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3 authors, including:

Mohammed Taleb Obaidat
Jordan University of Science and Technology; Jadara University

Turki I. Al-Suleiman (Obaidat)
Jordan University of Science and Technology

QUANTIFICATION OF PAVEMENT RUT DEPTH USING STEREO VISION TECHNOLOGY

Mohammed Taleb Obaidat[1], Turki I. Al-Suleiman[2], and Ghassan T. Abdul-Jabbar[3]

ABSTRACT

An attempt to investigate the potential capabilities and accuracy of the PC-based stereo vision system in quantification of pavement rut depth was performed. This process was demonstrated using three rutted sections of flexible pavement. Selected highway pavement sections were chosen using a representative criteria which assures randomness in their studied parameters to be used for the purpose of a semi-automatic rut depth quantification. Surface measurement were represented by 2-D and 3-D plots as well as contour maps for the rutted areas. Results obtained by this technique were compared with the one obtained by manual conventional method using straightedge in order to check the accuracy of it, and to adopt this new technology in Jordan's road network evaluation and monitoring. Comparison with manual conventional method showed that stereo vision using dual CCD cameras mounted on a stand on a moving vehicle has a consistent potential accuracy of about one pixel (i.e. about 1.5 cm) on average in measuring the rut depth for the three sections. This result is compatible with the human operator ability to point to the

[1] Assistant Professor of Civil Engineering, Jordan University of Science and Technology, (J.U.S.T.), Irbid, P.O. Box 3030, JORDAN.
[2] Associate Professor of Civil Engineering, Jordan University of Science and Technology, (J.U.S.T.), Irbid, P.O. Box 3030, JORDAN; Currently: on leave, United Arab Emirates University, Civil Eng. Dept., P.O. Box 17555, Al-Ain, United Arab Emirates (U.A.E.).
[3] Research Assistant, Graduate student at the Civil Engineering Department , Jordan University of Science and Technology, (J.U.S.T.), Irbid, P.O. Box 3030, JORDAN.

conjugate image points which has a potential accuracy of about one to two pixels. 3-D coordinates computation is expected to be improved when enhancing camera resolution, camera configuration, using higher image scale, and automating the stereo image matching process. Advantages of using stereo vision technique in order to quantify rut depth include: remote without touching the object being measured, safe, and having a real-time potential due to the use of digital format images.

Four statistical models expressing the relationship between traffic, pavement characteristics, and mix properties of pavement surface as well as their combination with the average rut depth were developed for the purpose of predicting estimated precision for rut depth.

INTRODUCTION

Pavement rutting refers to the formation of twin longitudinal surface depressions in the wheel paths from a progressive accumulation of permanent deformation in one or more of the pavement layers. The rate and magnitude of rutting depend on external and internal factors. External factors include load and volume of truck traffic, tire pressure, temperature, and construction practices. Internal factors include properties of the binder, the aggregate and the mix, and the thickness of the pavement layers. The effects of these factors are inter-linked with each other, where any deficiency in one of them might cancel the advantages of the others.

High traffic density roads subjected to closely channeled heavy usage have always been liable to rutting. Rutting in asphaltic pavement has become more serious as the wheel loads and tire pressure of truck traffic on highways have increased nowadays. Road network serviceability had been reduced and the problem of hydroplaning due to accumulation of rain water in the wheel paths became a serious matter affecting roads safety.

Structural design of an asphaltic concrete pavement is a complex procedure due to uncertainties with the loads to be carried, the response of the pavement system to the loads, and the effects of the environment on the characteristics of the materials in the pavement system. Pavement engineers have been challenged to use conventional methods to design cost-effective pavements that are expected to withstand unconventional wheel loads and tire pressures.

Pavement uplift may occur along the side of the rut, and in most cases, ruts are noticeable only after rain, when the wheel paths are filled with accumulated water (Shahin and Walther, 1990). This vertical depression caused by wheels traveling the same path on the road surface should be classified and recognized. Quantitative and subjective methods have been developed to manually quantity rut depth. Rut depth is usually calculated by laying a straight edge across the rutted area, measuring its depth, then averaging the measurements taken along the length of the rut (Benson *et. al*., 1988). Although, these methods are simple and accurate, they are time consuming, needs high expertise, and dangerous due to traffic movement. Thus, a rapid, convenient, and safe method should be proposed for the purpose of rutting depth measurement, categorization, and fitting in order to select the most efficient maintenance action.

One of the major challenging factors for rut depth is to automatically quantify its depth without any manual field measurement. In the wake of tedious manual measurements, various types of automated equipment have been developed for the purpose of pavement monitoring and evaluation. Recently, photogrammetry proved to be an excellent tool in pavement management and evaluation. Many agencies started adopting it in their pavement management instead of carrying manual evaluations.

The automation of pavement condition data collection and processing methods has become possible and within the reach of implementation within currently available equipment. It helped not only in conducting the task quickly, but also served in keeping permanent record that can be reviewed and updated whenever required, and provided accurate measurements that are not dependent on human judgment.

In tune with the current interest in improving pavement performance and management, many research have been conducted to study different factors affecting pavement rutting and to evaluate the suitability and accuracy of the different automated methods and equipment available for pavement rutting measurements.

This paper investigates the potential accuracy and limitations of stereo vision technique to quantify, evaluate, and classify rutting depth for selected road sections in Jordan. Further, an error propagation scheme is developed to control the potential precision of rutting depth prediction models.

MECHANISM OF RUTTING

Based on the results of AASHO Road Test (The AASHO Road Test, 1962), engineers investigated rutting phenomenon have generally agreed that: it is a longitudinal channel or depression that forms in the wheel path, due to compression or lateral movement, or both, in one or more of the pavement layers as a result of repeated traffic-load applications. Rutting is a manifestation of two different mechanisms densification or volume change where the material is pushed downward, and shear deformation or plastic flow with no volume change which causes the material to flow laterally and upward (Morris, 1973). The total rut depth is measured as the difference in elevation between the crest and sag of the surface. Longitudinal cracking will develop as a result of tensile stresses on the top surface outside of the loaded area.

Krugler *et at*. (1988) suggested that rutting problem falls primarily into three categories:

1. Excessive traffic consolidation in the upper portion of the pavement,
2. Plastic deformation due to insufficient mixture stability, and
3. Instability caused by stripping of asphalt below riding surface.

Traffic volume can not be controlled, but traffic loads can only be controlled through legislation and strict enforcement of the load regulations. Elimination of consolidation and plastic deformation by traffic will require the use of properly designed paving mixtures and structural systems as well as strict construction quality control. Stripping can be reduced by proper compaction, sealing and good drainage in order to minimize the exposure of the mixture to moisture.

In New Mexico (Hanson, 1984), Florida (Page, 1984), and Wyoming (Rutting Investigation, 1982) factors identified as a cause of rutting include: 1) Mixtures prepared at plants operating at low mixing temperature; 2) Excessive permissible moisture in the mix; 3) Elimination of multiple stockpiles requirements; 4) Excessive fines allowed in the mix; 5) Temperature susceptible asphalt cement; 6) Rounded aggregate or insufficient crushed particles; 7) Excessive asphalt content; and 8) Cold weather paving leading to low density.

Many sophisticated systems for pavement analysis and evaluation were introduced. "Minister de L'equipment" of France developed a device in the early 1970's for this purpose. PASCO had been developed in Japan (PASCO Corp, 1984). It uses a series of recording and measuring equipment mounted in specially designed vehicle, cameras are mounted on the front of the vehicle with its axis perpendicular to the road surface. Hair line projector system is mounted on the vehicle's bumper at a known angle with respect to the road surface for the purpose of rutting quantification. Three choices for measurements of rutting are provided for stereo operation user. These are best-fit plane, best-fit line, and a double line approach. Stereo photographs are digitized and analyzed for rut depth (Hinz *et al.*, 1989).

Benson *et al.* (1988) found that PASCO ROAD RECON-75 rut measurements correspond very well with the straight edge measurements. The maximum rut depth measurements made with Automatic Road Analyzer (ARAN) and Laser Road Surface Tester (Laser RST) were found to be less than those obtained by straight edge. However, the accuracy of these rut depths could not be directly evaluated against the straight edge measurements, due to difference in measurement intervals. PASCO measurements showed excellent repeatability, while ARAN and laser RST showed good repeatability.

The pavement distress data collection of the Long-Term Pavement Performance (LTPP) study, which was a part of the strategic Highway Research Program (SHRP), utilized the PASCO multifunction survey vehicles (Goulias *et al.*, 1990). Rut depths data were collected by ROAD RECON-75 system, the developed 35 mm films were enlarged ten times on the ROAD RECON film digitizer, then were converted into a computer data file for permanent record.

Other research work involved film-based non-metric cameras mounted on a van, followed by analysis using a stereoplotter (Hintz *et al*., 1989). Although this technology is reliable, it needs film processing and requires expensive equipment such as digitizer and stereoplotters. The same methodology could be adopted by using low-cost CCD stereo video cameras as well as PC-based stereo vision data reduction scheme. The later proposed work, which represents the research work reported in this paper, has the advantages of ease-of-use, low-cost, time saving, and it does not require any control on the pavement surface to measure rut depth.

OBJECT SPACE INTERSECTION GEOMETRY

Stereo bundle of rays mapped for the same scene from two different locations could be used to extract the object space coordinates. The space intersection algorithm utilized in this research work depends on the collinearity equations. The concept of these equations stated that: at the moment of exposure, the object point J, the exposure center of the lens X_i^c, Y_i^c, Z_i^c, and the associated image point j, all should lie on a common line. Any deviation from the straight line path is simply due to distortion effect. A simplified mathematical model is given by the following projective transformation equations (Obaidat, 1994):

$$X_j - X_i^c = \lambda_{ij}[m_{11}(x_{ij} - x_p + dx_{ij}) + m_{21}(y_{ij} - y_p + dy_{ij}) + m_{31}(-f)] \quad (1)$$

$$Y_j - Y_i^c = \lambda_{ij}\ [m_{12}(x_{ij} - x_p + dx_{ij}) + m_{22}(y_{ij} - y_p + dy_{ij}) + m_{32}(-f)] \quad (2)$$

$$Z_j - Z_i^c = \lambda_{ij}\ [m_{13}(x_{ij} - x_p + dx_{ij}) + m_{23}(y_{ij} - y_p + dy_{ij}) + m_{33}(-f)] \quad (3)$$

where:

$$dx_{ij} = \bar{x}_{ij}\left[L_1 r_{ij}{}^2 + L_2 r_{ij}{}^4 + L_3 r_{ij}{}^6 + L_4 r_{ij}{}^8\right] + \left[P_1(r_{ij}{}^2 + 2\bar{x}_{ij}{}^2) + 2P_2\bar{x}_{ij}\bar{y}_{ij}\right]\left[1 + P_3 r_{ij}{}^2\right] \quad (4)$$

$$dy_{ij} = \bar{y}_{ij}\left[L_1 r_{ij}{}^2 + L_2 r_{ij}{}^4 + L_3 r_{ij}{}^6 + L_4 r_{ij}{}^8\right] + \left[P_2(r_{ij}{}^2 + 2\bar{y}_{ij}{}^2) + 2P_1\bar{x}_{ij}\bar{y}_{ij}\right]\left[1 + P_3 r_{ij}{}^2\right] \quad (5)$$

$$\bar{x}_{ij} = (x_{ij} - x_p)(1 + k) \quad (6)$$

$$\bar{y}_{ij} = (y_{ij} - y_p) \quad (7)$$

$$r_{ij} = \sqrt{(\bar{x}_{ij} + \bar{y}_{ij})} \quad (8)$$

m_{11} - m_{33} = functions of rotation angles (ω, ϕ, κ) around the image axis x, y, and z respectively,

x_p, y_p = image coordinates of the principal point,

f = focal length,

X_j, Y_j, Z_j = the object space coordinates of the object point j,

λ_{ij} = photo scale factor at the image point j, on photo i,

= the object space coordinates at the exposure center of photo i, X_i^c, Y_i^c, Z_i^c

x_{ij}, y_{ij} = image point j on photograph i,

dx_{ij}, dy_{ij} = image point j on photograph i,

L_1, L_2, L_3, L_4 = parameters of radial lens distortion,

P_1, P_2, P_3 = parameters of asymmetric distortion, and

k = affine scale parameters.

Knowing the coordinates of stereo image points as well as the camera calibration parameters, the application of these equations enforces the bundles of conjugate rays (the left and right rays) to intersect, according to the distortion model, in the space at the common object points. Consequently, the ground coordinates could be computed for every point in the mapped stereo scene. For points appear on more than two stereo pairs a rigorous least-squares adjustment algorithm could be implemented in order to compute the most probable object space coordinates (Wong, 1980).

QUANTIFICATION OF RUT DEPTH USING STEREO VISION

Two of the most important factors which define pavement performance are cracking and rutting. Quantifying these two factors is easy but it is highly subjective and completely dependent on the skill of the person carrying this job. Therefore, it was thought necessary to use a reliable, quick, and precise technique in quantifying rut depth. A PC-based vision system is the technique which was used for this research program.

This section contains demonstrations of using stereometric vision techniques in order to quantify rut depth of highway pavements. Comparison with manual conventional method is also investigated. The potential accuracy as well as limitations of this technique are also given. Moreover, graphical representations of rut areas are demonstrated besides the used hardware and software.

Equipment

A digital image and data acquisition stereo vision system which is available at the Surveying and Photogrammetry Laboratory of the Civil Engineering Department, at Jordan University of Science and Technology (J.U.S.T.) was utilized in this work. It consists of the following:

1. A DTK 486 personal computer with SVGA monitor, equipped with an EPIX frame grabber (EPIX, 1993) with 20 MHz pixel clock and 1MB of image memory. The DTK 66-MHz 486/AT PC was equipped with 8 MB RAM, 550 MB hard disk drive, 5.25 and 3.5 inch high density drivers. Images were captured using standard PAL resolution; i.e. 752 * 480 pixels at 256 gray levels.
2. Two 50 800 8mm SAMSONG Charged-Coupled Devices (CCD) camcorders equipped with zoom lens capability. The two camcorders were mounted on a normal base stand at 80cm base. This type of cameras was used because of its real-time potential, ease-of-use, low-cost, and easy hand-held.

   Figure 1 shows a dual-based stereo cameras mounted on a stand of 1.3 m height with variable base potential.
3. A video monitor, dot matrix printer, and a scanner were used as a supporting equipment to the system.

Figure 2 shows the basic components of the off-the-shelf stereo vision system.

Software

For the purpose of image capturing, digitization, and analysis, four software were used (EPIX, 1993; and Obaidat, 1994):

1. SVIP: an interactive program for image capturing and digitization into 256 gray levels (8 bit per pixel) with a resolution of 752 (horizontal) * 480 (vertical) pixels.

The digitized images were stored as DOS files in two formats, either (XY) or (TIF) format. The software has other image processing capabilities which were not used because they were out of the scope of this research program.

2. DRSTEREO: a program that helps in determining image points coordinates from stereo images on PC, using manual matching process. It also has capabilities to quantify (XYZ) coordinates.

3. INTERSECTION: a program used in order to quantify rut depth and surface measurements from stereo images coordinates. The calibration parameters of the camera are also another input for this program. The (XYZ) coordinates could be found for any conjugate stereo image points.

4. PLANE: a camera calibration program used in order to model the passage of light passes through the camera lens to be calibrated. It quantifies both the interior as well as the exterior orientation parameters of the cameras using planer wall as a control object. Interior orientation parameters include the camera focal length(f), principal point coordinates (x_p, y_p), radial distortion parameters (L_1, L_2, and L_3), decentering distortion parameters (P_1, P_2, and P_3), and affine scaling parameter (*k*). Whereas, the exterior orientation parameters include: the camera orientation angles around its axis (ω, ϕ, κ) and the exposure center coordinates (X^c, Y^c, Z^c). Planer wall parameters (A, B, and C) are also computed.

It has to be noted here that the key for any stereometric measurements is the quantification of camera calibration parameters with certain estimated standard errors. This of course, depends on the camera configuration; i.e. the base and convergent photographs rotation angles as well as the certainty of the control measurements such as (XYZ) coordinates and distances. Other problems associated with calibration include: image resolution, image intensity, frame-grabber, and accuracy of measurements in image domain. Thus, under the available limited resources as well as low resolution image capturing using the available frame grabber, it was expected that the measurements accuracy will be degraded rapidly.

Data Acquisition Procedures

The following methodology were followed in order to obtain three dimensional coordinates for rutted pavement sections:

1. dual-camera calibration images capturing.
2. stereo image capturing of the rutted area.
3. re-calibration images capturing after coming back from the field.
4. image digitization using SVIP program.
5. PLANE program execution to find calibration parameters.
6. rut images digitization in order to find image coordinates using DRSTEREO program.
7. XYZ coordinates quantification using INTERSECTION program.
8. 2-D , 3-D, and contour representations of rut area.
9. comparison with actual rut measurements.

Cameras Calibration

In order to obtain the relative orientation of the stereo cameras as well as the interior geometry of the cameras that are mounted on the normal-based dual stand, a calibration wall (planer wall) was mapped for this purpose. This wall was filmed by both the left and the right cameras from two known locations (about 80cm distance). Stereo images of the planer wall control were captured before and after capturing images for the rutted areas in order to assure the geometric stability and fidelity of the used cameras. The average rotation angles were computed for each camera using the two locations, whereas, the interior calibration parameters were associated with each camera.

Figure 3 shows a sample of stereo images captured for the planer wall. Table 1 shows a sample output calibration parameters with their estimated standard errors for the captured camera calibration stereo images of the right camera. Computed standard error of unit weight of about 0.6 pixel in both cameras were achieved, which is an indicator for excellent calibration procedures as well as geometric fidelity of the used cameras (Fryer, 1989).

Stereo Images of Rutted Pavements

Three pairs of stereo images were captured for selected samples of the rutted sections of Jordanian highways. They were filmed for a period of less than two minutes, in order to give convenience for digitizing images on the frame grabber. Stereo images were captured using SVIP software and transformed into DOS files in two formats (TIF and XY), while the tape was in the play back mode. A pair of stereo images of the outer half of two sequential rutted sections is shown in Figure 4.

Image Coordinates

In order to simplify the identification of the conjugate image points of the stereo images, white dots had been sprayed on the pavement surface. The sprayed dots were selected to have 3-4 pixels size in image domain in order to overcome resolution problems associated with low cost frame grabber as well as scale problem. Although using large size image points is expected to affect the accuracy of the results, this action had been done for the purpose of comparing the actual rut depth measurements with the measurements extracted from the stereo vision system as well as to overcome problems associated with manual matching procedure. The image coordinates of the white marked points on the rutted pavement surface were extracted using DRSTEREO software by manually pointing to the conjugate image points in concern. Human operator matching error is normally varying between one to two pixels.

Spraying of the white dots is one of the limitations of this study, because it will affect the practicality of using vision system for rutting quantification task, but it was used in this research work, in order to introduce this technology into the professional work domain of rut distress quantification.

Rut Depth Measurements Using Stereo Vision

Conjugate image points of each stereo pair besides the calibration parameters for each camera have been used as an input to INTERSECTION software, in order to quantify the rutted area point locations; i.e. 3-D coordinates of the sprayed points.

The accuracy of the computed locations of these points depends on image matching accuracy, the camera calibration procedure, camera resolution, and the used camera configuration (Abdel-Aziz and Karara, 1974; Faig *et al.*, 1990; and MacCarley *et al.*, 1993).

Conventional Measurement Procedure

Actual rut depth measurements were recorded at the same white sprayed points. The locations of their coordinates were recorded, too, using a 2m straightedge and a measuring tape. The purpose of this process was to compare the actual values of the rut depth with the one extracted from stereo vision, which will indeed give the accuracy potential of stereo vision as a new technique to measure rut depth.

Graphical Representation of Rutted Areas

One of the by-product representation of the extracted surface measurements is to present them graphically. The surface measurements using both conventional (actual) method and stereo vision method were compared using: two dimensional (2-D), three dimensional (3-D), and contour mapping plots. Figure 5 shows 2-D plots generations for selected rutted areas with the X-axis being the road width, while the Y-axis being the rut depth. 3-D surface reconstruction is also shown in Figure 6 for the three mapped scenes for both manual and stereo vision process (rut depth unit is in mm while other two axis are in m). Figure 7 shows contour maps for the 3-D surfaces of the rutted areas which are also another by-product of the PC-based close-range photogrammetry system.

Comparison of Results

As shown in Figures 5, 6 and 7 noticeable differences in rut depths ere obtained between the two methods for sections 1 and 2 of the mapped scenes, while section number 3 has slight difference. the average mean absolute difference and its standard error are computed as shown in Table 2 for the three rutted sections. The average absolute difference of rut depth was about 14.6 mm which is equivalent to about 1.5 pixels in the image domain. This result is compatible with the human operator potential accuracy while pointing to the conjugate image points. Consequently, the better the operator makes the matching process, the better will be the 3-D coordinates output.

It is worthwhile mentioning here that data collection through vision system has been done twice, by which a preliminary study was done for the first data set in order to select the best camera configuration as well as the vision system resolution. The second data set is the one reported in this study.

The differences between manual conventional method and stereo vision method were also consistent in the three cases, by which the estimated standard error and the coefficient of variation were 12.7 mm and 0.87 respectively.

Differences of rut depth measurement between the two methods can be caused by many factors including:

1. Camera configuration: it is defined as the ratio between the base (*b*) to the object distance (*H*); i.e. *b*/*H*. With base of 80cm and object distance of about 9m, the resultant convergent angle is 5.65^{o} which is a small angle. Any mistake in the manual matching will result in an appreciable error in the 3-D measurements. It is expected that, increasing the base width will overcome this problem. Figure 8 shows the effect of convergent angle and matching errors on the intersection geometry of the extracted 3-D coordinates. Other errors are due to distortion of camera lens.
2. Image resolution: the available version of SVIP interactive software has a maximum resolution capability of standard PAL format (752 * 480 pixels). This resolution is considered as a low resolution for precise measurements, especially that 3-D coordinate computation is highly correlated with image measurements accuracy. Consequently, improving or upgrading image capturing resolution to (1040 * 480) pixels or better is expected to improve the quality of measurement.

3. Manual matching and scale: the accuracy of the matching process depends on the quality of the captured images (i.e. resolution) as well as the ability of the human operator to point to conjugate points. For example, an error of 1 pixel (0.02 mm) in matching between the left and right image will result in measurement difference of about 1 cm using a scale of 1/500. This difference depends on the scale of the image points which is defined as

$$\text{Scale} = f/H \tag{9}$$

where: f is the focal length and H is the object distance.

The captured image scale used in this research was about 1/500, which means that each pixel on the image represents 500 pixels on the measured object, and for a pixel size of 0.02 mm, one pixel error in matching process will result in 10 mm (i.e. 0.02 * 500) error in measurement.

Overcoming the deficiencies mentioned previously is expected to enhance the quality of stereo vision measurements. It is worthwhile mentioning here that the optimal configuration of convergent photo is not numerically known and stereo vision technology still under extensive research work and needs a lot of improvement in all data reduction as well as hardware techniques and component (Fraser, 1982). Obtaining such results with about 1 pixel accuracy in image domain using a low-cost, low-resolution CCD-cameras and limited resources hardware is promising toward the use of stereo vision technology in many other metrology applications.

RUT DEPTH PREDICTION MODELS

This section is devoted for the development of prediction models of the precision of the computed rut depth using field data investigations. The data variables used to predict rutting depth include: asphalt mix properties, pavement characteristics, and traffic parameters. Four different approaches using regression analysis were followed to study the separate effect of different variables included in the collected field data on pavement rutting. Also, the combined effect of the significant variables was investigated in order to predict rut depth. Data sets collected for main and secondary roads of four Jordanian districts were used (Abdul-Jabbar, 1995).

Criteria For Selection Of Pavement Sections

The following criteria were adopted in the selection of the pavement sections:

1. The selected sections should be from straight portions of the highway, having uniform soil characteristics. Steep longitudinal gradients and curves were avoided to eliminate the effect of speed reductions.
2. Variations in rut depths, pavement age, pavement thicknesses, and traffic volume were preferred in order to develop sound rut depth precision statistical models.
3. Drainage type and conditions were similar for all of the selected pavement sections, in order to cancel any effect of accumulated water on the characteristics of the pavement structure.
4. Pavement sections selected from secondary highways having high traffic volume and loading.
5. Section length was taken to be 10 m long.

Actual Measurement of Pavement Rutting

Rutting in the outer wheel path was considered as it is more noticeable in most of the rutted pavement sections. A 2-m straight edge and a graduated triangle were used to measure the rut depth. Five measurements for the maximum rut depth were taken at two meters intervals for each section. These values were averaged and the result was considered as the average rut depth of the section (ARD). Statistical characteristics of the actual measured average rut depth (ARD) is given in Table 3. This data set is consistent with the statistical rut depth data measured using stereo vision technique (Table 2).

Statistical Models

The following models were adopted in order to find the predicted rut depth precision (Hewling, 1985; and Abdul-Jabbar, 1995):

1. Pavement characteristics and traffic model: In this approach, pavement characteristics represented by subgrade CBR (SGCBR) and traffic parameters represented by the Average Annual Equivalent Single Axle Load (AESAL), were considered. The following model was adopted in order to predict the Average Rut Depth (ARD) in mm:

$$\text{Log}_{10}\ \text{ARD} = 1.73 - 0.802\ \text{Log}_{10}\ \text{SGCBR} + 292\text{x}10^{-09}\ \text{AESAL} \qquad (10)$$

2. Air void model: This approach dealt with Marshall test parameters. Significant investigated variable was the Difference of Air Voids between Rut and Center Line of the lane (DIFVIM). The following model was adopted to compute ARD in mm:

$$\text{ARD} = 5.68 + 6.025\ \text{DIFVIM} \qquad (11)$$

3. Dynamic creep model: In the third approach, dynamic creep test results represented by Dynamic modules (E) were related to pavement rutting formation. The following model was adopted to compute ARD in mm:

(12) $$ARD = 8.97 + 0.0025\ E_{1\text{-}C}$$

Dynamic modulus of the centerline bituminous core sample tested Where: $E_{1\text{-}C}$ =

at 1 Hz loading frequency, and a repeated load of 2.4605 KN.

4. Combination of significant factors model: The previous three factors were combined to produce a new model:

$$0.205\ Log_{10}\ E_{1\text{-}C} - 0.047\ SGCBR + 0.189\ Log_{10}\ AESAL + 0.105\ DIFVIM\ Log_{10}\ ARD =$$

(13) $(R^2=0.67\ ,\ \ adj\ R^2 = 0.63)$

These models were used to predict the average rut depth as well as to quantify the precision of the computed ARD as shown in the next section.

ERROR PROPAGATION OF MODELS

Suppose the value of a parameter Y can be calculated from the measured values of n other parameters, say $X_1, X_2, ..., X_n$. If Y is related to the n parameters by a continuous function F (Schmidt and Wong, 1985):

(14) $$Y = F(X_1, X_2, ..., X_n)$$

Furthermore, if σ_{Xi} is the estimated standard error of parameter X_i, and σ_Y is the estimated error of Y. Then, by the law of propagation of random errors:

(15) $$\sigma_Y^2 = \sum_{i=1}^{n}\left(\frac{\partial F}{\partial X_i}\right)^2 \sigma_{X_i}^2$$

Applying Equation 15 on the models represented by Equations 10, 11, 12 and 13 to obtain the estimated standard error of ARD (σ_{ARD}), which is a measure of how precise the prediction model will be, the following equation were obtained for this purpose:

$$\sigma^2_{ARD} = 2883.7\,[\left(10^{292E-9\,AESAL}\right)\left(-0.802\,CBR^{-1.802}\right)]^2\,\sigma^2_{CBR}$$

$$+[\left(CBR^{-0.802}\right)\left(10^{292E-9\,AESAL} * \ln 10^{292E-9}\right)]^2\,\sigma^2_{AESAL} \qquad (16)$$

$$(17) \qquad \sigma^2_{ARD} = (6.025)^2\,\sigma^2_{DIFVIM}$$

$$(18) \qquad \sigma^2_{ARD} = (0.0025)^2\,\sigma^2_{E1-C}$$

$$\sigma^2_{ARD} = [\left(0.205E_{1-C}{}^{-0.795}\right)\left(10^{-0.047\,CBR} * AESAL^{0.189} * 10^{0.105\,DIFVIM}\right)\sigma_{E1-C}]^2$$

$$+[\left(10^{-0.047CBR} * Ln10^{-0.047}\right)\left(E_{1-C}{}^{0.205} * AESAL^{0.189} * 10^{0.105}\,DIFVIM\right)\sigma_{CBR}]^2$$

$$+[\left(0.189\;AESAL\right)\left(E_{1-C} * 10^{-0.047\,CBR} * 10^{0.105\,DIFVIM}\right)\sigma_{AESAL}]^2$$

$$+[\left(10^{0.105DIFVIM} * Ln10^{-0.047}\right)\left(E_{1-C}{}^{0.205} * 10^{-0.047CBR} * AESAL^{0.189}\right)\sigma_{DIFVIM}]^2 \qquad (19)$$

The previous equations can give simple formulas to estimate precision of the computed mean rut depth for any laboratory investigation or/and data field study without physically measuring pavement rut depth.

POTENTIAL CONTRIBUTION TO THE FIELD

The research basically concentrated on quantification of rut depth values for selected roads in Jordan. Stereo vision using close-range photogrammetry was used for quantification of actual rut depth measurements. Whereas, the prediction of rutting depth precision using the statistical modeling which depends on the physical and mechanical properties of asphalt mix, and traffic parameters, is expected to have great impact on rut depth evaluation.

Accuracy limitations of stereo vision system for different configurations were not studied as it has its own problems. The pavement sections were selected at random depending on the presence of noticeable rutting at the surface.

Quantifying rut depth, using stereo vision technique, rather than performing actual measurements, is expected to have great impact on rut depth evaluation. It is anticipated that the quantification of rut depth will be effectively and conveniently done without physically touching the rutted area. Thus, reducing the risk of traffic movement interference. Time saving factor is also important in this domain. Consequently, maintenance action could be scheduled in advance. This will have a great impact on maintenance priorities and budgeting planning.

CONCLUSIONS

The following main conclusions were the most significant finding of this research work:

1. Stereo vision could be used as a quick and a consistent technique in order to quantify pavement rut depth.

2. Using stereo vision technique, a potential accuracy of one to two pixel in the image domain has been reported for rut depth, which was compatible with human operator matching ability.

3. In spite of an excellent geometric fidelity of camera calibration procedures using a planner wall facility, other factors such as resolution, configuration, matching, and image scale presumably play major factors in accuracy of rut depth measurements.

4. A quantitative measure for rut depth precision could be estimated if the estimated errors of traffic and pavement characteristics as well as the bituminous mix properties are known. This error propagation scheme is useful to control the potential precision of predicted rut depth using statistical models.

Based upon the findings of this research work, the following recommendations were drawn:

1. Further research work should be held to study the effect of scale, resolution, camera configuration, and image matching in 3-D coordinates computation using vision system.
2. Different camera types and frame grabbers should also be tested for other studies.
3. Proper camera calibration, configuration, and stability should be investigated to find the optimal camera configuration.
4. Automation of stereo image matching is a must to enhance the accuracy potential and to increase degree of measurement's automation.
5. The applications of stereo vision equipped with CCD-cameras in different metrology applications of pavement maintenance and evaluation should also be wide spreaded.

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A full report of the research reported in this paper can be found in Abdul-Jabbar (1995).

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Table 3: Statistical characteristics of the average rut depth for the studied sections.

Variable	**N**	**Mean**	**Standard Deviation**	**C.O.V.**	**Range**	
					Minimum	Maximum
ARD, mm	51	16.26	11.36	0.69	2.20	47.40

Table 1: Right camera calibration parameters and their respective standard errors.

Interior Orientation			**Exterior Orientation**		
Parameter	Value (Pixels)	Standard Error	Parameter	Value	Standard Error
Xp	377.951	1.779E+01	X^c(m)	101.48	0.000
Yp	237.769	1.720E-01	Y^c(m)	95.48	0.000
f	1034	0.000	Z^c(m)	100.5	0.000
K	2.11E-02	4.08E-03	ω(degree)	-90.411	0.000
L_1	1.301E-07	1.100E-07	ϕ(degree)	-0.211	0.000
L_2	-9.957E-13	9.992E-13	k (degree)	5.496	0.000
P_1	-1.464E-05	4.266E-06	Planer wall parameters		
P_2	-9.477E-06	8.697E-06	Parameter	Value	Standard Error
P_3	-1.236E-06	3.199E-06	A	-1.001E-14	5.973E-10

	B	1.011E-02	1.158E-08
	C	1.679E-15	0.000

Table 2: Differences between conventional and vision measurements.

Section Number	**Mean Absolute Difference (mm)**	**Standard Error (mm)**	**Coefficient of Variation (C.O.V.)**
1	15.11	12.4	0.82
2	17.63	15.9	0.90
3	11.07	9.94	0.89
Average	14.6	12.7	0.87