materials. While the evaluation made by NTPEP covers a very wide range of products and materials, this work is only concerned with pavement markings.

Pavement markings, as an important form of traffic control devices, provide positive travelling guidance to the public in terms of the road geometry, especially at night. Currently, a total of 10 states covering different environmental and traffic conditions have set up test decks, involving themselves into in NTPEP programs that evaluate pavement marking materials.

The Mississippi NTPEP test deck located along U.S. Highway 78 is an NTPEP test PMM deck for the southeast region. In 2006, a new field test deck was also set up in Mississippi, which has installed a pavement markings test deck for the NTEPEP evaluation program in 1999, 2002 and 2004, respectively. There are two sites located in a flat area, including a concrete pavement site and an asphalt site. Both sites meet the criteria for ASTM-713 for site location. A total of 46 different pavement marking materials provided by 8 vendors were installed at this Mississippi test deck in 2006. The performance of the pavement markings, including retroreflectivity, durability, and color, is periodically monitored in intervals of two or three months from the initial set of readings over three years. At the time of measurement, the photograph for each pavement marking was recorded by digital camera as well. These photos can be used to test the effectiveness and robustness of the whole system developed in this study. At each measurement, the presence conditions of pavement markings were also produced by averaging five experts' grades, and recorded in an Excel file. An example image of pavement markings transversely installed at Mississippi test deck is illustrated in Figure 34.

Figure 34 An Example Image of Mississippi Test Deck

During the period of evaluation over three years, a total of 2,065 photographs were collected from July 2006 to July 2009. More than 10,530 pavement markings (including repeated counts) appeared in these photographs. The photograph resolution is 1,024 × 768 in JPEG format. To evaluate the proposed algorithm, 844 photographs were chosen, covering two different types of pavement surfaces and various lighting conditions. 391 photographs were taken from asphalt surfaces and 453 photographs from concrete surfaces. These NTPEP photographs are the only ones with corresponding ratings conducted by experts' observation.

Additionally, in order to further test the capability to determine the presence conditions of pavement markings for the proposed system, a total of 20 criteria photographs used in the NTPEP Mississippi test deck are adopted in this study as well. The criteria photographs labeled from level 1 to 10 are produced with a variety of pavement surfaces and various out-door conditions such as lighting, weather, etc. Examples of criteria photographs are illustrated in Figure 35.

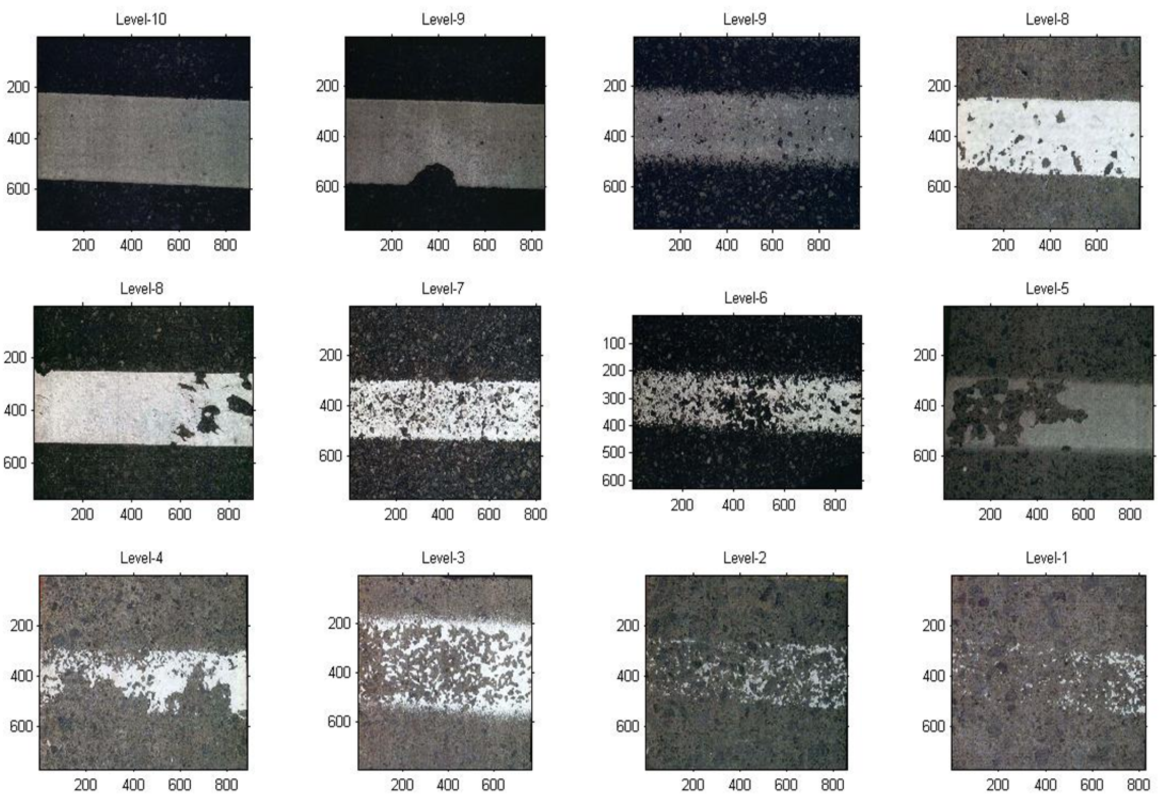

Figure 35 Examples of Criteria Photographs

5.3 Comparison with the Manual Method

In order to assess the system, with respect to the percentage of remaining pavement markings, the manual method is adopted in this study by comparing an estimate of the number of remaining pixels of remaining pavement markings with the ideal pixels of pavement markings using external observations and Matlab image processing. With visual observation, the edge lines of ideal pavement markings are selected manually and recorded with respect to the corresponding geometric properties. The remaining area is cropped within two ideal selected edges. By manually choosing the optimized threshold value, the area of remaining pavement markings in the image is converted to binary, where each pixel of pavement markings with a grid is represented by 1, and one of others is represented by 0, aiming for results that are approximately close to actual conditions. The actual area of remaining pavement markings is then assessed by summing up the squares represented by 1 within two ideal selected edge lines. Correspondingly, the ideal area of pavement markings is calculated by multiplying the width of pavement markings by the length of the image. Thereafter, the percentage of remaining pavement markings in the image can be determined by the ratio of the actual area and the ideal area of pavement markings manually calculated by eye and Matlab image processing tool. This percentage is considered as accurate for further comparison. It needs to be noted that since the manual method is very time-consuming with a high labor-cost (which limits the number of samples used to test the developed system), all criteria photographs used for testing are converted to a resolution of

250×280 pixels in order to simplify the evaluation and comparison with less time and labor.

In order to investigate the accuracy and reliability of the whole system, the comparison with the percentage of pavement markings determined manually for 20 criteria photographs is demonstrated in Table 4.

Table 4 Comparison of Percentage of Pavement Markings Using Criteria Images

Criteria Photographs (Level)	No. Pixels of Remaining Pavement Markings	Percentage of Remaining Pavement Markings	
		Manual Method	Proposed System
10	32220	97.81%	96.34%
9	30288	92.93%	91.58%
9	23677	91.61%	93.24%
9	25473	93.43%	90.93%
9	22777	94.11%	93.14%
8	22217	89.13%	85.68%
8	24172	85.80%	83.51%
8	25463	88.18%	87.50%
8	21997	85.70%	83.67%
8	22161	86.97%	84.56%
8	22322	85.31%	84.03%
7	17435	76.48%	79.36%
6	16392	63.74%	67.33%
6	16383	68.89%	62.53%
5	14902	52.22%	50.73%
5	15768	58.78%	54.11%
4	9827	43.15%	42.53%
3	8119	38.65%	43.02%
2	3458	19.03%	18.98%
1	1587	12.84%	11.16%

Furthermore, the statistical analysis is made to test whether the developed system is reliable in the determination of presence conditions of pavement markings as the manual method is. A paired T-test is used here to investigate the difference of the percentage of remaining pavement markings between the proposed algorithm and the manual method for each criteria photograph based on the calculated *t*-value with the confidence interval 95%. From Table 5, it can be seen that the means of the percentage conducted by two methods are very close, and the *t*-value is greater than 0.05, indicating that there is no statistically significant difference between the percentages of presence conditions of pavement markings calculated by the manual method and the developed system, respectively.

Table 5 Comparison between the Developed System and the Manual Method

t-Test: Paired Two Sample for Means

	Manual Method	*Developed System*
Mean	0.70888	0.698965
Variance	0.071018	0.068527
Observations	20	20
Pearson Correlation	0.995295	
Hypothesized Mean Difference	0	
Df	19	
t Stat	1.702033	
P(T<=t) one-tail	0.052528	
t Critical one-tail	1.729133	
P(T<=t) two-tail	0.105055	
t Critical two-tail	2.093024	

5.4 Test Using the Test Deck Photographs

The developed system is tested using the photograph datasets provided by the NTPEP Mississippi test deck. In order to test the effectiveness and robustness of the system developed in this study, a total of 3253 pavement markings under asphalt and concrete surfaces, including 22 products provided by 8 vendors in 844 photographs, were measured via inclusion into the whole system. Each pavement marking used for testing the system has a grade of the presence condition by averaging grades from five experts' observations, considering as the ground-truth values for the comparison with grades conducted by the developed system.

A total of 1631 pavement markings on asphalt surfaces recorded in 391 photographs and 1978 pavement markings on concrete surfaces recorded in 453 photographs over three years were measured here with the comparison of the corresponding grades made by experts' observation.

First of all, Table 6 shows the performance of camera calibration proposed in the study along with the percentage of success. It can be seen that the proposed calibration method generally achieved a percentage of more than 90% for successfully correcting the geometric deformity caused by the digital camera in test deck photographs. As a rule of thumb, a rate in the range of 90-99% is generally considered as "good" in camera calibration. Therefore, the proposed method of camera calibration has a good capability to handle the geometric deformity occurred in the NTPEP test deck photographs. However, there are still 73 photographs (31 under asphalt surface and 42 under concrete surface) in which the proposed method cannot be applied. As briefly mentioned earlier, the proposed method of camera calibration could automatically detect the vanishing point used to calculate the geometric properties of the camera, strongly depending on the edge detection and Hough transformation which cannot be used for photographs taken by the camera under very strong light. In that case, the objectives are very difficult to be extracted from the background in the photographs. After examining the 73 photographs in which the proposed method failed, it was found that 52 of them (22 of asphalt surface and 30 of concrete surface) were taken under very strong light conditions, and the rest of the photographs (6 of asphalt surface and 15 of concrete surface) were contained too many interferences such as vehicles, people, equipment, etc. Obviously, the rate of successfully implementing the proposed camera calibration method for pavement markings on concrete surfaces is worse than that for pavement markings on asphalt surfaces. This rate difference exists because the color of pavement markings, especially for white ones, is closer to that of concrete than that of asphalt. This color similarity significantly increases the difficulty of extracting pavement markings from photographs, and further causes the failure of detecting the vanish point which strongly depends on the results of edge detection and Hough transformation affected by strong outdoor light, as stated previously. However, it should be noted that there is no significant difference between rates of successfully implementing the camera calibration in test deck photographs with the backgrounds of asphalt and concrete surfaces as well, which means that the camera calibration method proposed in this study is capable of correcting the geometric deformity that occurs in test deck photographs for both pavement surfaces without extreme light conditions. Additionally, the presence conditions of pavement markings still can be determined through the developed system without the process of camera calibration.

Table 6 Results for Camera Calibration in Test Deck Photographs

	Asphalt		Concrete		Total	
	Quantity	***Percentage***	***Quantity***	***Percentage***	***Quantity***	***Percentage***
Total Images	391	100.00%	453	100.00%	844	100.00%
Failure in Camera Calibration	31	7.93%	42	9.27%	73	8.65%
Success in Camera Calibration	360	92.07%	407	90.73%	767	91.35%

In this study, a total of 3609 pavement markings in 844 photographs (1631 on asphalt surfaces and 1978 on concrete surfaces) were adopted to test the capability of determining the presence conditions of pavement markings for the developed system with the high accuracy and robustness. In order to investigate how well the developed system performed, it is better to start from analyzing the pavement markings for which the developed system in this study cannot work very well. Some pavement markings cannot be accurately evaluated by the developed system because they were installed too close to each other, which could cause the bias of the edge line detection of pavement markings and further confuse the developed system. Furthermore, it is found that such failures also happened in some pavement markings that were very difficult to be extracted from the pavement surface due to similar coloring with the background (pavement surface). According to the overall observation in this study, 80.05% of levels of presence conditions of pavement markings obtained by the developed system are consistent with ones conducted by experts' observations, which means that the proposed algorithm does not yield significant different performance in the determination of presence conditions of pavement markings over the expert observations. Apparently, the developed system in this study performed worse on pavement markings applied on concrete surfaces than those applied on asphalt surfaces. However, it did not yield a significant difference in the rate of determining the presence conditions consistent with experts' observation between pavement markings applied on asphalt and concrete surfaces. Comparing the results in this test, it is obvious that the developed system is capable of determining the presence condition of pavement markings applied on a asphalt surfaces with a better accuracy and success rate than those applied on a concrete surfaces.

Table 7 Results for Testing the Developed System with Test Deck Photographs

	Asphalt		**Concrete**		**Total**	
	Quantity	***Percentage***	***Quantity***	***Percentage***	***Quantity***	***Percentage***
Total Images	391	100.00%	453	100.00%	844	100.00%
Total Pavement Markings (lines)	1631	100.00%	1978	100.00%	3609	100%
Inconsistency with Observation Results	274	16.80%	446	22.55%	720	19.95%
Consistency with Observation Results	1347	83.20%	1532	77.45%	2708	80.05%

Note: ***Consistency*** means that the level of presence condition of pavement markings produced by the developed system is exactly equal to the one conducted by expert's observation, and vice versa.

Though there are 720 ratings inconsistent with ratings provided by experts' observations, it should be noticed that the differences are ± 1 in most cases, as shown in Figure 36. This demonstrates that the error distributions for pavement markings applied on both asphalt and concrete surfaces. In general, tests for pavement markings on concrete surfaces conducted with more and larger errors than tests for pavement markings on asphalt surfaces.

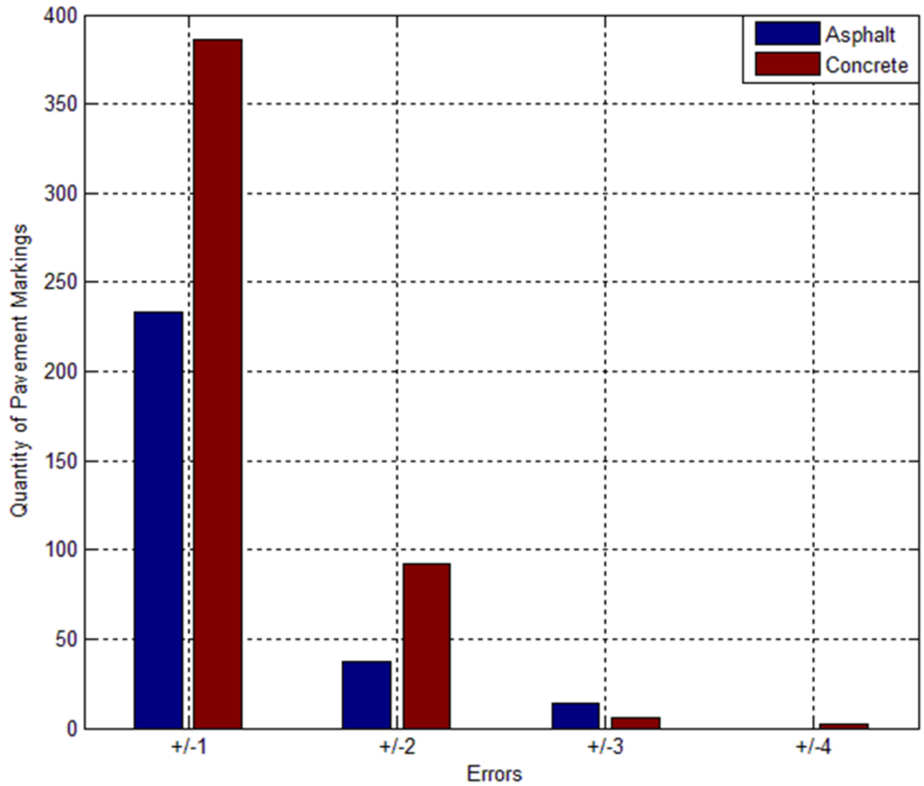

Figure 36 Error Distributions for Testing the Developed System

The error distributions for each level of pavement markings are specifically illustrated in Table 8, supporting the conclusions stated. Clearly, a ± 1 error accounts for a large proportion of tested errors for pavement markings graded from the level 10 to 1. Sometimes, it is difficult to distinguish pavement markings graded by the level 10 and 9 by eyes for experts as well.

Table 8 Error Distributions for Each Level of Pavement Markings

Level of Presence Conditions of Pavement Markings	***Asphalt*** Error Distribution				***Concrete*** Error Distribution				
	±1	±2	±3	Total	±1	±2	±3	±4	Total
10	99	25	7	131	159	65	3	1	228
9	103	3	3	109	115	10	0	0	125
8	14	7	2	23	45	4	0	0	49
7	2	2	0	4	23	10	2	1	36
6	0	0	1	1	6	2	1	0	9
5	1	0	1	2	3	1	0	0	4
4	0	0	0	0	1	0	0	0	1
3	0	0	0	0	0	0	0	0	0
2	1	0	0	1	0	0	0	0	0
1	3	0	0	3	0	0	0	0	0
Total	223	37	14	274	346	92	6	2	446

Based on visual inspection, most of these pavement markings inconsistent with the results from the expert observations are graded by the level 10 or 9. This is because experts will focus on the horizontal erosion of pavement markings as well as the vertical erosion such as the change of thickness, the wear of glass beads, etc. Commonly, that the wear of pavement markings in the perpendicular direction (thickness) is generally greater than wear in the horizontal for pavement markings graded by the level 10 or 9, especially in the 2 or 3 years after the initial application. Nevertheless, as the system cannot evaluate the presence conditions of pavement markings in the perpendicular direction due to the limitations of 2-D photographs adopted as the data source in this study which would result in the errors stated above. It is expected that more errors appeared in the pavement markings on concrete surfaces than asphalt surfaces because of more samples in the former, in addition to the previously stated similarity of colors. Note that the maximum error is ± 4, which only occurred in 2 pavement markings applied on the concrete surface with the levels 10 and 7 graded by experts. Compared with the amount of pavement markings evaluated here, such errors are only a small part of it, making them insignificant to the broader picture. Additionally, the visual inspection does not completely support the field ratings due to subjective evaluation. Generally, the error distributions in this case study can be accepted to demonstrate that the determinations produced by the developed system are not greatly dispersed comparing with those made by experts.

In this study, as mentioned earlier, there are a total of 20 different products of pavement markings, such as Temporary Tape, Thermoplastic, Methyl Methacrylate (MMA), Waterborne, Epoxy, and Solvent-borne, which are all used to test the system's performance. According to the levels graded by the expert observations for each pavement marking displayed in test deck photographs, the results revealed that the developed system did not perform very well for pavement markings made from materials such as Methyl Methacrylate (MMA) (which exists as a solid that is mixed in a static mixer immediately prior to application) on both asphalt and concrete surfaces.. Figure 37 and Figure 38 show the comparison between the levels of presence conditions conducted by the expert observations and the developed system for four MMA markings located in the NTPEP Mississippi test deck. It is clearly shown that for all measurements, the levels graded by the developed system are equal to or lower than ones made by the expert observations during the whole period of evaluation. Additionally, visual inspection of the curves indicates that the differences of levels between two algorithms become smaller over time, which implies that the developed system is capable of performing better over time. This occurs because Methyl Methacrylate (MMA) markings did not cover all pavement surfaces within the area of markings, even at the beginning of the installation. Hence, the developed system depending on the percentage of remaining pavement marking pixels and the correlation with the histograms of criteria photographs determined the lower levels of the presence conditions of pavement markings that did not covering all pavement surface within the area of markings than corresponding ones made by the expert observations.

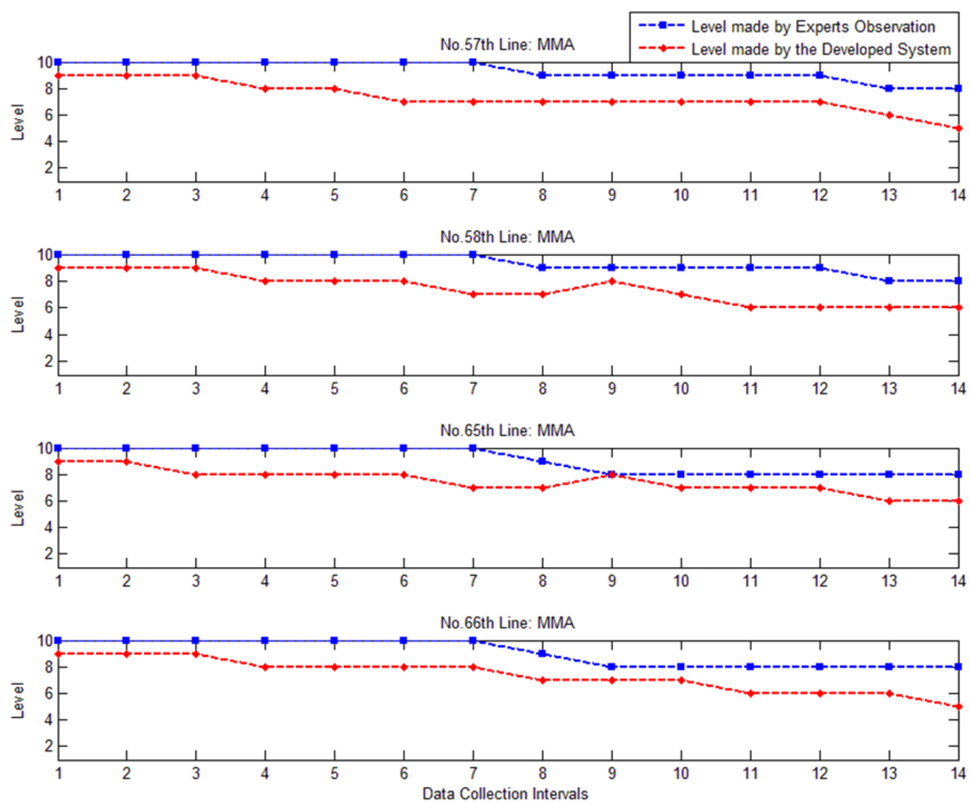

Figure 37 Comparison between Two Methods for the MMA Markings on Asphalt Surfaces

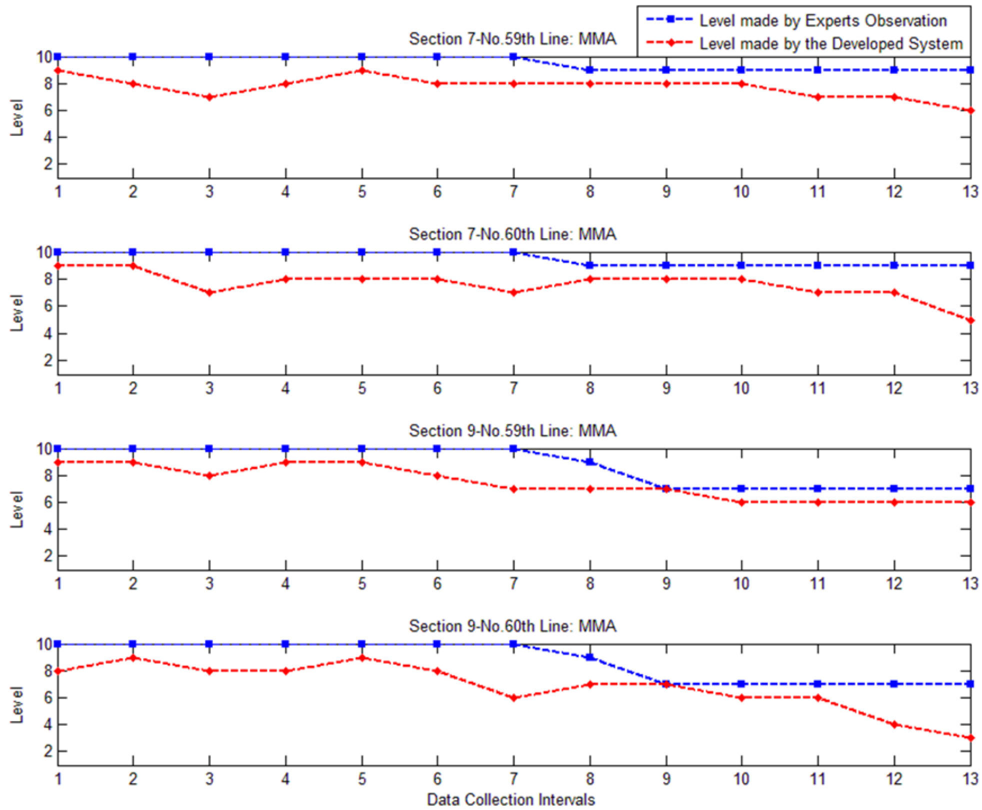

Figure 38 Comparison between Two Methods for the MMA Markings on Concrete Surfaces

Meanwhile, after examining results of pavement markings on asphalt and concrete surfaces, it can be seen that the developed system may be not appropriate for evaluating Thermoplastic pavement markings in the first 3 years as well because of over-evaluation such as grading the level 9 pavement markings by 10. Thermoplastic pavement markings, as the most common pavement markings used on roadways in Texas for years, have been known to last from 5 to 8 years depending on traffic volumes. At the beginning of 2 to 3 years, the erosion of Thermoplastic pavement markings occurred mostly in the vertical direction, and slightly in the horizontal direction. As stated previously, the developed system in this study only focused on the horizontal erosion of pavement markings, which is the main reason for over-grading Thermoplastic pavement markings. The same problem of over-grading the presence conditions can be found in Performed Thermoplastic markings, which would be slightly worn in the horizontal direction at the beginning of 2 or 3 years. Therefore, the developed system is still potential to determine the presence conditions of Thermoplastic pavement markings well after 2 or 3 years.

Correspondingly, as shown in Table 9, there are several pavement markings such as Durable Tape, Waterborne and Temporary Tape in which the developed system is capable of better determining the presence conditions because of the high rate of consistency with the levels made by the experts' observations.

Table 9 Results of Testing Pavement Markings: Durable Tape and Waterborne

Pavement Marking Type	**Consistency with the Levels graded by the Experts' Observation**	
	Quantity/Total (markings)	***Percentage***
Durable Tape	190/196	96%
Waterborne	143/156	93%
Temporary Tape	273/288	95%

In all, the developed system can perform very well in the determination of presence conditions of pavement markings such as Durable Tape, Waterborne, and Temporary Thermoplastic. For Methyl Methacrylate (MMA) and Thermoplastic markings, the developed system is capable of determining the present conditions very well only after 2 or 3 years after the application since there is no need to use the system when the markings are still very good.

5.5 Evaluation of the Interactivity

To estimate the interactivity of the developed system, ten volunteers were invited to score the system using a simple survey. The survey contained four categories: Appearance, Simplicity, Operability, and Reliability. Using these four categories, the volunteers were asked to describe and evaluate the system. Appearance was mainly for evaluating the design and aesthetics, such as the placement of buttons, menu settings, etc. Simplicity is for whether users can get clear instructions on how to operate. Operability is for if the developed system is easy to be used. Reliability, as its name suggests, is for how reliable the developed system works. Each subject is graded on a numerical scale from 1 (worst) to 10 (best). Figure 39 demonstrates the result of this feedback. The score for each subject is conducted by averaging the scores of all volunteers, and specific information about the result of survey can be found in the Appendix. In general, the developed system performed well for all volunteers. Both simplicity and operability got an average score of 8, indicating that the developed system could achieve all functions with simply operations and clear instructions. However, it is also obvious that the appearance of the developed system was considered a little bit simple, needing to be enhanced further to become more user-friendly.

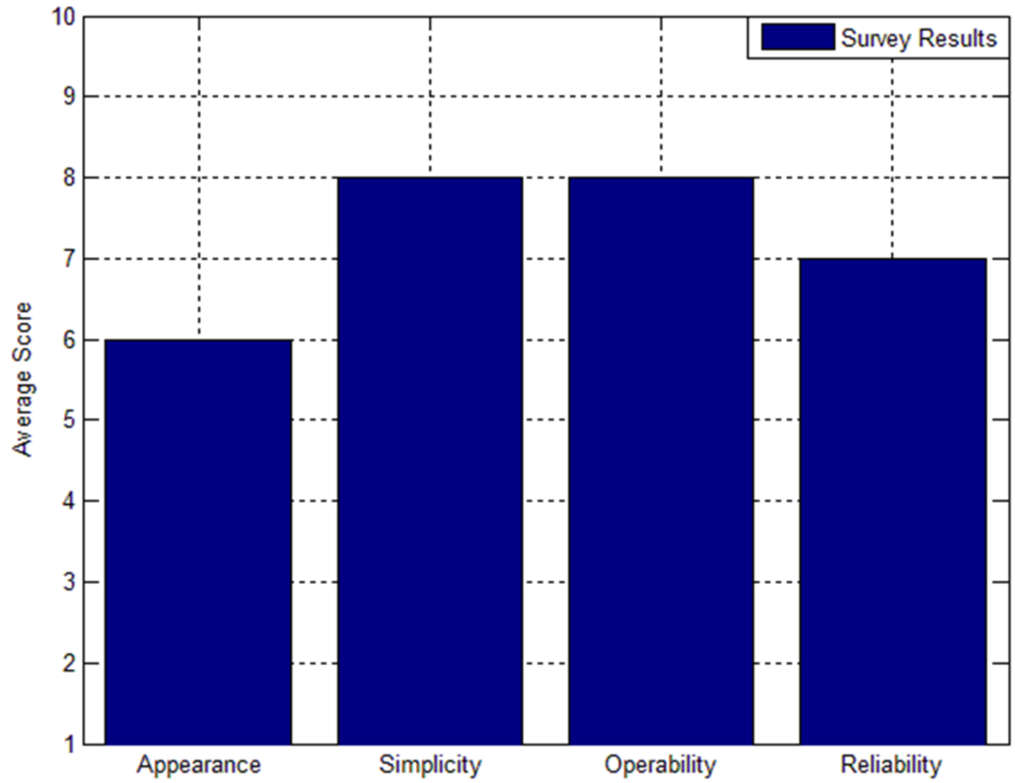

Figure 39 Evaluation Results from 10 Volunteers

6. RECOMMENDATION AND FUTURE WORK

6.1 Summary

In this study, a systematic methodology is developed to automatically determine the presence conditions of pavement markings using digital image processing techniques. The work has focused on the development of a process for the analysis of presence conditions for pavement markings as a theoretical foundation for further mutually applying image processing techniques into the evaluation of pavement markings. The whole system developed in this study consists of five components which can be used to correct the geometric deformity occurred in the NTPEP test deck photographs, detect colors of pavement markings, segment images, enhance images, detect the edge lines of pavement markings and recognize features of pavement markings. To enhance and facilitate the overall process, a software package with a user-friendly interface was developed by Graphic User Interface (GUI) of Matlab as a platform to implement all functions proposed in this study. The developed system (the interface) can open files, calibrate cameras, and perform a variety of other operations to images.

All photographs used to test the effectiveness and reliability of the developed system are provided by the NTPEP. These photos are divisible into two sections: 20 criteria photographs, and 844 real test deck photographs from Mississippi test deck from 2006 to 2009, containing a total of 3609 pavement markings provided by 8 vendors. The first 20 criteria photographs are adopted to compare the accuracy of the proposed algorithm with that of the manual method (considered as reliable, but time-consuming and labor-intensive). The test deck photographs are used to investigate the capability of the proposed algorithm for both the single and multiple pavement markings and evaluate the developed software package. Additionally, ten volunteers were invited to try out the developed system and score it by filling out the surveys in order to estimate the interactivity. Comparisons and discussions on their respective implications are made.

6.2 Findings and Limitations

The empirical studies in this thesis research have shown satisfactory capability to automatically determine the presence condition of pavement markings for the developed system. All findings are listed below:

- The developed system is capable of grading the level of presence conditions of pavement markings in the criteria photographs, consistent with the results from the manual method. It can be found that there is no statistically significant difference in the percentages of presence conditions of pavement markings calculated by the manual method and the developed system, respectively.
- The camera calibration method proposed in this study performed very well with a percentage of more than 90% in terms of successfully correcting the geometric deformity caused by the digital camera in the test deck photographs. However, the photographs taken under very strong light are not appropriate to be analyzed by the proposed camera calibration method, which is the reason

why there are 73 photographs (31 of asphalt surfaces and 42 of concrete surfaces) unsuccessfully implemented by the proposed method.

- Most calculated levels of pavement markings inconsistent with those made by the expert observations have errors of ± 1. From visual inspections, such pavement markings are ones graded at level 10 or 9 in most of cases by the expert since the vertical wear of such pavement markings is significantly greater than that the horizontal one at the beginning of 2 or 3 years.
- To overcome the affection of various outdoor conditions in the photographs, the statistical pavement marking color model was proposed in this study, and performed very well to achieve the goal of pavement marking color detection, which could greatly increase the accuracy of extracting pavement markings from the background in further analysis.
- By comparing three different segmentation methods, Minimum Error Thresholding Method was adopted to extract the objectives (pavement markings) from the background of photographs (pavement surfaces) in this thesis study with a better capability than others.
- The developed system is capable of determining the presence conditions of pavement markings such as Durable Tape, Waterborne, and Temporary Thermoplastic with the high rates of consistency with the corresponding levels made by experts rather than Epoxy and Solvenborne markings. However, it is not the limitation for the developed system.

- Due to the feedbacks from ten volunteers, the developed software package can be generally accepted and satisfied though its appearance need to be further enhanced.

It is said that nothing in the world is perfect. Therefore, other than the slight issues within the findings stated above, there are some limitations for the developed system as follows:

- To demonstrate the accuracy of the developed system, the sample size of 20 criteria photographs used in this study might be small. There is a need to increase the sample size to produce more convincing conclusions. However, it cannot be denied that the manual method is very time-consuming and labor-intensive.
- The developed system is not appropriate for use with pavement markings which did not completely cover pavement surface within the area of markings at the beginning of two to three years after the application such as Methyl Methacrylate (MMA) markings, which leads to lower determination results of presence conditions. After two years after the application, the developed system can still work well.
- The developed system (only focusing on the horizontal erosion of pavement marking)s cannot be appropriately used in Thermoplastic markings at the beginning of two to three years after initial application, since such markings are mainly worn in the vertical direction, and slightly in the horizontal

direction at the beginning of two to three years. After two years after the application, the developed system can work well.

- The photographs taken by the camera under very strong light cannot be correctly analyzed by the developed system in this study, as pavement markings have failed to be extracted from the background, which means that the robustness of the developed system needs to be further improved.

6.3 Future Work

Notwithstanding the satisfactory performances of the developed system in this study, the developed system only focuses on the erosion of pavement markings in the horizontal based on 2-D photographs. It is expected to extend the work to measure other important characteristics of pavement markings such as luminance, retroreflectivity, and so on. For a system potential to be used in practice, it should be more reliable and accurate in the camera calibration and the detection of edge lines of ideal pavement markings. Due to the ability to determine the presence conditions of pavement markings, the developed system in this study can potentially achieve such determination with video log datasets as a real-time processing technique. Further attempts can be made to improve the robustness of the developed system for processing the images taken under strong light and the complicated background. Moreover, the incorporation of the developed system into Geographic Information System (GIS) should be able to help agencies manage pavement markings with better decisions. Additionally, as stated in the test using the test deck photographs, the developed system cannot conduct levels of the presence conditions of pavement markings such as Methyl Methacrylate (MMA) inconsistent with ones graded by the expert observations at the beginning of two to three years after the application. Further efforts could be made to work out these discrepancies.

The importance of this work is that it complements the determination of presence conditions of pavement markings made by the experts' eyes as an important reference when experts want to grade pavement markings, which could help them make more accurate and consistent grades. Furthermore, it can be integrated into mobile pavement marking retroreflectometer van for more comprehensive and faster evaluating pavement markings associated with the measurement of retroreflectivity. The final goal of the developed system is to automatically determine the presence conditions of pavement markings with 2-D photographs or video logs under various outdoor conditions, completely replacing evaluations by experts.

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APPENDIX

Table A Products List Used in the Study

Manufacture	Product Name	Product Type
3M	Stamark High Performance 380T	Durable Tape
3M	Stamark Tape 270ES	Durable Tape
3M	Stamark Wet Reflective 380WR-ES	Durable Tape
3M	All Weather Paint Series 90	2-Year Durable
3M	All Weather Paint Series 70	2-Year Durable
3M	Wet Reflective Removable Tape Series 780	Temporary Tape
Advance Traffic markings	Series 400	Durable Tape
Advance Traffic markings	Series 300	Durable Tape
Ennis Paint Co.	885631	Thermoplastic
Ennis Paint Co.	885630	Thermoplastic
Ennis Paint Co.	999109	MMA
Ennis Paint Co.	999111	MMA
Epoplex	LS70DD	Epoxy
Epoplex	LS90DD	Epoxy
Flint Trading (LFK, Inc)	PreMark Plus	Preformed Thermplastic
Flint Trading (LFK, Inc)	HotTape Hight Optic	Preformed Thermplastic
Sherwin-Williams Company	2005-058-036	Waterborne
Sherwin-Williams Company	2005-058-030	Waterborne
Sherwin-Williams Company	2005-058-034	Solventborne
Sherwin-Williams Company	2005-058-032	Solventborne
Swarco Industries	Swarcotherm Alkyd	Temporary Tape
Crown Technoogies II	Tuffline Select	Thermoplastic

Table B Feedback of 10 Volunteers for the Interactivity of the Developed System

Survey Subjects	Volunteer Number										Average
	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	No. 8	No. 9	No. 10	
Appearance	6	7	8	5	6	7	6	7	7	5	6.4
Simplicity	8	9	8	7	8	7	7	8	9	7	7.8
Operability	8	8	7	8	7	6	7	9	9	8	7.7
Reliability	7	7	7	7	8	8	6	7	7	8	7.2

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