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16. Abstract:
In this project, the researcher successfully developed a highway speed vehicle-mounted thermoplastic pavement marking material (TPMM) thickness measurement device based on the research results in Project 0-4882, Refinement of a Non-Contact Method to Determine the Thickness and Uniformity of Application for Thermoplastic Pavement Marking Material. The device can be used in routine TxDOT project monitoring practice.

In Project 0-4882, a compact, light-weight pushcart laser device was successfully developed for measuring TPMM thickness. In comparison with the laser device developed in Project 0-4882, two new versions of vehicle mount laser thickness measurement devices have been developed in this project. The first new version, a point laser device, uses three synchronized point laser units to solve the inaccuracy problem caused by the slope of the road. The second new version, a scanning laser device, was developed based on the auto-synchronized laser scanning principle. This new scanning device can scan in the transverse direction and measure the average cross-section TPMM thickness. Since the scanning laser covers an area wider than the TPMM, the driver doesn't need to strictly follow the stripe, and the measurement accuracy will be increased on a bumpy or sloping road.

In this report, the laser triangulation and auto-synchronized scanning laser method is briefly reviewed. Then, the specifications of the laser devices and field test results are presented.

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Development of Vehicle-mounted Measuring Devices for Non-Contact Thickness and Uniformity Measurement of Thermoplastic Pavement Marking Material

by

Richard Liu, Yuanhang Chen, Aditya Ekbote, Wei Sun, Xuemin Chen, Jing Li and Pankaj Chopra

Research Report 0-5882-1
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Performed in Cooperation with the
Texas Department of Transportation
and the
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by the

Subsurface Sensing Laboratory
Department of Electrical and Computer Engineering
University of Houston

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DISCLAIMERS

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the Federal Highway Administration (FHWA) or the Texas Department of Transportation (TxDOT). This report does not constitute a standard, specification, or regulation.

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CHAPTER 1: INTRODUCTION

1.1 PROJECT OVERVIEW

In Project 0-4882, Refinement of a Non-Contact Method to Determine the Thickness and Uniformity of Application for Thermoplastic Pavement Marking Material, a compact, light-weight pushcart laser device was successfully developed for measuring thermoplastic pavement marking material (TPMM) thickness. A prototype of the vehicle-mounted laser thickness-measurement device was also developed. The prototype vehicle-mounted laser thickness-measurement device, which consists of two synchronized point laser units, was installed on a golf cart. However, measurement speed is limited and frequent traffic slow down is inevitable.

Based on Project 0-4882, a high speed vehicle-mounted device was developed. This vehicle-mounted device can conduct thickness measurements of pavement markings up to 30 mph, and collect large amounts of data with little or no impact on traffic. It is particularly effective in high traffic areas where there is often a concern about the performance of the pavement markings. It is very useful for job acceptance when minimum pavement marking thickness is specified, for monitoring striping performance and for the evaluation of new materials.

Compared with the laser device developed in Project 0-4882, two new versions of vehicle mount laser thickness measurement devices have been developed in this project. The first new version, a point laser device, uses three synchronized point laser units instead of the two used in the golf cart version to solve the inaccuracy problem caused by the slope of the road. The second new version, a scanning laser device, was developed based on the auto-synchronized laser scanning principle. This new scanning device can scan in the transverse direction and measure the average cross-section TPMM thickness. Since the scanning laser covers an area wider than the pavement marking, the driver doesn’t need to strictly follow the stripe and the measurement accuracy will be increased on a bumpy or sloping road.

Both of those two new versions are installed on the testing vehicle and have been tested at the University of Houston (UH) testing site and TxDOT Cedar Park testing site. The experiment results are very close to the real thickness of thermoplastic tape. A driving guide system is also installed in the testing vehicle in order to help the driver direct the vehicle along the thermoplastic tape.

In this report, the point laser and auto-synchronized scanning laser methods are briefly reviewed. Then, the specifications of the laser devices and field test results are presented.

CHAPTER 2: POINT LASER SYSTEM DESIGN AND SPECIFICATIONS

2.1 INTRODUCTION

To increase the speed of thickness measurement of TPMM, a vehicle-mounted laser measurement system was developed. Three independent laser devices are installed on a van. One laser device projects a laser beam onto the pavement with markings, and the other two lasers project a beam onto the pavement without markings. The marking thickness is obtained by processing the three laser devices' output signals. Figure 1 shows the developed device, and Figure 2 demonstrates the block diagram of the vehicle-mounted measurement device.

Figure 1 Designed vehicle-mounted device.

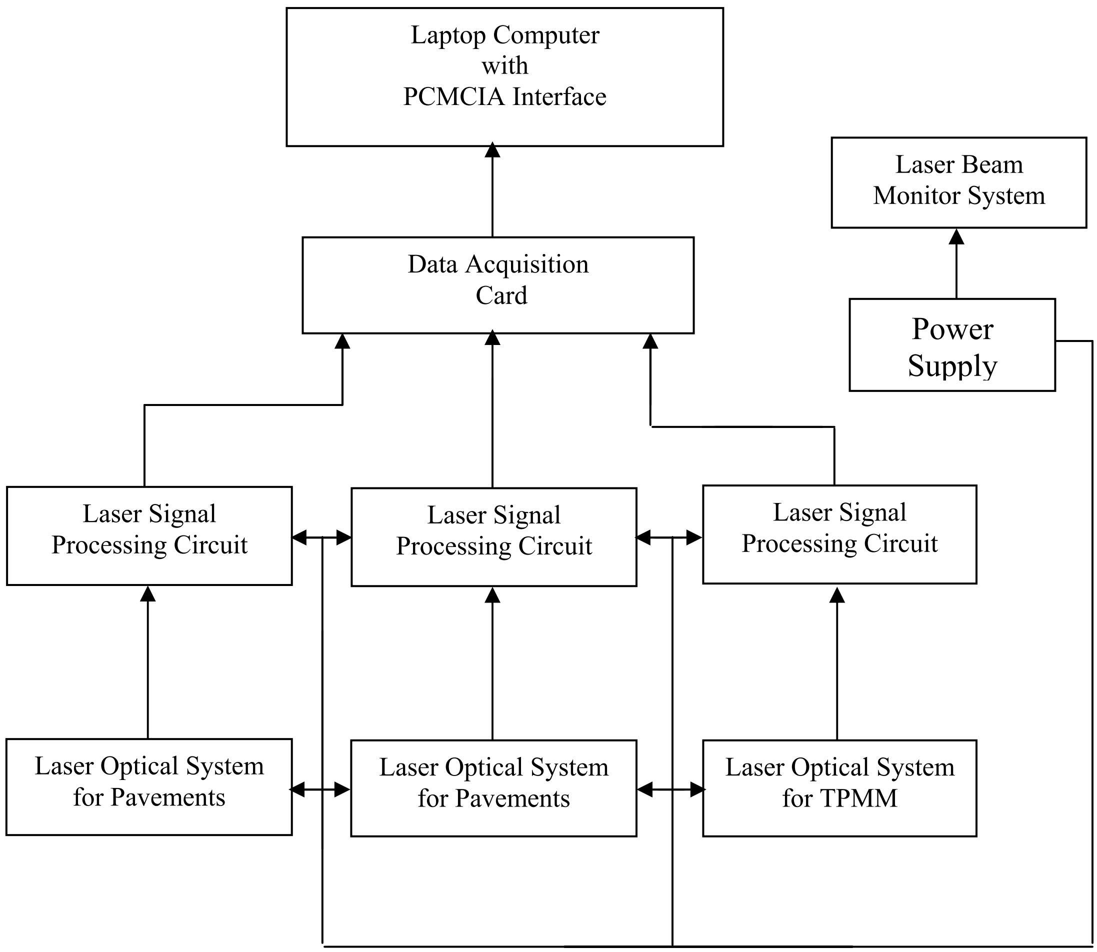


Figure 2 Block diagram of the vehicle-mounted device.

A 12 V automobile battery is used as the power source. A laser beam monitor system helps the driver to manage the driving direction. Through the power supply, 12 V is converted into different voltages required by the measurement device. Three separated laser optical systems simultaneously detect the position of the TPMM and the pavement. Three laser signal processing units process the detected laser signals and transfer the position signals to the different input channels of the data acquisition card. By subtracting and averaging the three position signals, the software package displays and stores the TPMM thickness imaging.

The thickness measurement of the TPMM by using three independent laser devices is illustrated in Figure 3.

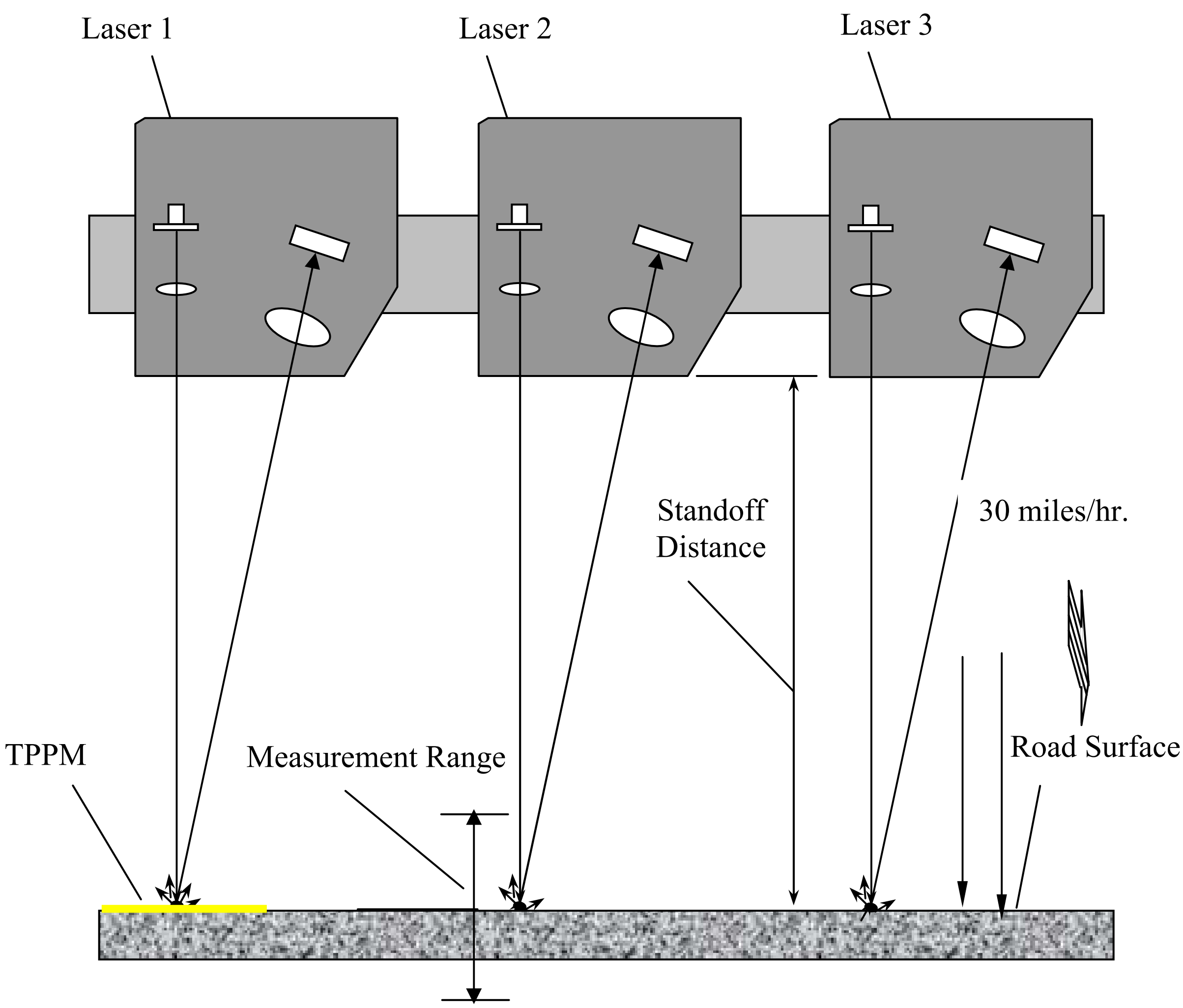
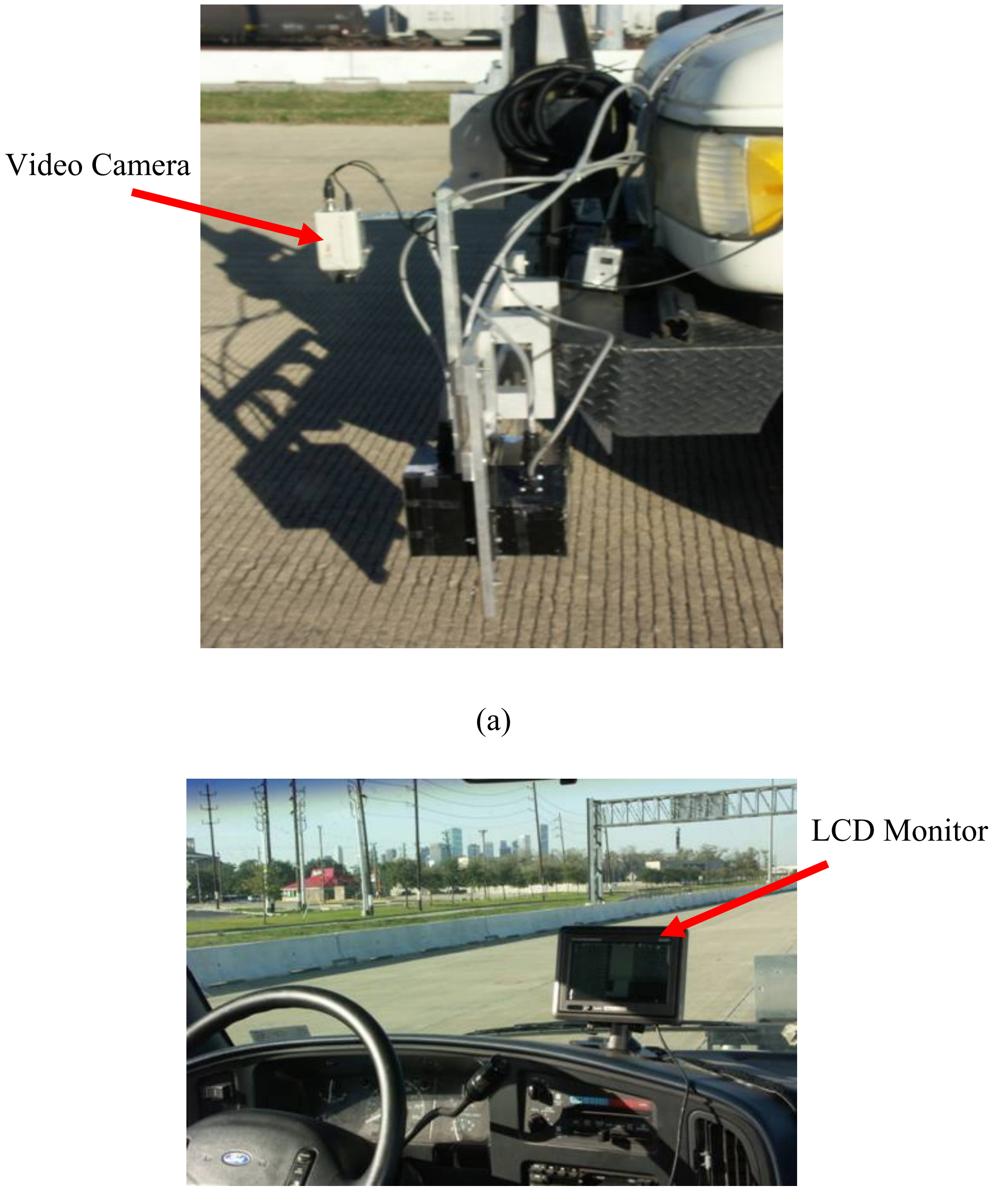


Figure 3 Using three independent laser devices to measure the thickness of TPMM.

In Figure 3, one laser is used to detect the position change of the pavement marking, and other two lasers are used to detect the position information of the pavement surface. Since both positions of TPMM and pavement are simultaneously detected by separated laser devices, there is no need to scan the laser source.

2.2 LASER BEAM MONITOR SYSTEM

The laser beam monitor system consists of a video camera and liquid crystal diode (LCD) display. The video camera was installed over the laser device to detect the laser beam and the LCD display was installed in the van to help the driver manage the driving direction. Figure 4 shows the configuration of laser beam monitor system.



(a)

(b)

Figure 4 Laser beam monitor system.

2.3 SOFTWARE PACKAGE

The software package processes the measured data and records the TPMM thickness information. Figure 5 shows the software interface for the vehicle-mounted device. TPMM thickness, distance measurement, and Global Positioning System (GPS) position are displayed on the software interface.

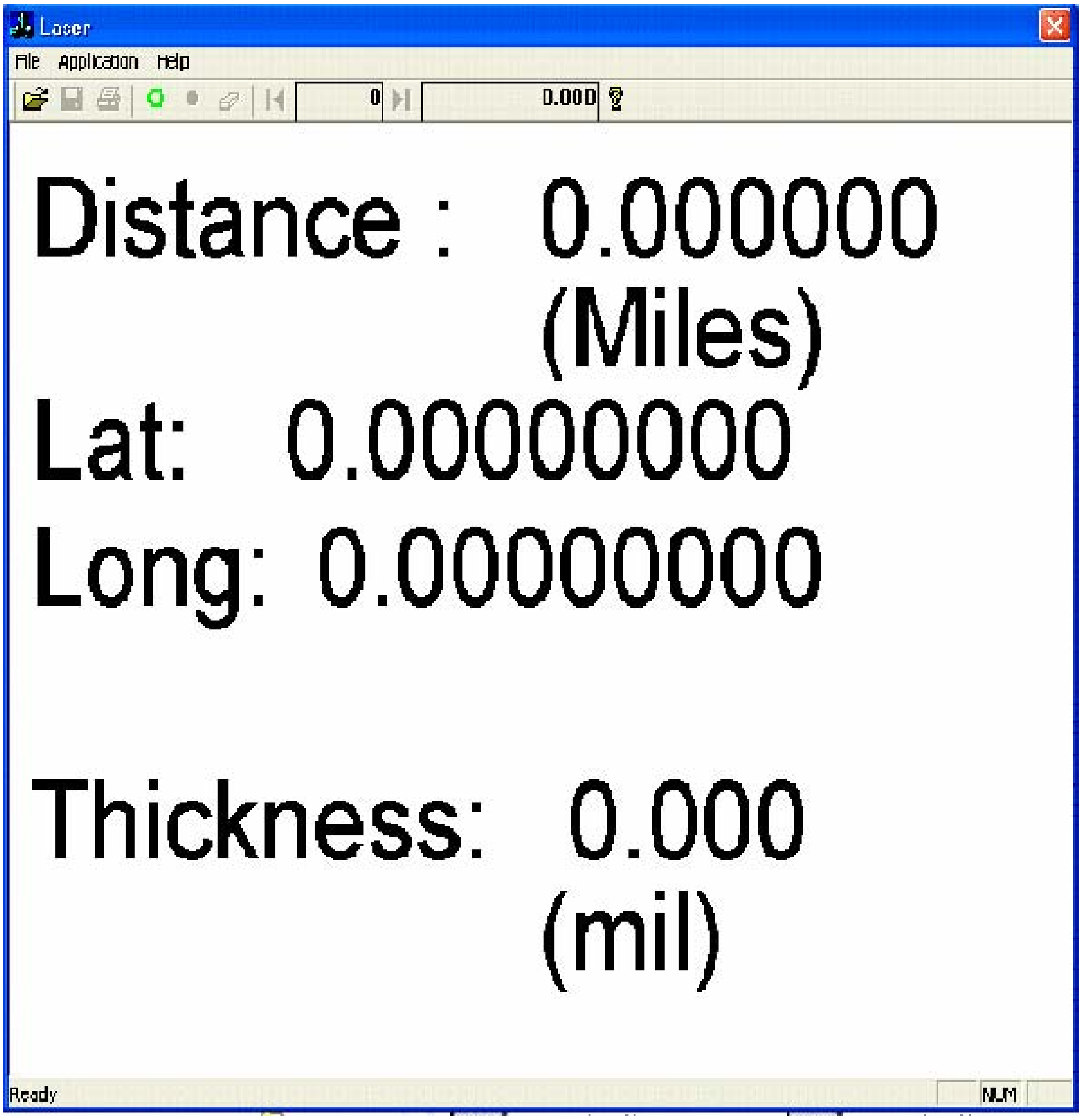


Figure 5 Software interface for the vehicle-mounted device.

The software interface in Figure 5 continuously displays collected TPMM thicknesses and distance measuring instrument (DMI) and GPS data. DMI data represents the measured distance; GPS data represents the position where the vehicle-mounted device is; and the thickness data represents the average difference between collected TPMM and pavement position information.

2.4 MOVING AVERAGE FILTER

The moving average filter is a simple low pass finite impulse response (FIR) filter commonly used for smoothing an array of sampled data [1]. The actual measured position signals contain random uniform noise. In order to smooth irregularities and random variations in the measured signals, a moving average filter is used to process the position signals. Figure 6 illustrates how the moving average filter can help remove noise that has been added to the desired signal.

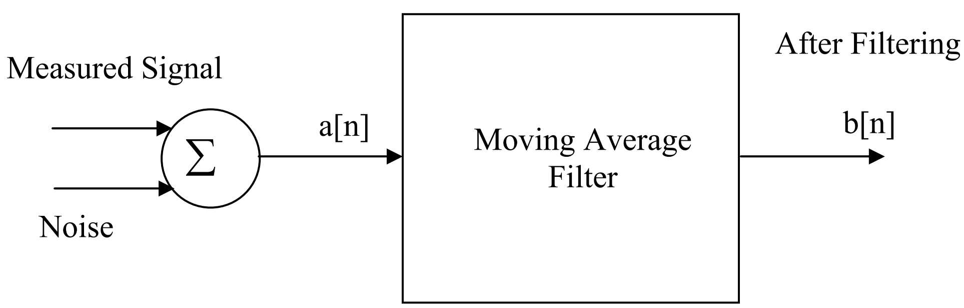


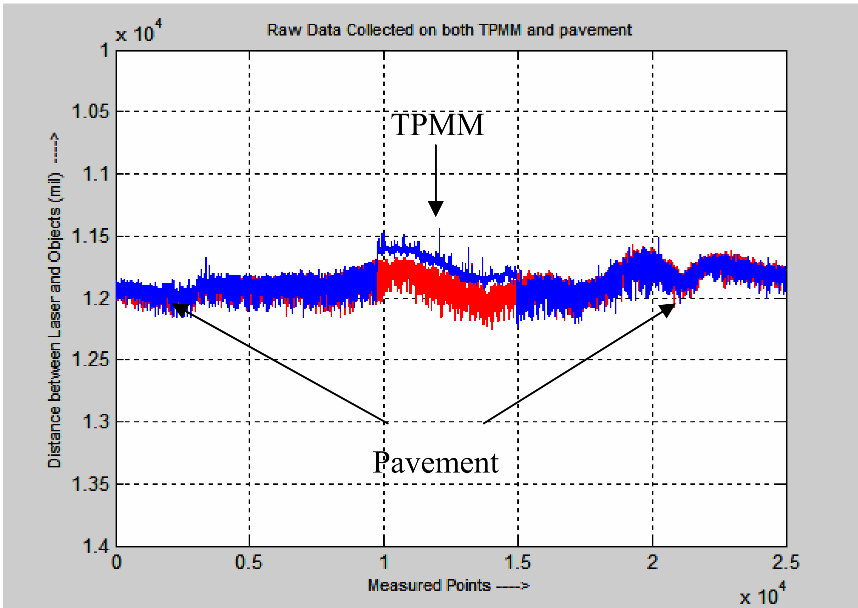
Figure 6 Signal through a moving average filter.

A moving average filter can be modeled mathematically as shown in Equation 1,

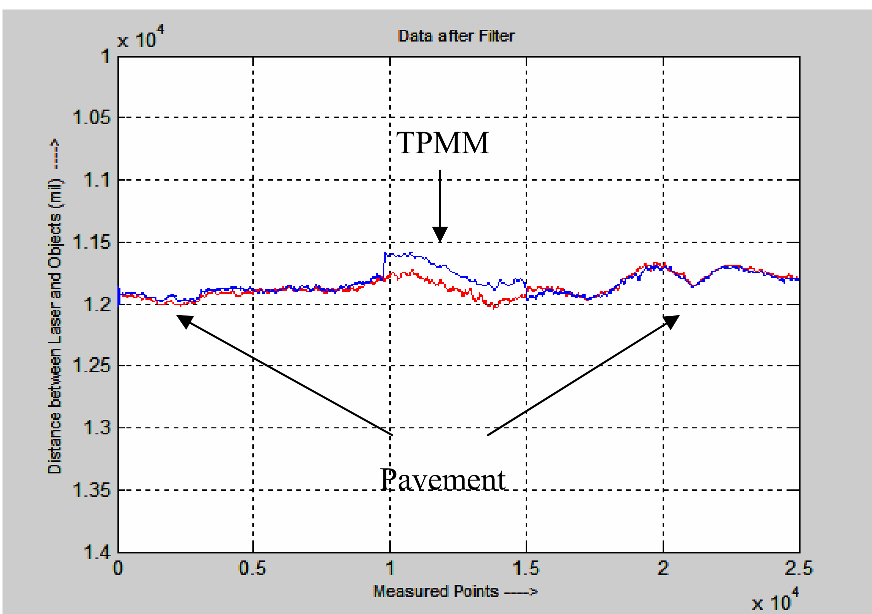
$$b[n] = \frac{1}{S}\sum_{k=0}^{S-1} a[n-k], \tag{1}$$

where a[n] is output of the data acquisition card, b[n] is the position data after the moving average filter, and S is the number of input signals for averaging.

Figure 7 shows the comparison of the TPMM profile before and after using a moving average filter. Figure 7(a) illustrates the output from the data acquisition card, and Figure 7(b) demonstrates the TPMM profile after using the moving average filter. The X-axis is the measured points per measurement, and the Y-axis is the corresponding distance information. We can see that the random noise is coupled with the measured position signal in Figure 7.



(a)



(b)

Figure 7 (a) TPMM profile before using filter; (b) TPMM profile after using filter.

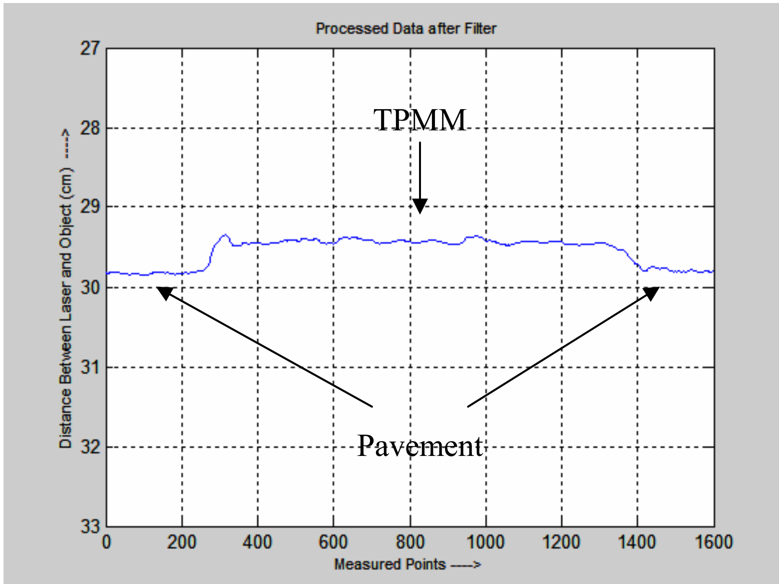
2.5 METHOD FOR DETECTING PRESENCE OF TPMM

In the field, some pavements have very irregular appearances. Since the system conducts measurement under moving or driving conditions, it is very important for the measurement system to automatically identify if the received position signal includes TPMM information.

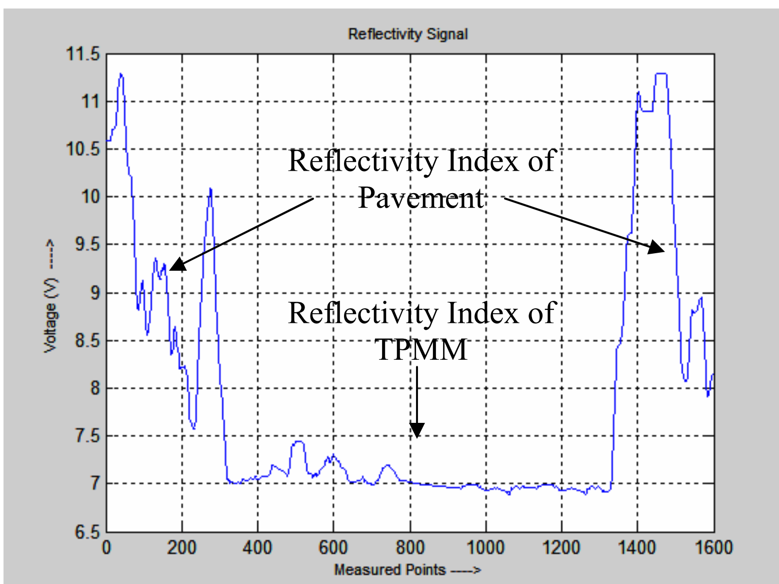
TPMM is a highly reflective material which can provide excellent nighttime delineation during either dry conditions or rainfall. Generally, TPMM is applied in white and yellow colors, and the reflectivity of those colors is above 90%. The materials of pavement are concrete, pebble, and asphalt, and reflectivity of those materials is less than 30%.

When the laser scans over the TPMM, the position sensing device (PSD) receives a strong energy level signal because of the high reflectivity of the TPMM. When the laser scans over pavement, the PSD receives a weak energy level signal due to the low reflectivity of the pavement. In the developed laser device, a power input (PI) controller is used to automatically adjust laser power according to the change of color and distance of object. Generally the output of the PI controller is larger than 8.5 V when the laser projects on the pavement, and is less than 7.5 V when the laser projects on the TPMM. Therefore, we use the output of PI as a reflectivity index to detect if the TPMM are presented in the received signals.

Figure 8 shows that the measured reflectivity index signal helps identify the start and end position of the TPMM. Figure 8(a) illustrates the measured TPMM profile, and Figure 8(b) demonstrates the corresponding measured reflectivity index. The X-axis is the measured points per measurement, and the Y-axis is the corresponding distance information and reflectivity index.



(a)



(b)

Figure 8 (a) Measured TPMM profile; (b) Corresponding reflectivity index.

2.6 SPECIFICATIONS

The vehicle-mounted device uses three laser devices instead of one laser device, and TPMM thickness is measured at a speed of about 30 mph.

The specifications of the vehicle-mounted device are described as follows:

(1) Measurement speed: 30 mph

(2) Standoff distance: 12 inches

(3) Data update rate: 150 kHz

(4) Maximum range of measured thickness: 6 inches

(5) System clock: 1.5 MHz

(6) Digitization resolution: 12 bit

(7) Average power consumption: 2 A at 12 V

(8) Maximum measurement resolution: 5 mils

(9) User can obtain the thickness profiles from the save results.

(10) Maximum number of traces in one page for multi-trace display: 5

(11) Total display pages: 300

CHAPTER 3: SCANNING LASER SYSTEM DESIGN AND SPECIFICATIONS

3.1 PRINCIPLE REVIEW OF LASER TRIANGULATION

The triangulation method [2][3] is the most commonly used approach in modern industry for applications requiring an operating range that is less than 10 meters. Currently, there is a limited number of triangulation-based sensors available commercially for the ranges between 2 meters and 10 meters. The fundamental geometrical principle of optical triangulation is shown in Figure 9. The shape of the triangle can be determined by knowing two angles (α and $\Delta\beta$) of the triangle to its base (baseline d). Measuring the change $\Delta\beta$ can evaluate the incremental change of distance Δz. To measure a profile, one needs to scan the spot. Figure 10 shows the basic geometrical principle of laser scanning triangulation. The laser beam is deflected by a scanning mirror and scans over the object. A camera, constituted of lens and a position sensitive photodetector, measures the location of the image of the illuminated point on the object.

So far, the laser-optic triangulation has been widely used in many applications of both profiling and range measurement for its advantages of low cost, simplicity, robustness and good resolution. Although having those advantages, the classical triangulation technique has some limitations. To show the limitations of triangulation, people approximated the measurement uncertainty of error in depth z by the law of propagation of errors. The measurement uncertainty in z is inversely proportional to both the effective focal length f of the lens and the separation distance d between the laser and the detector, but directly proportional to the square of the distance. Unfortunately, f and d can't be made as large as desired. The separation distance d is limited mainly by the mechanical structure of the optical setup (stability of the whole system decreases as d increases) and by shadow effects (self-occlusion problems increase with d) which are shown in Figure 11. The focal length f is limited by the issue of the field of view Φ_x.

Both of the uncertainty in z and the field of view Φ_x are inversely proportional to f, which means there is always a compromise consideration between the accuracy and the field of view in conventional triangulation setup [4].

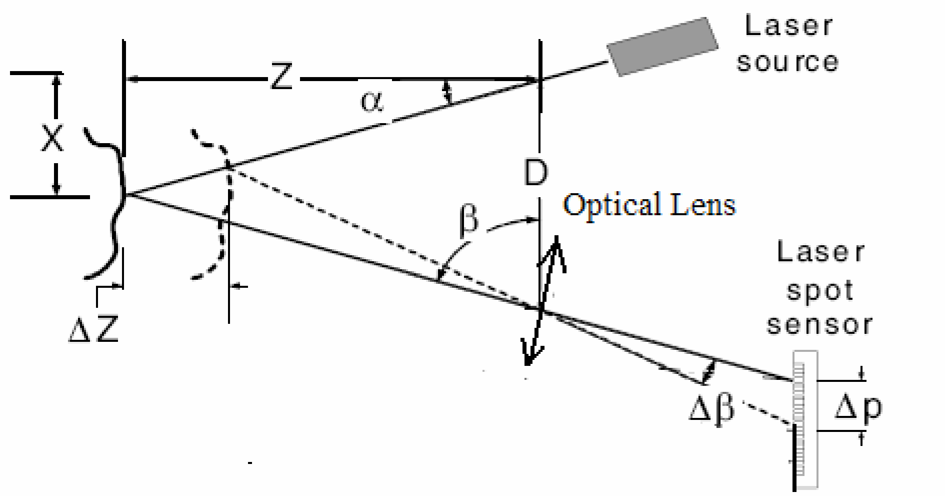


Figure 9 Geometrical principle of triangulation.

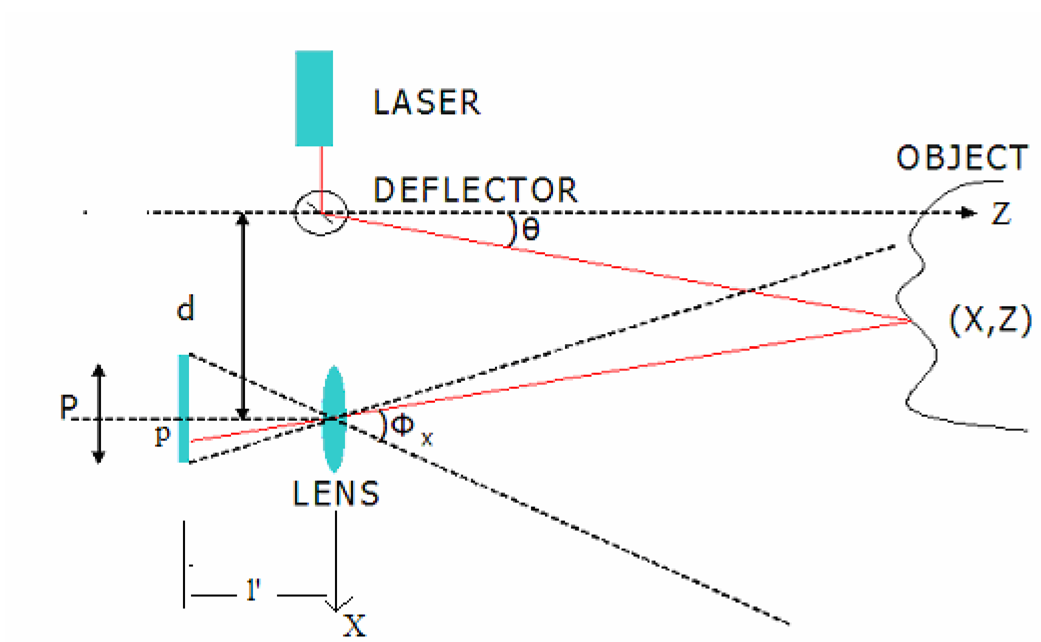


Figure 10 Geometrical principle of laser scanning triangulation.

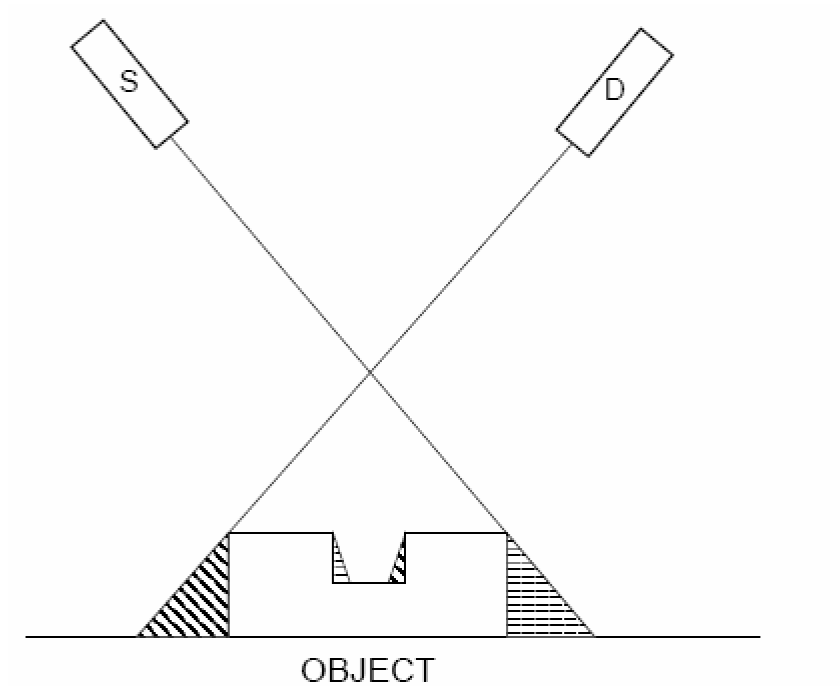


Figure 11 Shadow Effects.

To alleviate the problems associated with the classical triangulation, we introduce an innovative approach called auto-synchronized scanning mechanism that allows a very large field of view without compromising the performance of the system.

3.2 AUTO-SYNCHRONIZED LASER SCANNING PRINCIPLE

3.2.1 Optical Configuration of Auto-synchronized Scanning Laser Principle

The innovative approach of auto-synchronized scanning technique was presented by Rioux [5] in 1994. The basic idea is to synchronize the projection of a light spot with its detection. Figure 12 shows the optical configuration of the auto-synchronized scanning laser system. A double-sided coated mirror is used as a scanning device. One side of the mirror is used to deflect the laser beam. The other side collects the reflected light from the scene. By using this configuration, the instantaneous field of view follows the laser spot as it scans over the scene, which means the focal length of lens f is therefore related only to the desired depth of field or measurement range.

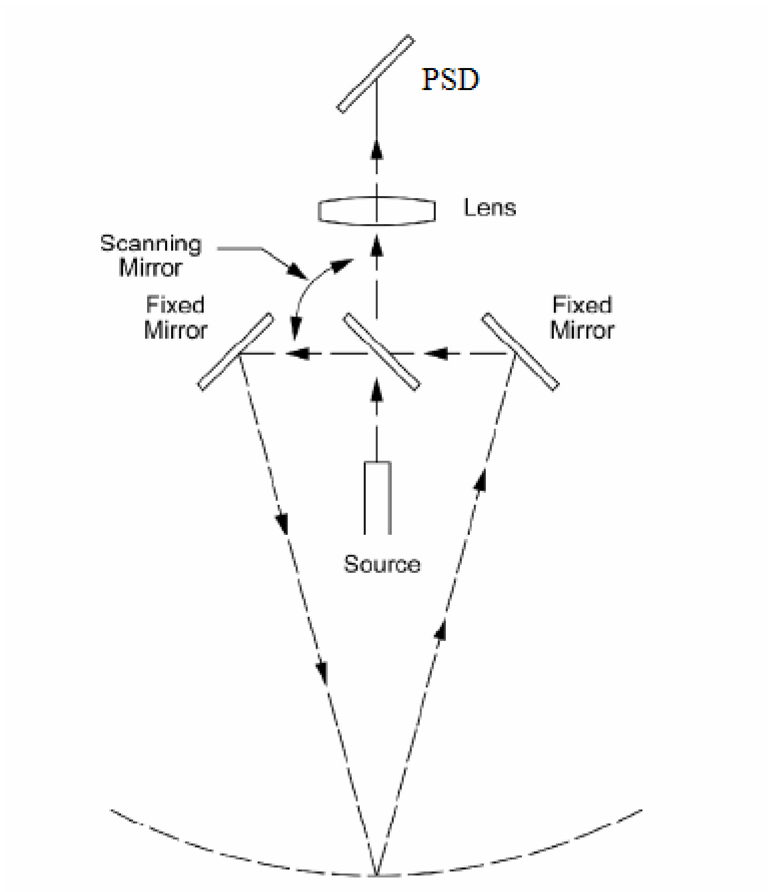


Figure 12 Optical configuration of auto-synchronized laser scanning.

3.2.2 Algorithm of Auto-synchronized Laser Scanning Technique

Figure 13 shows the geometry used for the triangulation where the projection and collection axes have been unfolded. The synchronized geometry shows that, at a spot position p = 0 (point A), the acute angle between the projection and collection paths is equal to a constant γ. So we can deduce all the other angles from this. Based on the triangulation geometry, we can prove two triangles OAC-OED are similar, as are triangles OBC-OFD. From these, we can deduce the following relation.

$$\frac{R_p(\theta) - R_0(\theta)}{R_p(\theta) - R_{-\infty}(\theta)} = \frac{p}{P_\infty} \tag{2}$$

Where p is the image position on the detector (detection axis), PSD, of the laser spot and for a given deflected angle θ, and $R_p(\theta)$ is the distance R(θ) along the projection axis corresponding to p. $R_{-\infty}(\theta)$ is the location of the vanishing point on the projection axis, and $R_0(\theta)$ is the location corresponding to p = 0. P_∞ is the location on the position detector of the vanishing point on the detection axis and is described as:

$$P_\infty = f_0 \frac{\sin(\gamma)}{\cos(\beta - \gamma)} = \frac{(f_0 - f)}{\sin(\beta)} \tag{3}$$

Where f is the focal length of the lens, f_0 is the effective distance of the position detector to the imaging lens, β is the tilt angle of the position detector and γ is the triangulation angle.

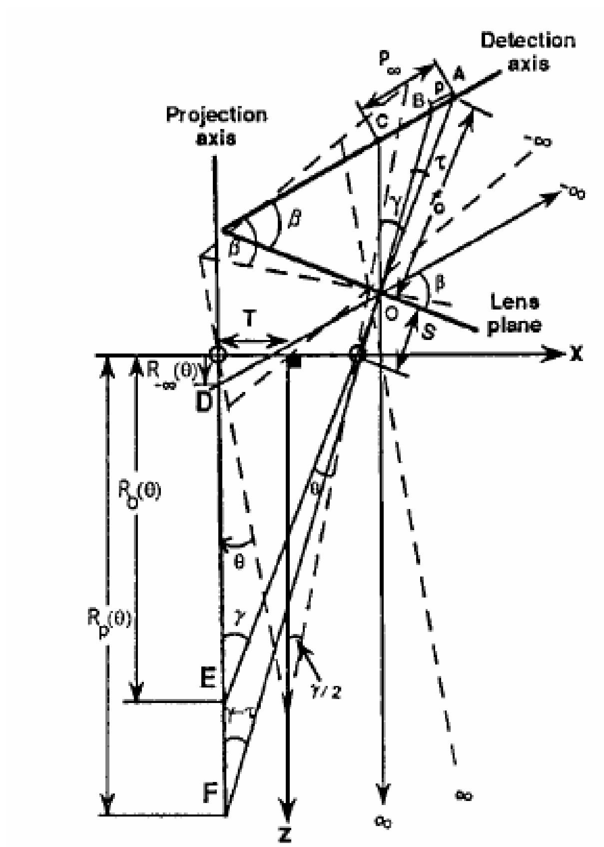


Figure 13 Unfold geometry of auto-synchronized laser scanning triangulation.

The transformation of the above equation to an (X, Z) representation is computed from the fact that two points D and E and a third point F belong to the same straight line if the vectors DE and DF are linearly dependent. Hence,

$$\frac{X_p(\theta) - X_0(\theta)}{X_p(\theta) - X_{-\infty}(\theta)} = \frac{Z_p(\theta) - Z_0(\theta)}{Z_p(\theta) - Z_{-\infty}(\theta)} = \frac{p}{P_\infty} \tag{4}$$

The above equations are decomposable in both orthogonal directions, i.e.,

$$x(p,\theta) = X_{-\infty}(\theta) + P_\infty \frac{X_0(\theta) - X_{-\infty}(\theta)}{P_\infty - p} \tag{5}$$

$$z(p,\theta) = Z_{-\infty}(\theta) + P_\infty \frac{Z_0(\theta) - Z_{-\infty}(\theta)}{P_\infty - p} \tag{6}$$

These linear fractional equations, also known as logistic equations, emphasize the nature of the Schemipflug geometry [6], that is, the limiting response ($R = R_{-\infty}$) for p as it approaches -∞ (collection path parallel to the position detector) and ($p = P_\infty$) for R as it approaches +∞ (projected ray parallel to collection path).

The coordinates of points D, E, and F are

$$X_{-\infty}(\theta) = -\frac{T\cos(\beta - 2\theta) + S\cos(\beta)\sin(\gamma/2 - \theta)}{\cos(\beta - \gamma)} \tag{7}$$

$$Z_{-\infty}(\theta) = \frac{T(\sin(\beta - 2\theta) + \sin(\beta - \gamma))}{\cos(\beta - \gamma)} - \frac{S\cos(\beta)\cos(\gamma/2 - \theta)}{\cos(\beta - \gamma)} \tag{8}$$

$$X_0(\theta) = -T\frac{\sin(2\theta)}{\sin(\gamma)} \tag{9}$$

$$Z_0(\theta) = T\frac{\cos(2\theta)+\cos(\gamma)}{\sin(\gamma)} \tag{10}$$

Where S is the distance between the lens and the effective position of the collection axis pivot and T is the half-distance between the projection and collection pivots. Those equations constitute the basis for the calibration algorithm.

3.3 DEVICE DESCRIPTION

The developed auto-synchronized scanning laser thickness measurement device is shown in Figure 14.

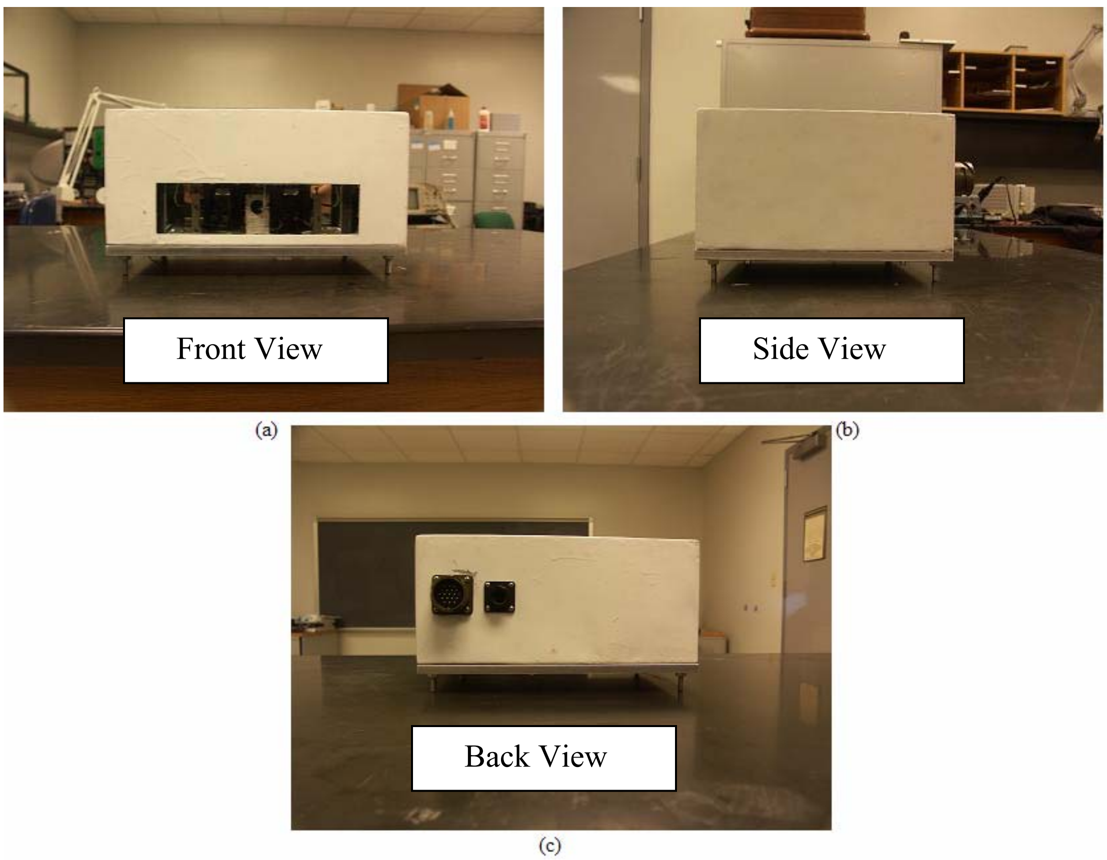


Figure 14 Laser Device based on auto-synchronized scanning principle.

The physical dimensions of the laser device are 12 inches width, 10 inches depth and 5.75 inches height. The total weight is 12 lb.

The internal structure of the scanning laser device is shown in Figure 15. The device consists of a laser diode, scanning mirror, projection mirror, recollection mirror, lens, position sensitive detector, signal processing circuitry and power supply.

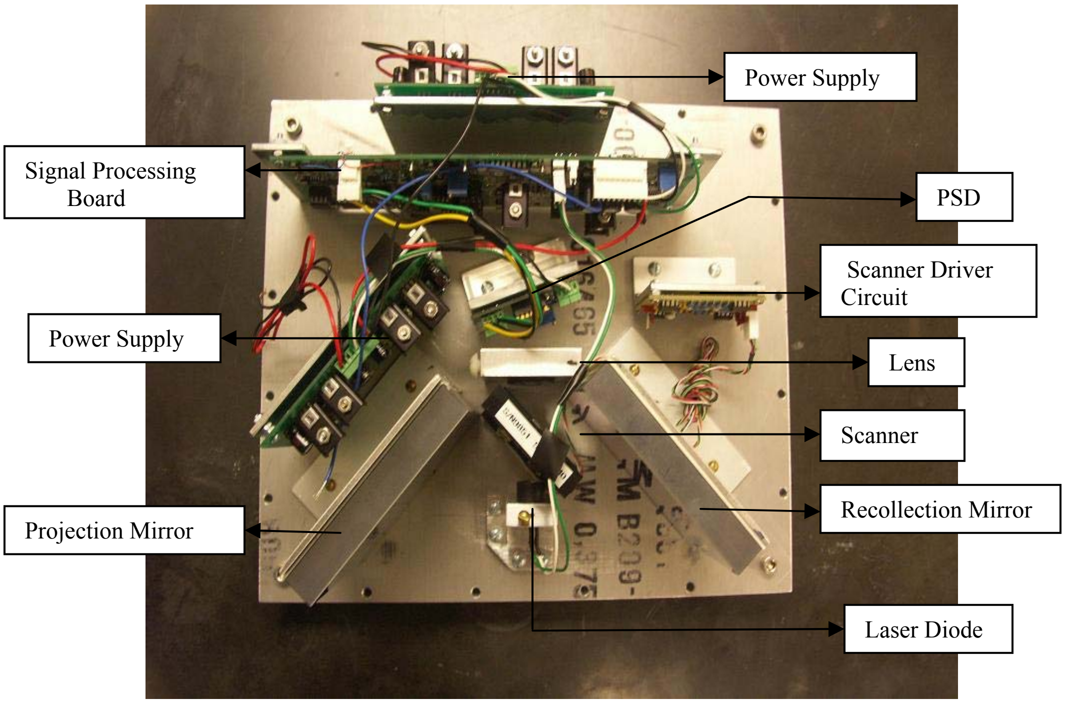


Figure 15 Internal structure of the scanning laser device.

3.3.1 Optical Specification

A 500 mW He-Ne laser diode is used as the laser beam source. The wavelength of the laser diode is 808 nm which is near the sensitivity spectrum of the PSD sensor. The diode is placed in an optical holder which collimates the laser beam for the required measuring range. A double side mirror coated with enhanced aluminum on both sides is attached to a resonant scanner, which gives up to a 40° field of view (corresponding 12 inches width at standoff distance which is also 12 inches). A lens of 30 mm focal length is used to focus the scattered light from the scene onto the PSD sensor. The PSD sensor is placed at a tilting angle β of 71.7° with the lens axis to comply with the Scheimpflug condition [6] in order to provide a considerable improvement in the depth of view without compromising the collected energy. Two same dimension single side coated mirrors are used. The dimension of each one is 100 mm (length) x 100 mm (height) x 15 mm (thickness). One is used as projection directing and the other is used as reflection directing. Both of them are coated with enhanced aluminum.

To get rid of the optical noise from the sunshine, a laser bandpass filter is installed behind the lens. The bandpass filter, also called as interference filter, can transmit the laser of some specific wavelength and block other wavelengths by using the light interference. Figure 16 shows the picture of the interference filter used in the auto-synchronized scanning laser device.

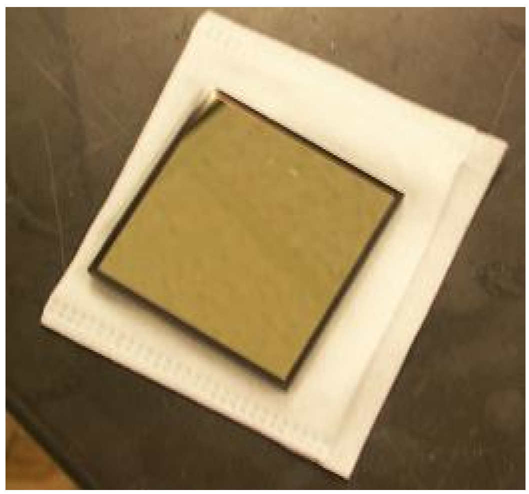


Figure 16 Laser bandpass filter.

The dimension of this bandpass filter is 2.0 inches (length) x 2.0 inches (height) x 0.2 inch (thickness). The central wavelength is 800 nm, and the bandwidth is +/-10 nm. The peak transmittance is above 50%. Figure 17 shows the transmittance chart of the bandpass filter.

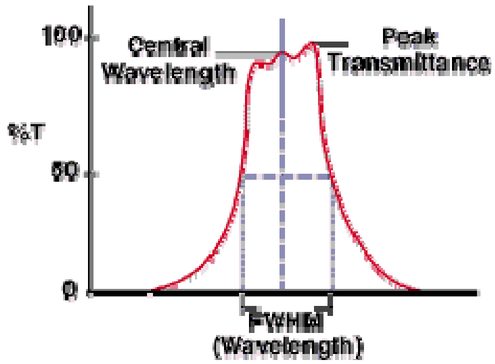


Figure 17 Transmittance chart of the bandpass filter.

Figure 18 shows the output electronic signal of the system under the sunshine without installation of the bandpass filter.

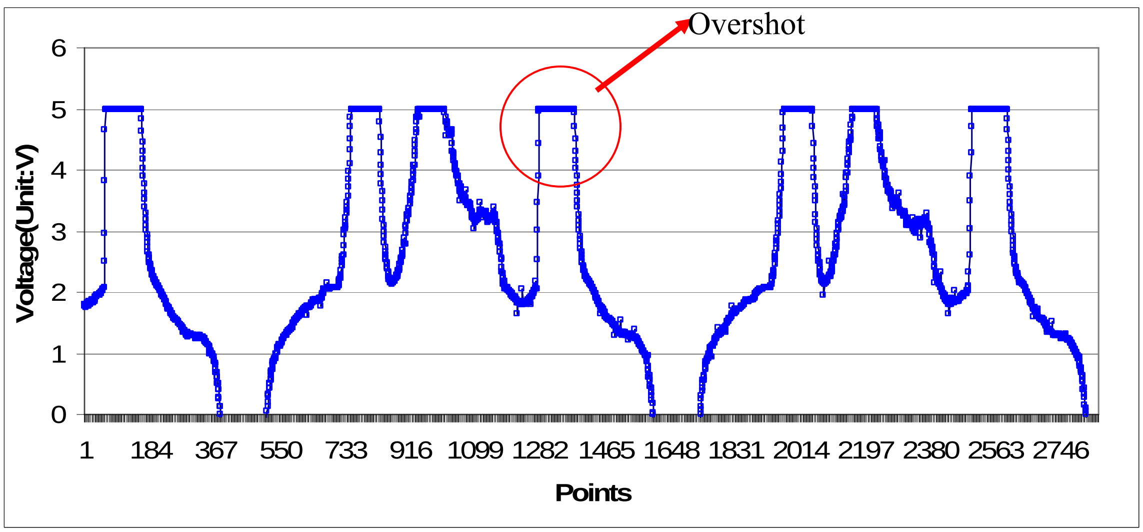


Figure 18 Output electronic signal under sunshine without filter.

Figure 19 shows the output electronic signal of the system under sunshine with the bandpass filter.

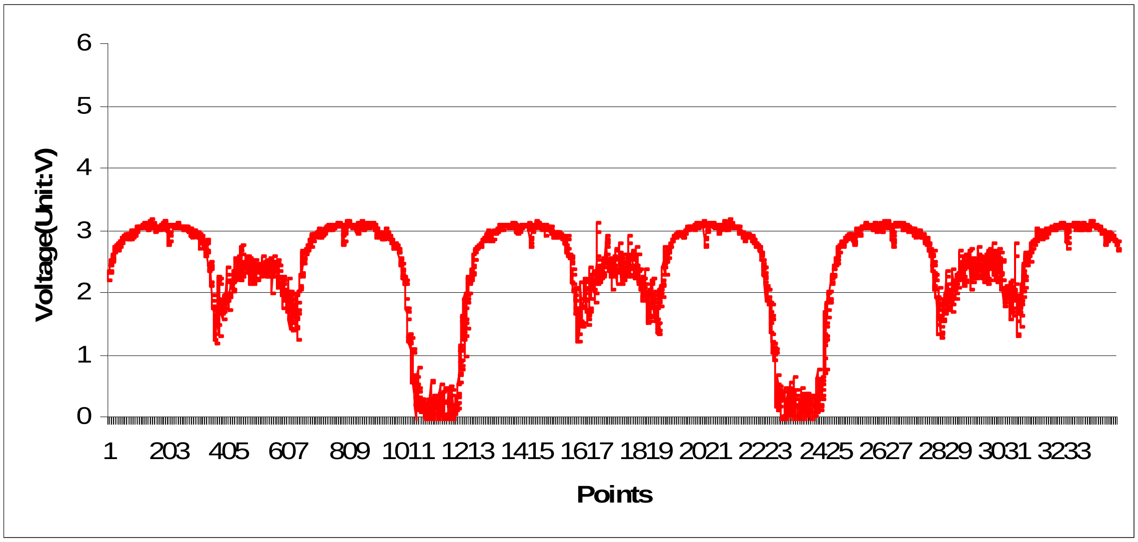


Figure 19 Output electronic signal under sunshine with bandpass filter.

From the above two figures, we can see the bandpass filter can effectively remove the overshot signal which is caused by the sunshine.

3.3.2 Scanning Laser System Structure

To descript the architecture of the device, a simple hardware block diagram is depicted in Figure 20.

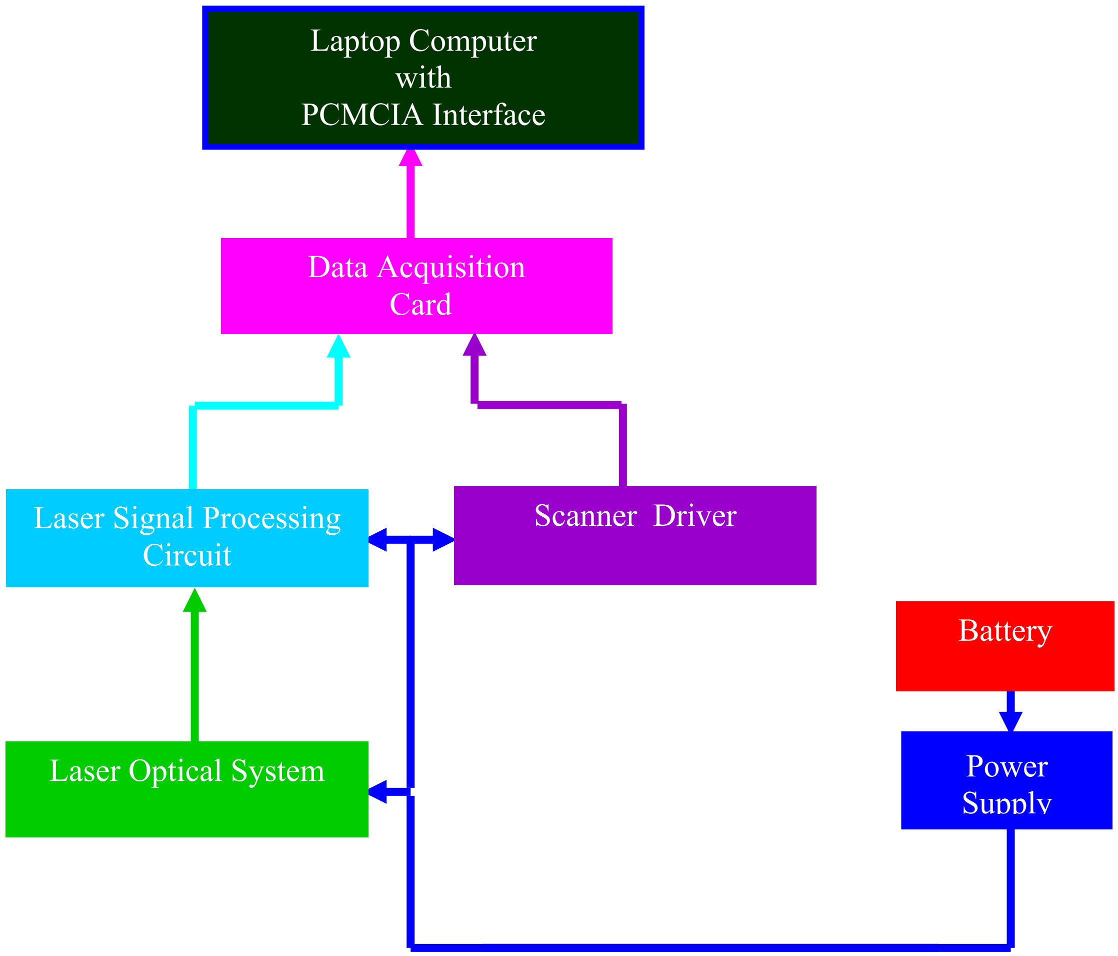


Figure 20 Block diagram of hardware.

The prototype hardware of the pavement marking thickness measurement system based on the auto-synchronize laser scanning technique is composed of a laser optical subsystem, electronic processing and control subsystem, and power supply subsystem. The laser optical subsystem has been described before. The electronic processing and control subsystem consists of a laser signal processing circuit, scanning driver circuit and data acquisition. Only a 12 V direct-current (DC) power supply is necessary for the device. By using DC-DC voltage converters and voltage regulators, the 12 V output from the DC power supply is converted to +15 V and +5 V, which is necessary for the laser electronic signal processing circuit.

The scanning laser device is mounted on the left front side of the vehicle shown in Figure 21, just behind the signal laser point TPMM thickness measurement device. A driving guide system shown in Figure 22 is also installed on the vehicle which can help the driver keep the laser scanning on the tape when the vehicle is advancing on highway. The driving guide system consists of a camera installed outside the vehicle and a monitor installed inside the vehicle.

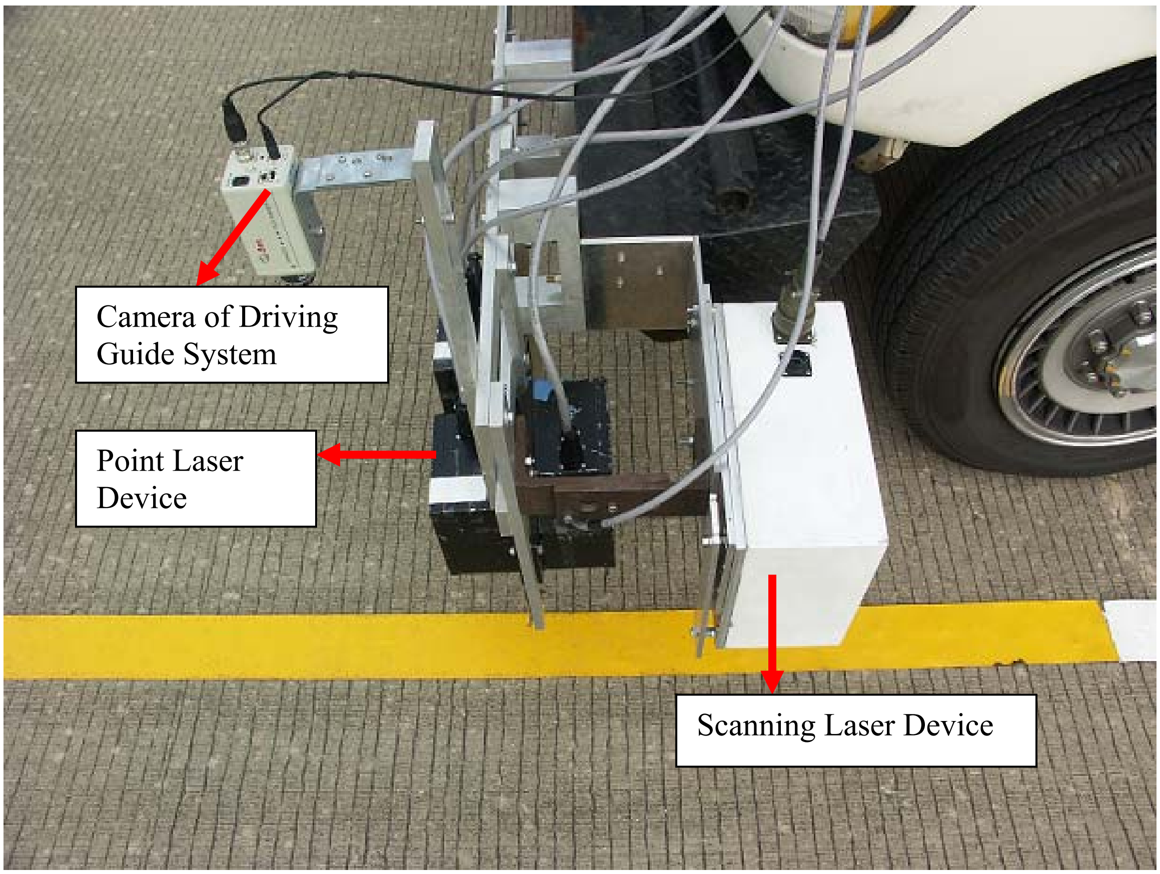


Figure 21 Scanning laser device mounted on the left (driver) side of the vehicle.

Figure 22 LCD monitor for the driving guide system.

3.3.3 Software Development

Software was developed to process, store and display the data measured by the hardware. Figure 23 shows the software interface of the vehicle mount scanning laser TPMM thickness measurement system.

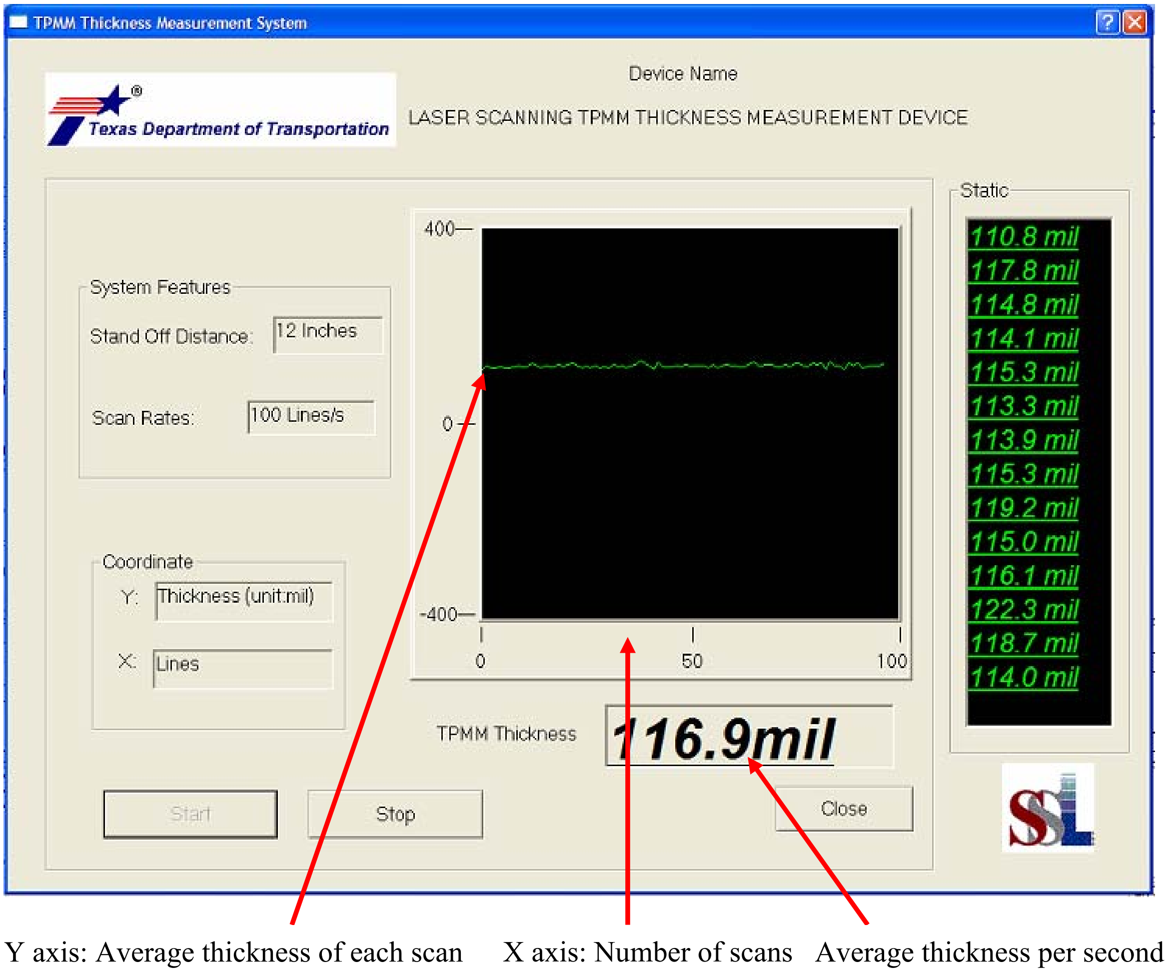


Figure 23 Software interface for TPMM thickness measurement system.

3.4 SYSTEM SPECIFICATION OF SCANNING LASER DEVICE FOR TPMM THICKNESS MEASUREMENT

1. Standoff distance: 12 inches

2. Data update rate: 60 kHz

   The laser source is operated at the frequency range of 30 kHz.

3. Maximum range of measured thickness: ±4 inches

4. Scan rates: 100 lines/s

5. Scan width: 12 inches

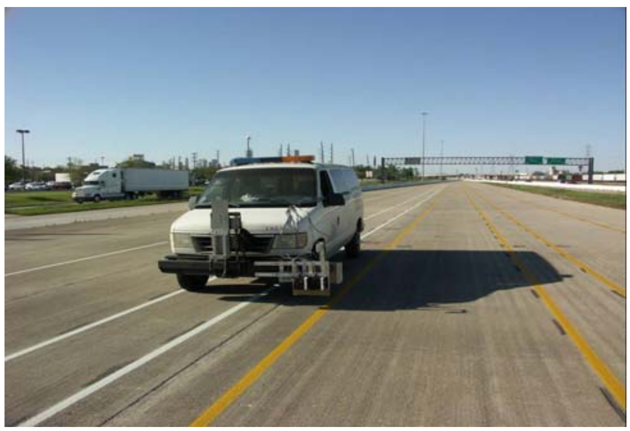
6. Digitization resolution: 12 bits

7. Average power assumption: 1.6 A at 12 V

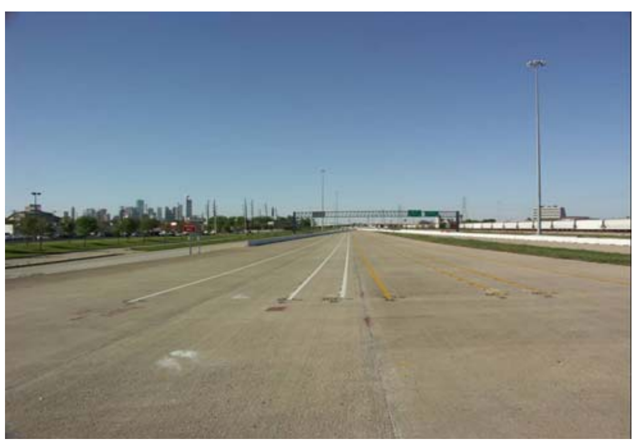
CHAPTER 4: POINT LASER DEVICE TEST RESULTS AND ANALYSIS

4.1 INTRODUCTION

The purpose of the field test is to verify the implementation possibility of the vehicle-mounted device. The experiments were conducted on UH testing site near Spur 5. Figure 24 shows the experiment setup for the vehicle-mounted device. The point laser device was installed on the left (driver) side. The experiments were set to test the accuracy of the thickness measurement system. Marking materials with different thickness were placed on the concrete surface. The materials are permanent TPMM in white and yellow colors.



(a)



(b)

Figure 24 (a) Vehicle-mounted device; (b) Marking materials on the UH testing site.

Multiple tests were conducted on the marking materials provided by TxDOT at different speeds of up to 30 mph.

The point laser device can also be mounted on the right (passenger) side shown in Figure 25. The test results show that the position of point laser device doesn't affect the usability and accuracy.

Figure 25 Point laser device mounted on the right (passenger) side.

4.2 FIELD TEST

Figure 26 shows thermoplastic marking materials on the concrete surface. Those making materials are weather resistant and provide excellent color retention. Since there are glass beads on the surface of TPMM, the thickness of TPMM becomes non-uniform. The actual thickness of TPMM on the field site is within the range of 40 mils to100 mils.

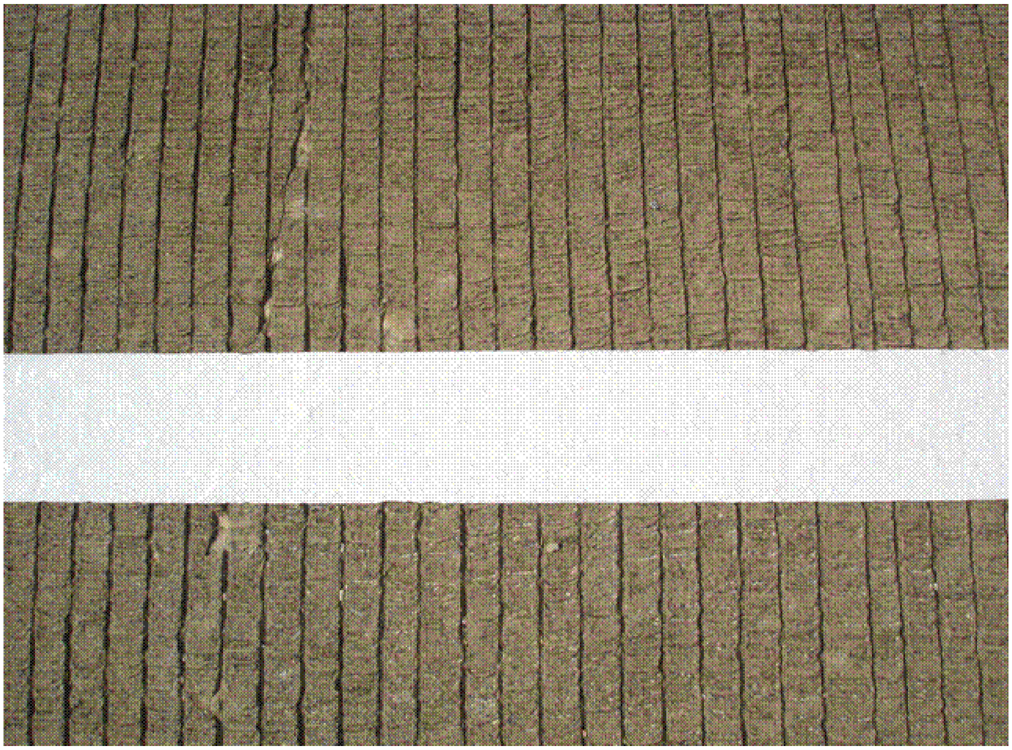


Figure 26 Thermoplastic marking materials on highway.

4.2.1 Testing Results as the Point Laser Device Mounted on Left Side

Figure 27 shows the measurement results at 30 mph speed for marking materials with thicknesses of 100 mils. Length of marking materials measured was about 60 feet. In Figure 27, the X-axis represents measured distance; the Y-axis represents distance between laser and surfaces in mils.

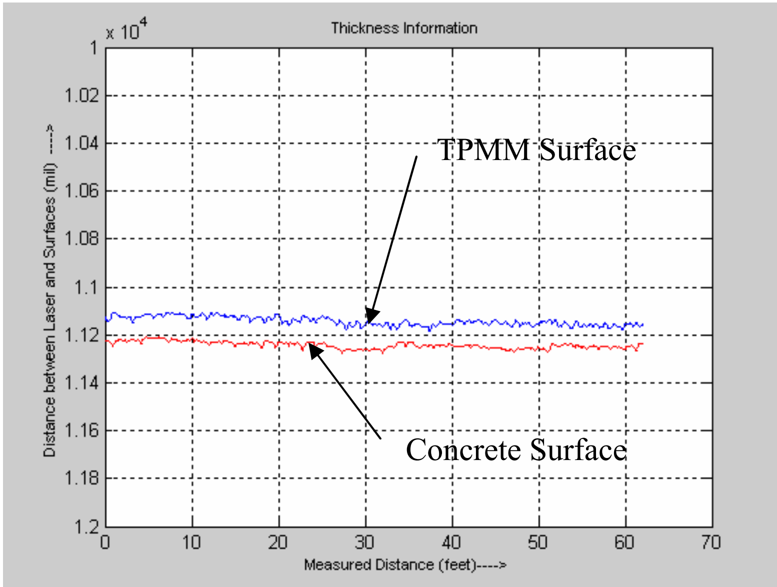


Figure 27 Test results of the TPMM (marked with 100 mils) on highway.

Figure 28 shows a continuous measured thickness profile of the TPMM which is 60 feet long. The measured average thickness of the white TPMM tape is 98 mils.

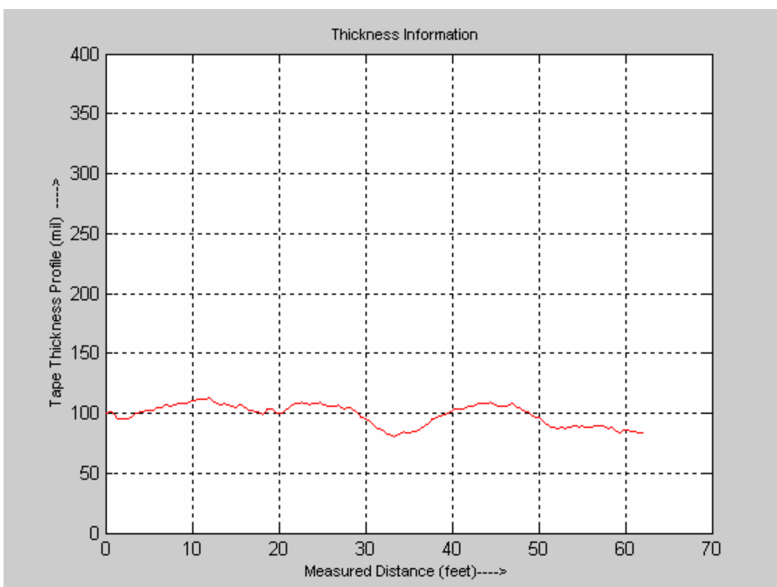
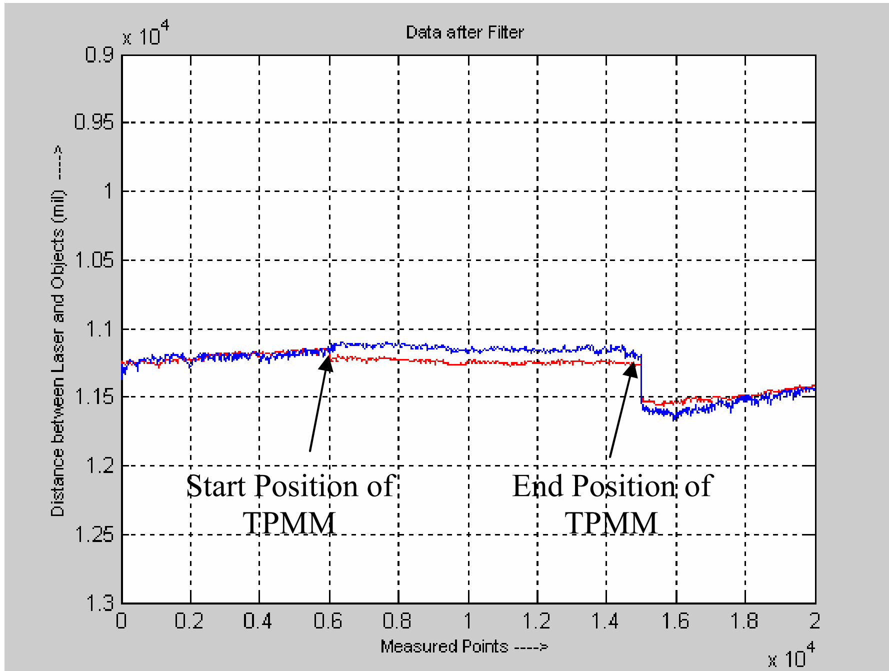
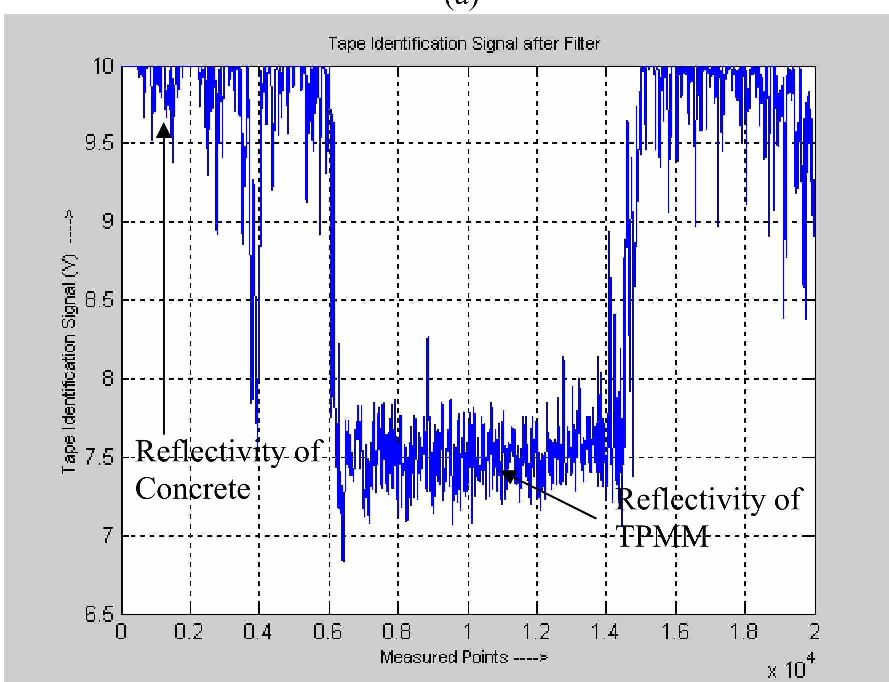


Figure 28 Thickness profile of TPMM (marked with 100 mils).

Figure 29 shows the measured reflectivity signals of the TPMM and the pavement, which help to identify the start and end position of the TPMM.



(a)



(b)

Figure 29 (a) Profiles of the TPMM and the pavement; (b) Reflectivity results of the TPMM and the pavement.

Figure 30 shows the measurement results of marking materials with thickness marked with 60 mils.

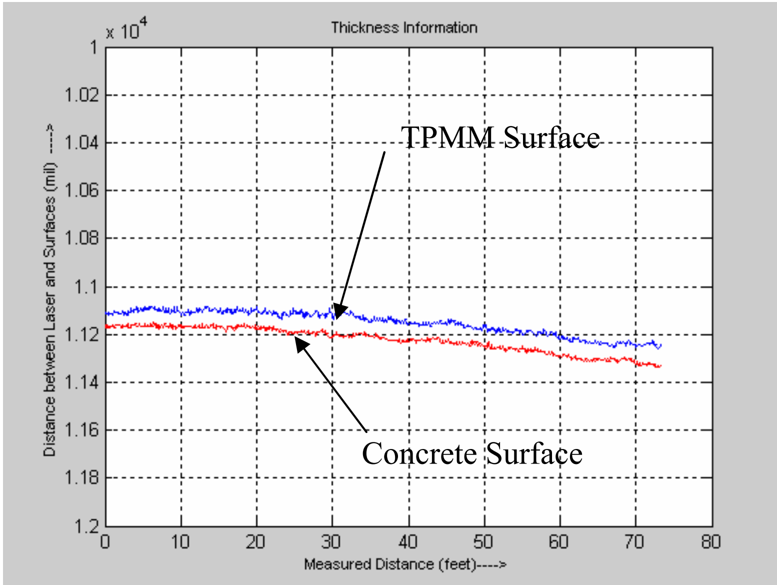


Figure 30 Test results of the TPMM (marked with 60 mils) on highway.

Figure 31 shows a continuous measured thickness profile of the TPMM which is 70 feet long. The measured average thickness of the white TPMM tape is 63 mils.

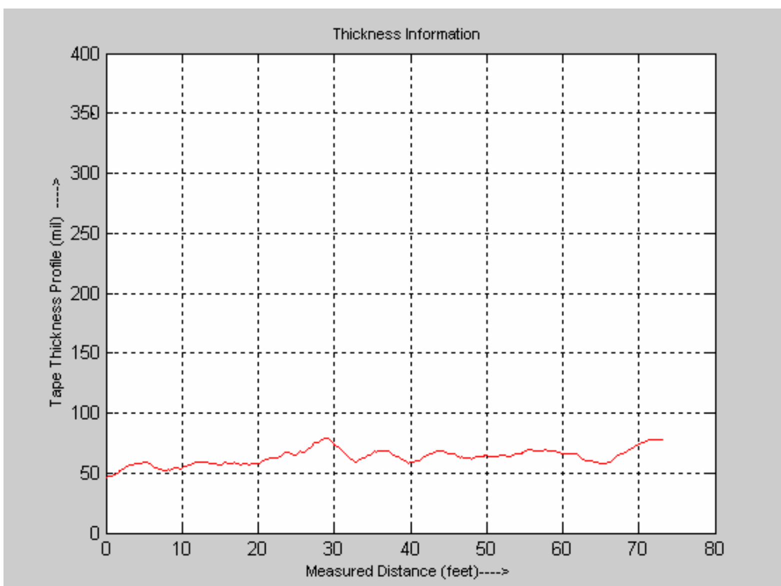


Figure 31 Thickness profile of TPMM (marked with 60 mils).

Figure 32 shows the measurement results of marking materials with thickness marked with 40 mils.

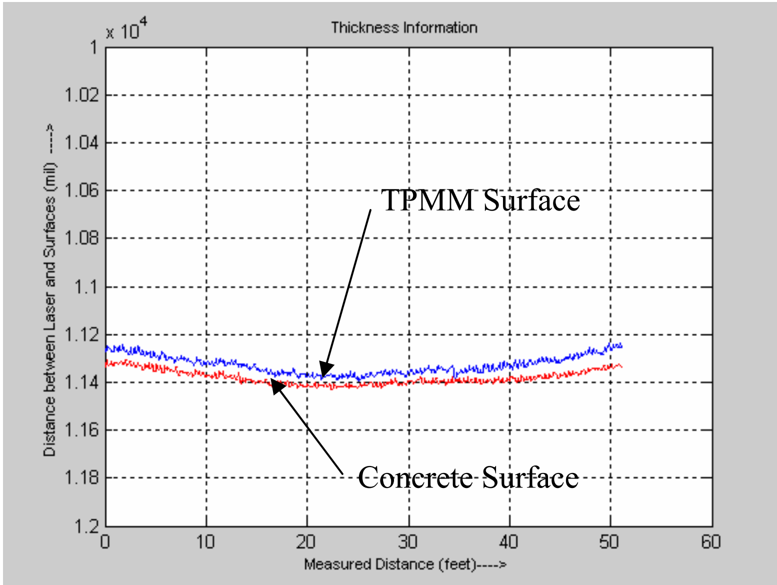


Figure 32 Test results of the TPMM (marked with 40 mils) on highway.

Figure 33 shows a continuous measured thickness profile of the TPMM which is 70 feet long. The measured average thickness of the white TPMM tape is 44 mils.

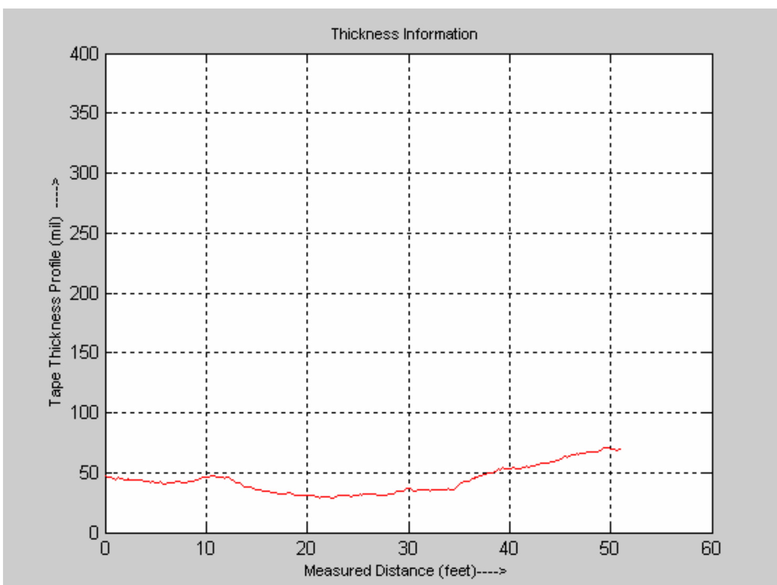


Figure 33 Thickness profile of TPMM (marked with 40 mils).

4.2.2 Testing Results as the Point Laser Device Mounted on Right Side

Figure 34 shows the measurement results at a 10 mph speed for marking materials with a thickness of 100 mils. The length of the marking materials measured was about 75 feet. In Figure 34, the X-axis represents the measured distance; the Y-axis represents the distance between the laser and surfaces in mils.

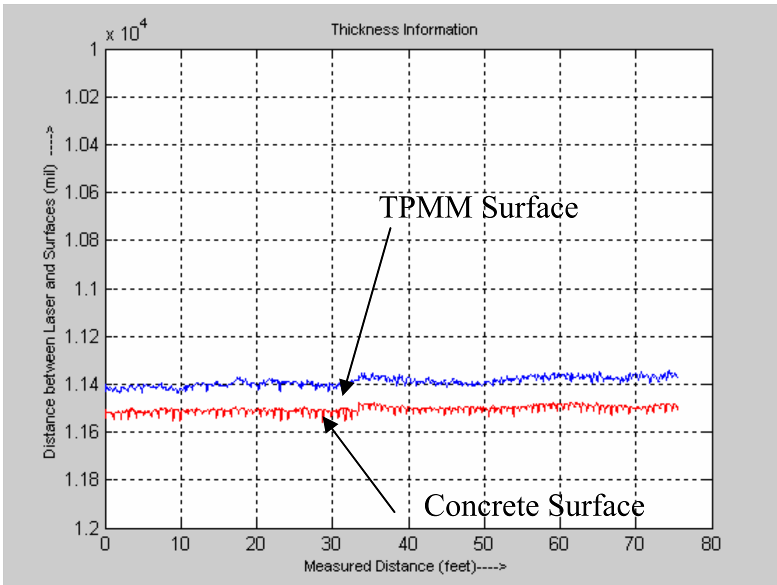


Figure 34 Test results of the TPMM (marked with 100 mils) on highway.

Figure 35 shows a continuous measured thickness profile of the TPMM which is 75 feet long. The measured average thickness of the white TPMM tape is 109 mils.

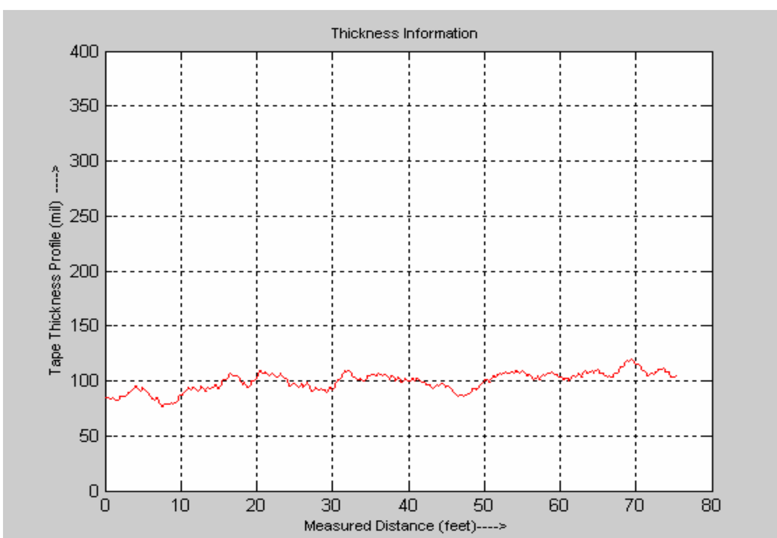


Figure 35 Thickness profile of TPMM (marked with 100 mils).

Figure 36 shows the measurement results of marking materials with thickness marked with 60 mils.

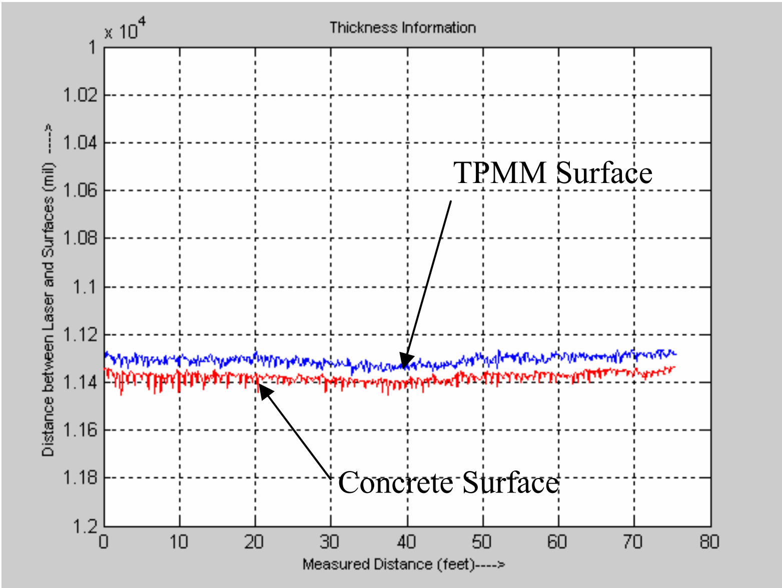


Figure 36 Test results of the TPMM (marked with 60 mils) on highway

Figure 37 shows a continuous measured thickness profile of the TPMM which is 75 feet long. The measured average thickness of the white TPMM tape is 70 mils.

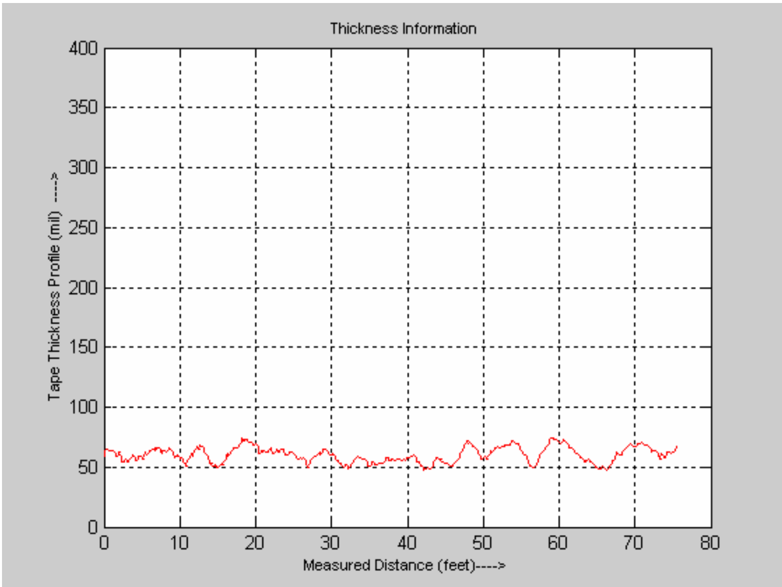


Figure 37 Thickness profile of TPMM (marked with 60 mils).

Figure 38 shows the measurement results of marking materials with thickness marked with 40 mils.

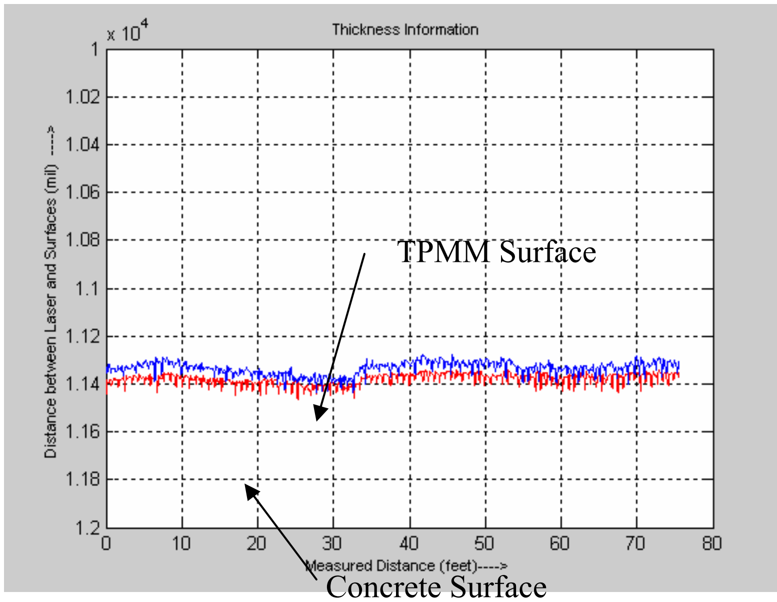


Figure 38 Test results of the TPMM (marked with 40 mils) on highway.

Figure 39 shows a continuous measured thickness profile of the TPMM which is 75 feet long. The measured average thickness of the white TPMM tape is 47 mils.

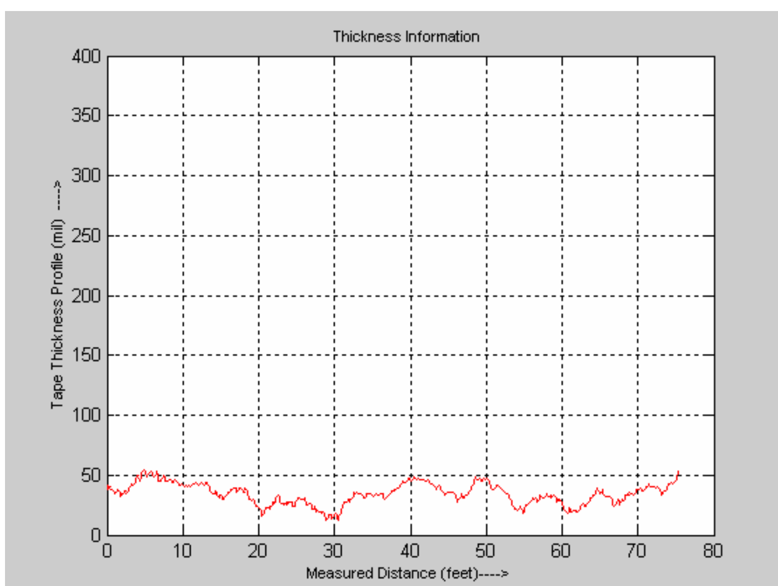


Figure 39 Thickness profile of TPMM (marked with 40 mils).

4.2.3 Repeatability Test

A repeatability test was conducted on different marking materials when the point laser device was mounted on the right side of the vehicle. The thicknesses of different marking materials were measured eight times at 25 feet distance. The test results are shown in Table 1. The mean value for each tape agrees with the marking values. The maximum standard deviation is 10.24 mils for the yellow 40 mil tape. The reason for the high standard deviation is that the 40 mil marking material is too thin to cover the small gaps on the pavement. The laser reading should be bigger than we expect in this scenario.

Table 1 Repeatable test in 25 feet distance.

	Test 1 (mil)	Test 2 (mil)	Test 3 (mil)	Test 4 (mil)	Test 5 (mil)	Test 6 (mil)	Test 7 (mil)	Test 8 (mil)	Mean Value (mil)	Standard Deviation (mil)
100 mils marking in white color	93	104	105	105	107	89	98	107	101.00	6.87
80 mils marking in white color	85	94	84	79	80	84	79	91	84.50	5.53
60 mils marking in white color	61	60	56	58	66	57	59	59	59.50	3.07
100 mils marking in yellow color	90	108	107	101	108	109	106	113	105.25	7.01
80 mils marking in yellow color	76	75	83	76	82	94	90	82	82.25	6.86
60 mils marking in yellow color	66	63	72	59	62	55	59	66	62.75	5.28
40 mils marking in yellow color	34	41	45	59	52	41	63	39	46.75	10.24

4.3 RETROREFLECTIVITY COMPARISON OF DIFFERENT TAPES

The variation on the TPMM and pavement surfaces is demonstrated in two principal features: different materials and the different colors of materials. To investigate the retroreflectivity of different marking materials, three different marking materials were placed on the concrete surface. The materials tested were permanent TPMM in white and yellow colors and temporary Flex-O-Line tape in white color. Figure 40 shows the retroreflectivity experiment setup.

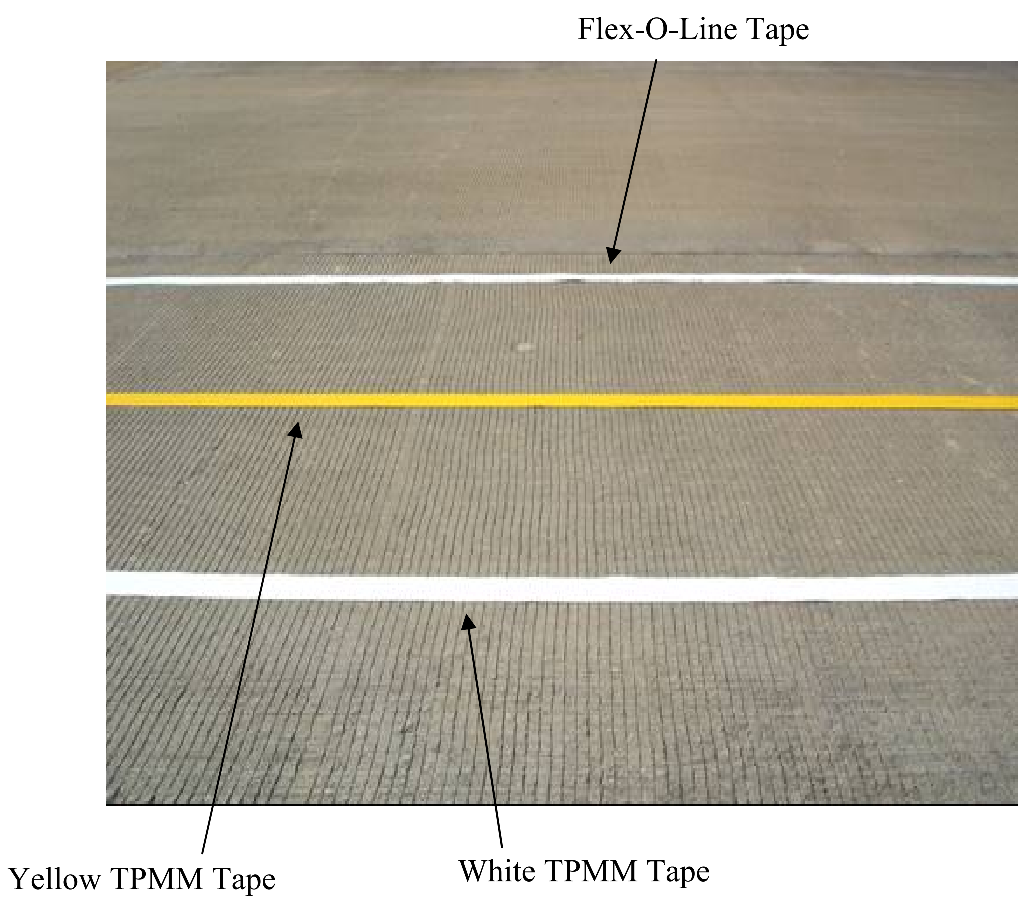


Figure 40 Retroreflectivity experiment setup.

Figure 41 shows the retroreflectivity index comparison of different marking materials in 12 foot lengths. The retroreflectivity index is defined as the difference between maximum output of the PI controller and actual output of the PI controller. The average retroreflectivity index values of white TPMM, yellow TPMM and Flex-O-Line tape are 6.4568, 6.1738, and 6.0613 respectively. Among those marking materials, the white TPMM has the highest average retroreflectivity.

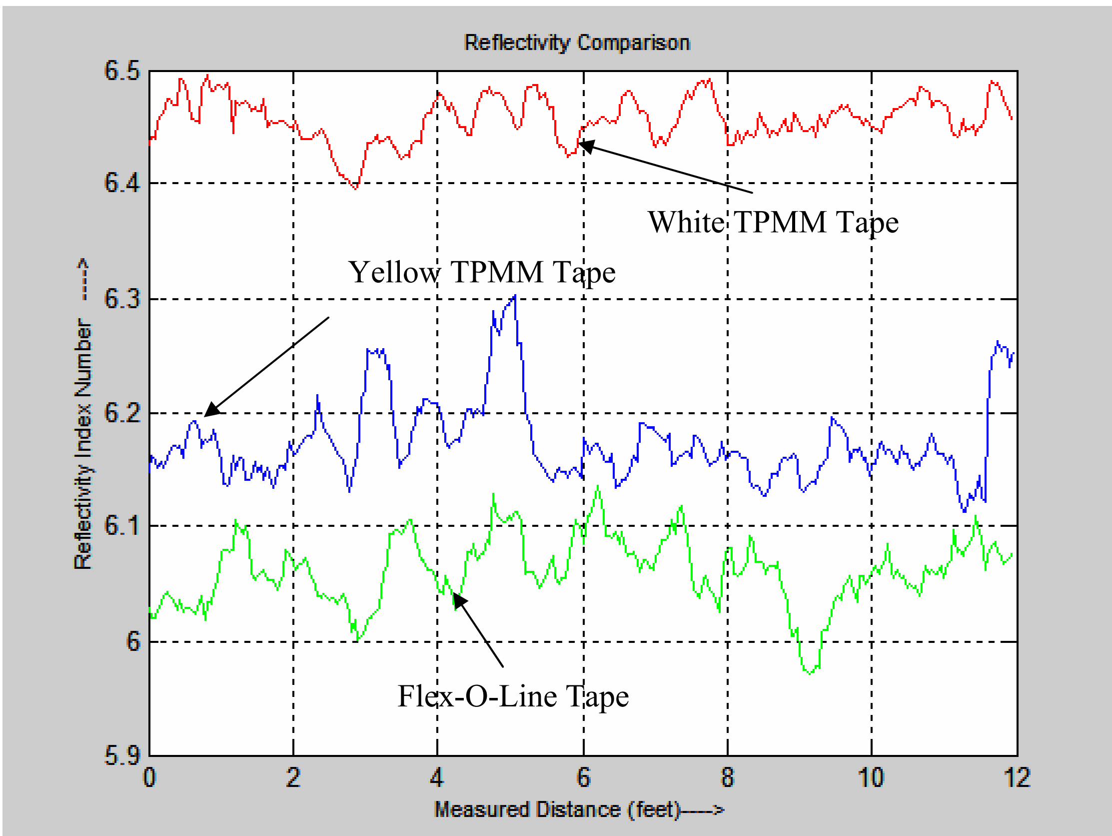


Figure 41 Retroreflectivity comparison of different marking materials.

CHAPTER 5: SCANNING LASER DEVICES TEST RESULTS

5.1 LAB TEST

Figure 42 shows the configuration of the lab test bench which has been set up in the subsurface sensing lab. An experimental result was obtained by measuring the thickness of a sample of the white color TPMM. The test sample was attached to a flat, polished metallic bar which was used as a background reference object. The bar was coated with white paint to meet the common assumption made on surface roughness. The average thickness of the test sample was 80 mils measured by a caliper. The distance between the device and the reference bar was 12 inches.

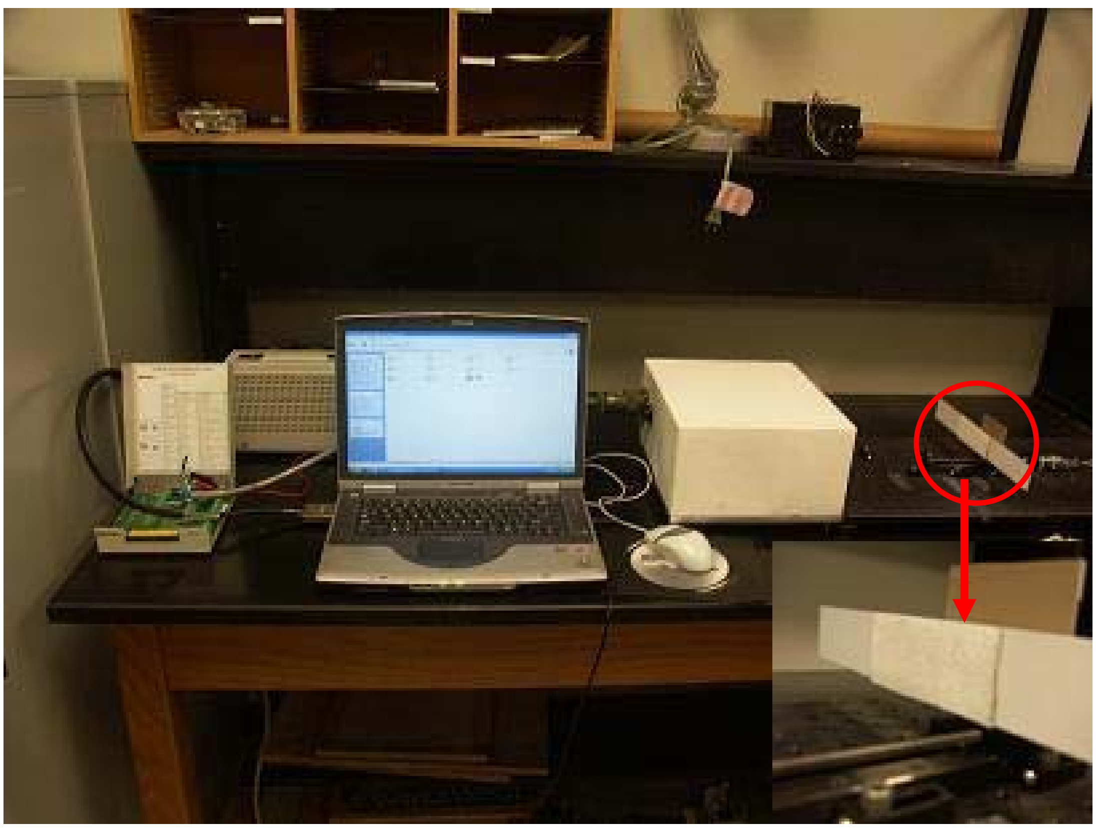


Figure 42 Lab test bench.

In this experiment, a laser beam scanned the sample TPMM on the surface of the reference bar and the texture of the marking material and the reference bar was correctly recorded. By comparing the range distance difference between the marking material and the reference, the average thickness of TPMM was computed. The result of thickness profile of the sample TPMM is shown in Figure 43. The average thickness of the marking material measured by the scanning laser device is 83 mils.

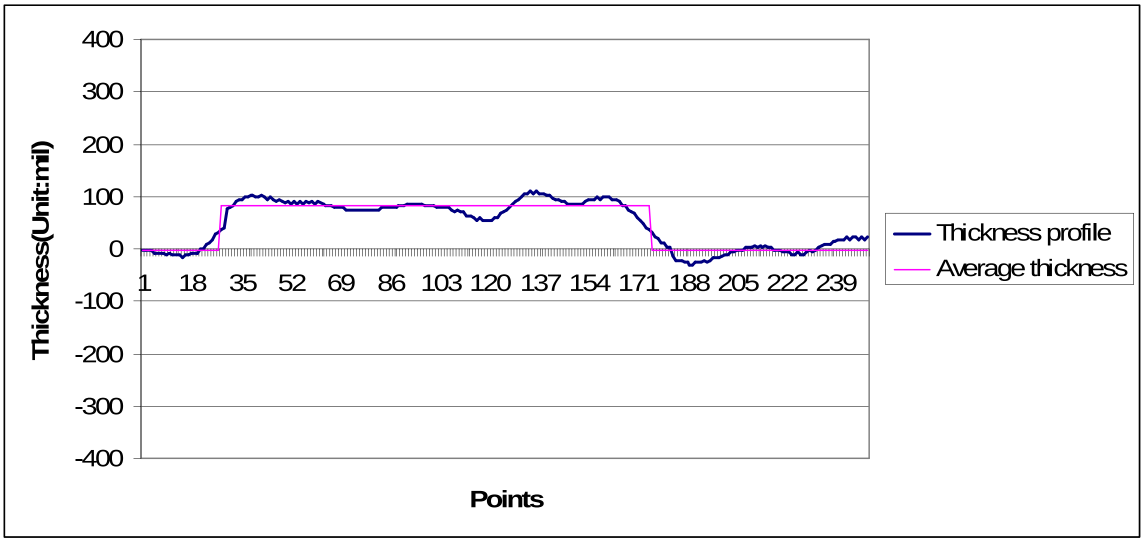


Figure 43 Lab test result.

5.2 FIELD TEST

5.2.1 Field Test Demo at Austin

On February 22, 2006, a field test demo was conducted using the vehicle-mounted laser scanning TPMM thickness measurement device. The demo was conducted at the TxDOT Cedar Park testing site, as shown in Figure 44.

Figure 44 Field demo at Austin.

Self-attachable TPMM tapes were used for test. The average thickness of the tape was measured by caliper at the field site as shown in Figure 45. Figure 46 shows the test result on the 60 mil thickness yellow TPMM tape measured by the scanning laser device. The average thickness measured by the scanning laser device is read out as 55.6 mils.

Figure 45 TPMM tape measured by caliper in the field test at Austin.

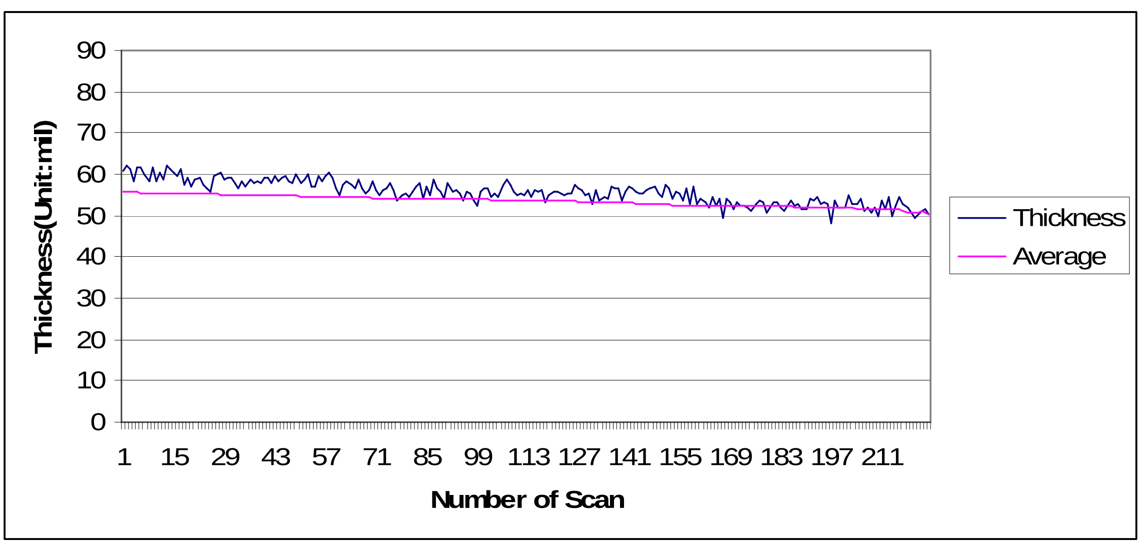


Figure 46 Test result on the 60 mil yellow tape by scanning laser device.

5.2.2 Field Test at UH Test Site

To verify the performance of scanning laser device, the researchers performed two sets of tests at the UH testing site. In the first scenario, the scanning laser was mounted on the left (driver) side shown in Figure 47. The vehicle remained stationary during the data collections.

Figure 47 Field test of laser scanning device on spur 5.

Two types of TPMM tapes were used: 12 feet long, 100 mil thickness regular tape and 30 feet long, 30 mil thickness Flex-O-Line thin tape. After data processing, the thickness profiles of both thermoplastic tapes were plotted in Figure 48 and Figure 49. The average thicknesses of the two tapes measured by the device were 106 mils and 30.92 mils, respectively.

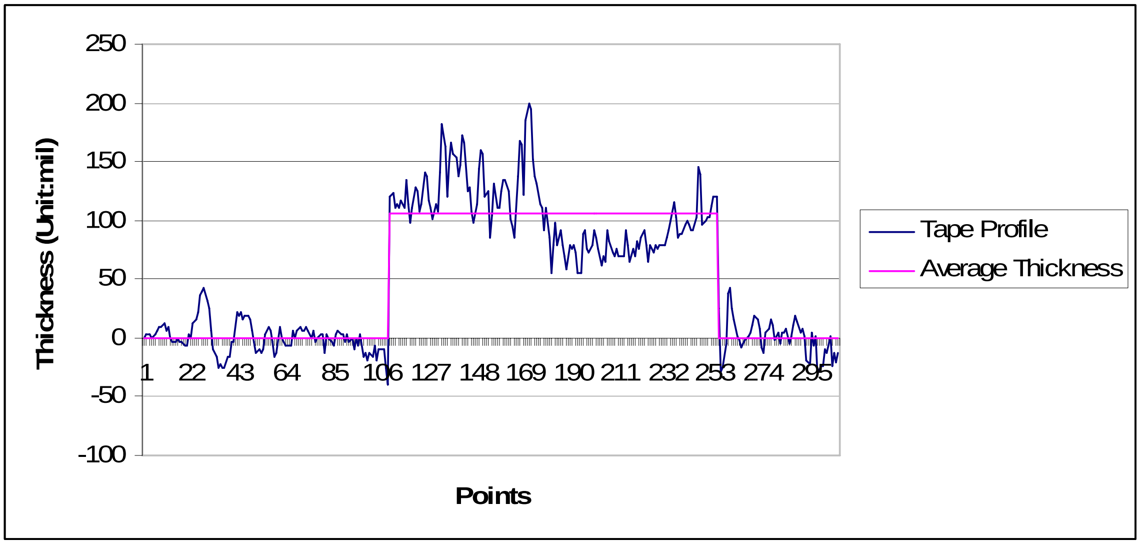


Figure 48 Thickness Profile of the 100 mil Thickness Tape.

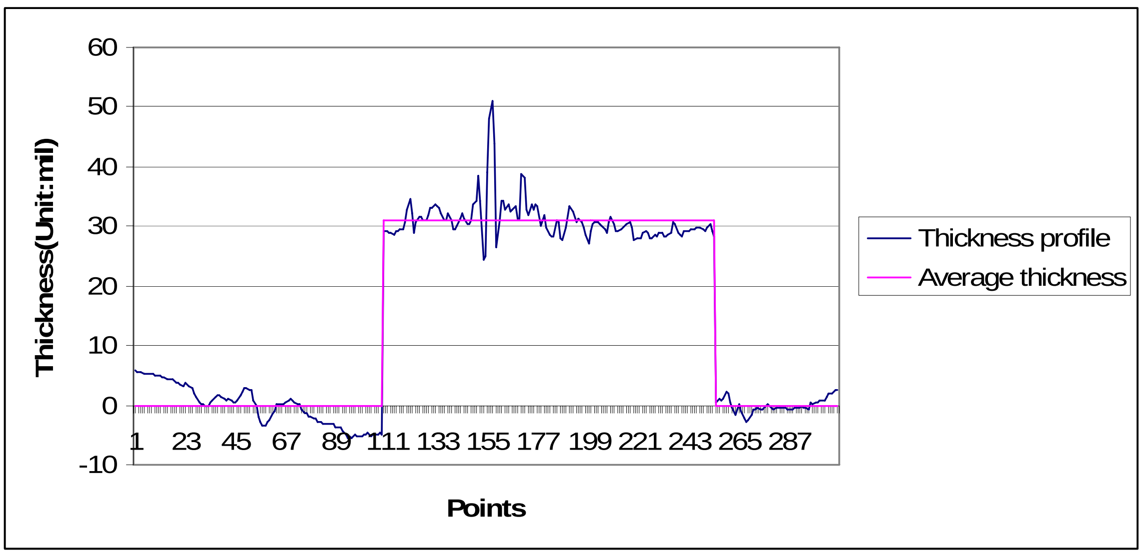


Figure 49 Thickness Profile of the Flex-O-Line thickness of 30 mil tape.

In the second testing scenario, the scanning laser device was mounted on the left (driver) side and right (passenger) side of the vehicle with a speed up to 30 mph. Figure 50 shows the device installed on the left side of the vehicle.

Figure 50 Measurement device mounted on the left side of the vehicle.

Figure 51 and Figure 52 show the tapes and the thickness measurement results of the scanning laser device installed on the left side.

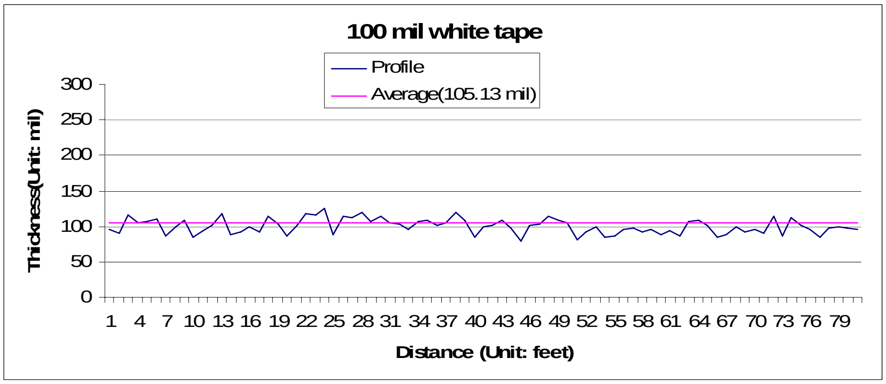


Figure 51 Thickness measurement result of 100 mil white tape.

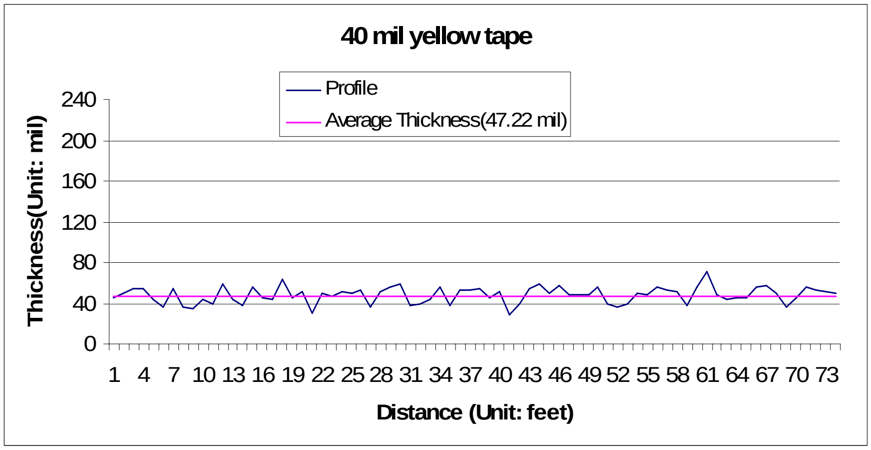


Figure 52 Thickness measurement result of 40 mil yellow tape.

Figure 53 shows the device installed on the right (passenger) side of the vehicle.

Figure 53 Measurement device mounted on the right side of the vehicle.

Figure 54 to Figure 56 show the tapes and thickness measurement results of scanning laser device installed on the right side of the vehicle.

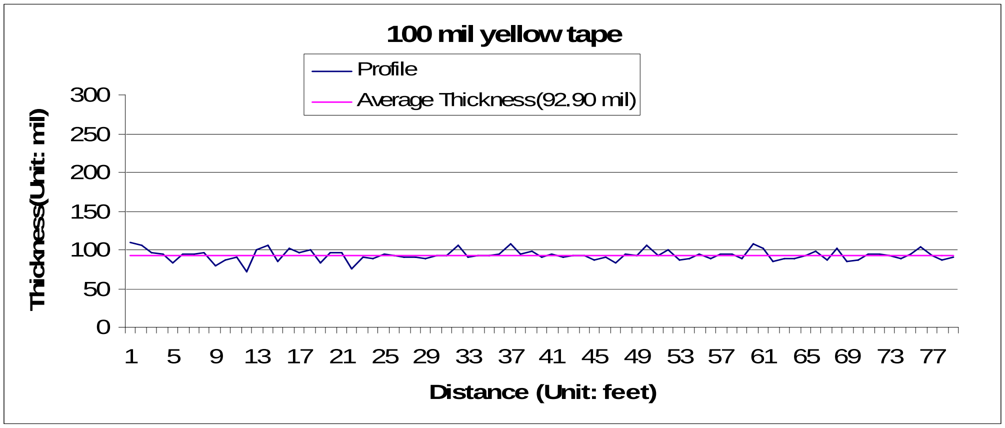


Figure 54 Thickness measurement result for the 100 mil yellow tape.

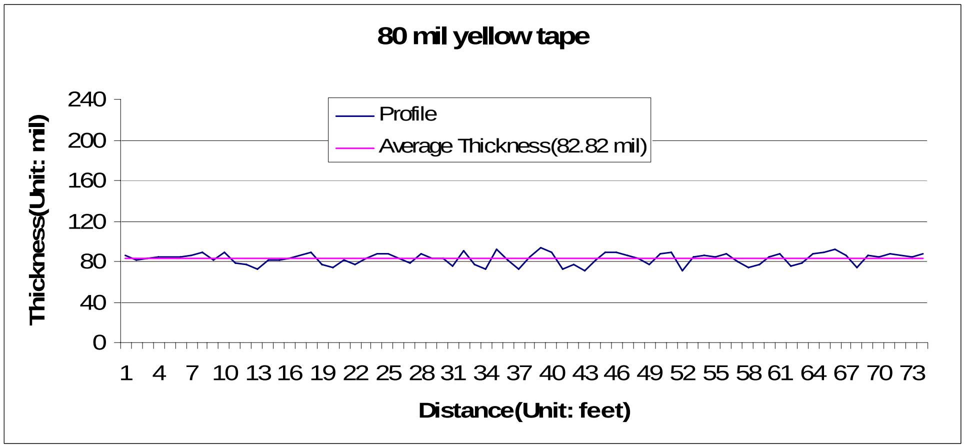


Figure 55 Thickness measurement result for the 80 mil yellow tape.

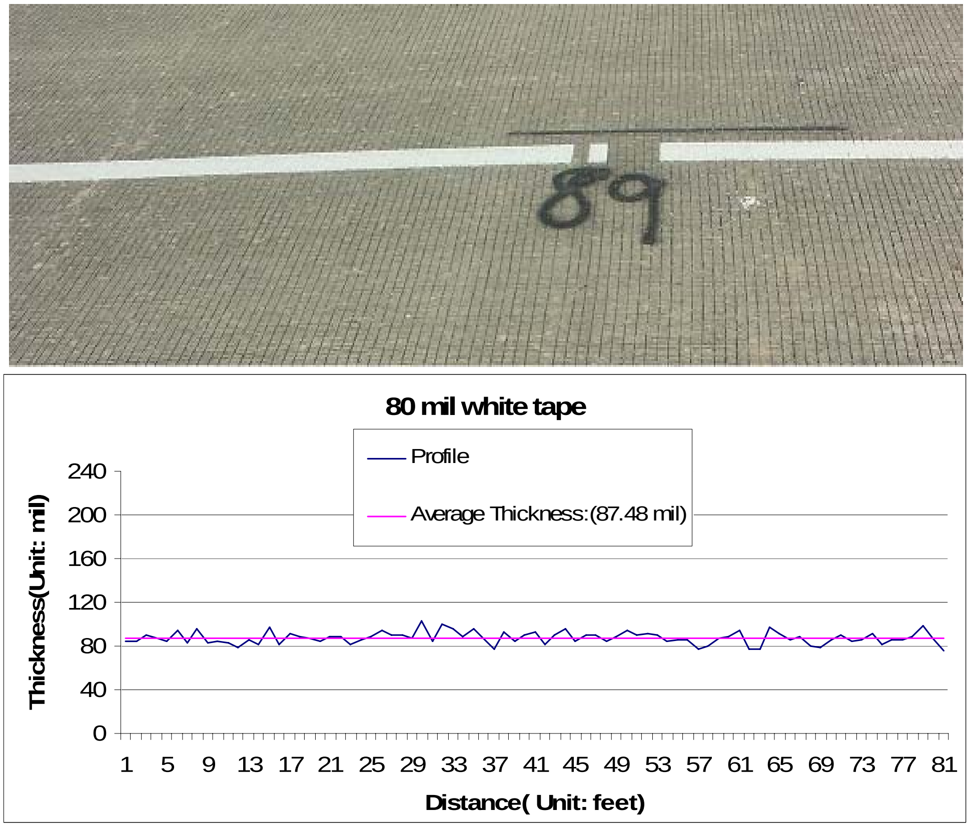


Figure 56 Thickness measurement result of 80 mil white tape.

The testing results show that the scanning laser device can work on both sides with satisfactory accuracy.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

In this project, we successfully developed the new vehicle mount point laser and scanning laser TPMM thickness measurement devices. Field tests were conducted at the TxDOT Cedar Park testing site and the UH Spur 5 testing site. By using the reflectivity information collected by the laser measurement devices, the measurement system automatically identified the TPMM and pavement positions. The test results prove that the non-contact measurement system can be used to measure the thickness of TPMM with high accuracy and can be installed on the left (driver) side or right (passenger) side. But there is still room for improving the scanning laser device. By using a focus lens with a longer focal length, the resolution of the device can be significantly improved. The other issue concerns the accuracy and stability of the scanner. By replacing the resonant scanner with a new galvanometer scanner, we can obtain more accurate information about the deflected angle of the laser beam, and the measurement accuracy of the system will be increased.

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