DHT 49

A Rut Measurement System Based on Continuous Transverse Profiles from a 3-D System

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A Rut Measurement System Based on Continuous Transverse Profiles From a 3-D System

Research and Development Project Report

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Executive Summary

For the past 13 years, the Texas Department of Transportation (TxDOT) has operated a five-point acoustic sensor rut measurement system for statewide Pavement Management Information System (PMIS) rut data collection. The accuracy of this method is questionable due to the weaknesses inherent to the system. The five-point sensor rut system often underestimates rutting value—up to 40% of the ground rut level—especially when the surveyed lane is too narrow or too wide. Other researchers have reported similar findings when using point-based rut measurement systems. Vehicle wander during data collection often causes sensors to move in and out of the wheel path. In addition, varying traffic patterns create unusual profiles on road surfaces, which do not match with the designed sensor location. As a result, wheel path sensors often point to locations other than the rut path. Usually these systems report significantly less or even negative rut when compared to the actual ground truth measurements.

In 2007 TxDOT initiated an in-house development effort to create a rut measurement system based on a continuous transverse road profile using a high-speed 3-D surface inspection technology. The 3-D system consists of a laser line projector and a high-speed 3-D camera. The laser projector has a wide fan angle lens and projects a 14-foot wide laser beam across the measured lane; the camera captures an image of the laser line for each inch of road traveled. Each image contains information of laser line variations caused by surface elevation differences. Using a pre-calibrated laser triangulation algorithm, the 3-D camera converts the laser line variation into a surface elevation data array called the Range Image (RI). The 3-D camera also captures high-resolution, linescan-style surface brightness images, or Pavement Intensity Images (PII). These intensity images are synchronized to the range images to detect lane stripes and other surface features. Reliable lane stripe detection provides a reference point for the rut measurement algorithm, which helps to eliminate improper rut measurements taken outside the surveyed lane.

The TxDOT team developed a custom software package to implement the 3-D technology and process the image information. The software controls the laser and camera for real-time data collection by adjusting the camera scan rate to synchronize with the vehicle speed. It also controls the camera exposure time to achieve the best quality PII and conducts image and data processing in real time. The software averages twelve raw transverse profiles to reduce aggregate noise and creates a profile

representing a 1-foot traveled pavement section for each rut measurement. This averaged profile is then filtered to remove cracks and other non-rut objects. A specially designed straightedge algorithm simulates the manual straightedge rut measurement method by placing two 6-foot long virtual straightedge bars on top of the filtered profile data. The maximum difference between these virtual straightedge bars and the profile is measured as rut depth for the left and right wheel paths. The algorithm is implemented to meet the requirements of the ASTM E1703 standard, and the results are comparable to a manual straightedge measurement taken on the pavement surface.

The final product of this project is a highly accurate 3-D pavement surface image-based rut measurement system called VRUT. VRUT can be directly interfaced to TxDOT's Vehicle Automation Measurement Operating System (VAMOS), and the output data can be sent directly to the PMIS data storage mainframe. VRUT receives a speed signal from VAMOS and returns rut statistics at a required distance interval through an Ethernet connection. VRUT can operate at any speed between 10 and 70 mph and process data in real time, with a minimum speed of 10 mph set by the TxDOT laser safety program. VRUT captures a 1536 by 576 pixel image frame during data collection, with each frame covering a 672-square foot pavement area. It can measure exact pavement elevation (height) changes in a range of -8 to +8 inches with a resolution better than 0.03 inches. Its longitudinal resolution is 1 inch for network-level data collection and is user selectable if needed for project level data collection. Its transverse resolution is 0.11 inches for the current camera setup.

TxDOT conducted an extensive manual rut and VRUT comparison test on an assortment of roads. The sample roads included smooth-textured asphalt concrete pavement (ACP) and rough-textured sealcoat (chip seal) surface types and ranged from narrow county roads to wide highways. A team manually collected data with a 6-foot straightedge for each wheel path at 15-foot intervals of the test sections. The exact bar location was marked on the side of the road for VRUT data reproduction. After the manual measurements were complete, VRUT traveled the same length of road at the posted speed limit, collected data on the test sites, and saved the raw data to disk. Post processing was used to analyze the VRUT data at all of the marked locations, and these data points were then compared to the manual straightedge data result. Measurements from over six thousand data points showed a high correlation between the manual data and the VRUT measurements. T-tests confirmed that, at a 99% confidence level, the VRUT and the manual data do not have a statistically significant difference. Currently, the manual straightedge rut measurement is a standard method widely trusted for rut testing. Considering the correlation of the data from the manual measurements and the VRUT, the VRUT system can be considered an accurate pavement rut measurement instrument.

Introduction

Pavement rut, defined as the longitudinal depression of pavement structure, is a critical measure of pavement condition. Severe rutting not only indicates the level of pavement distress, but also alludes to potential safety hazards. Rutted pavement may hold rainwater and increase wet weather driving hazards such as hydroplaning. Rutting also impacts ride quality, as indicated by the IRI value. Since it is very difficult to collect rut data manually or visually on a network level, point sensor-based automatic or semi-automatic rut measurement instruments have been widely used since their development nearly a decade ago [1,2,3]. Despite their widespread use, these instruments were created using technologies that were available at the time of development, and they all display various degrees of inaccuracy.

TxDOT currently uses a five-point acoustic system for its PMIS rut data collection, as shown in Figure 1. The principle of the five-point rut measurement system, as described in ASSHTO PP38, is based on an ideal transverse profile on the road surface. This ideal profile should have left and right ruts located evenly from vehicle center at predetermined distances. Wheel path sensors must be positioned in the exact rut locations to calculate the correct rut depth measurement. In addition, the center and two outside sensors should measure the inner and outer reference edges of the rut. In all other non-ideal situations, the five-point rut system can not provide accurate rut measurement, as compared to the actual pavement profile.

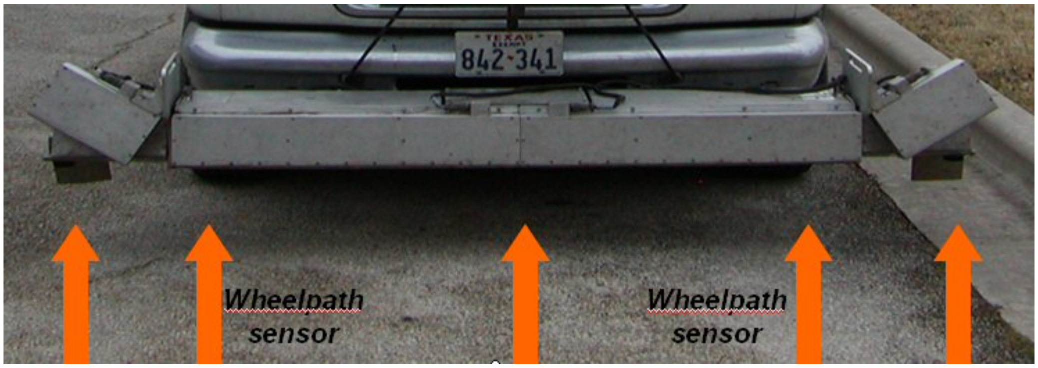
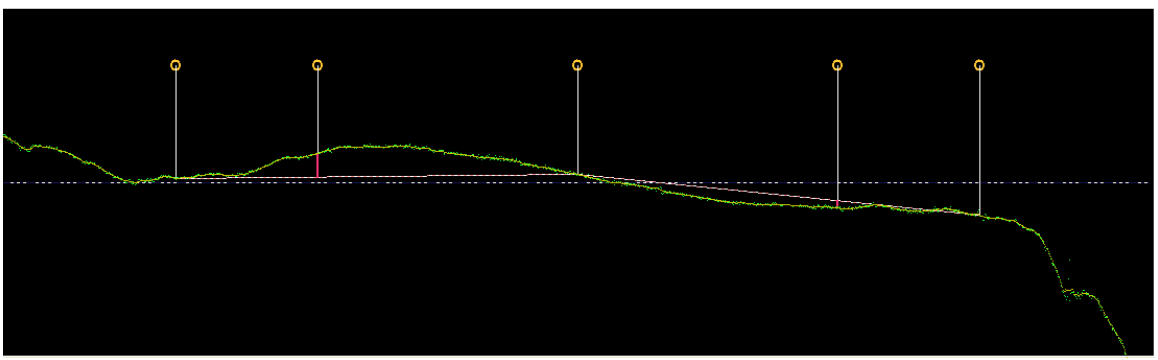


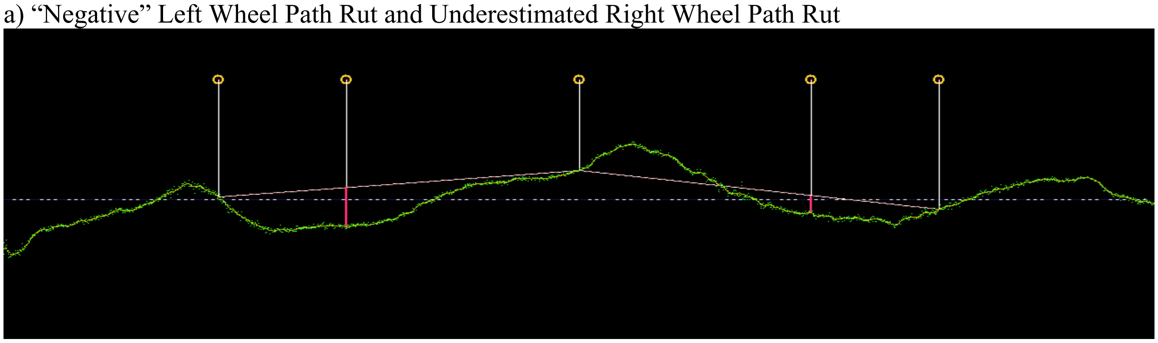
Figure 1. TxDOT Five-Point Sensor Rut System.

During real data collection, there are two main reasons that inaccuracies occur with point-based systems. Vehicle wandering while traveling moves the wheel path measurement sensors out of the actual rut tracks. For this reason, the five-point sensor rut measurement will statistically introduce at least a ± 0.276 inch error into the data [2]. In addition, five-point systems often collect data on roads with transverse profiles that do not match the ideal model used in the initial development of the point-based system. Misalignment between the sensor and the rut will cause point sensor systems to measure less rut, sometimes calculating a negative rut value during data collection. This greatly reduces the utility of collected data, as negative rut is not a meaningful measurement of the pavement rut.

Figure 2 shows some examples of virtual point-based rut system sensor locations on a continuous transverse profile. The transverse profile shown was captured using the TxDOT VRUT system, with five virtual rut sensors placed at the same intervals and locations as in the TxDOT five-point rut system. These images illustrate that the center reference sensor does not point to the correct reference location between the left and right rut, and the two wheel path rut sensors do not point to the correct rut bottoms.



a) "Negative" Left Wheel Path Rut and Underestimated Right Wheel Path Rut



b) Sensor Locations Are Not Matched with a Wide, Deep Rut—Rut Value is Under-Measured

Figure 2. Five Sensor Locations on a Continuous Transverse Profile.

In 2007, TxDOT initiated an in-house development effort to create a rut measurement system based on a continuous transverse profile. A number of requirements were set for the target system to improve performance over the existing five-point acoustic or laser sensor-based rut measurement systems. The system must be self-guided to the correct lane position, so an automatic lane stripe or pavement edge detection algorithm must be implemented to ensure that rut measurements are only taken in the driving lane. The system must also be flexible to operate with different lane widths and rut formations; it should be able to follow the surface contour and automatically locate the rut traces and reference points. In addition, the system must tolerate a certain amount of vehicle wander and vibration, so as not to introduce significant errors to the rut measurement data.

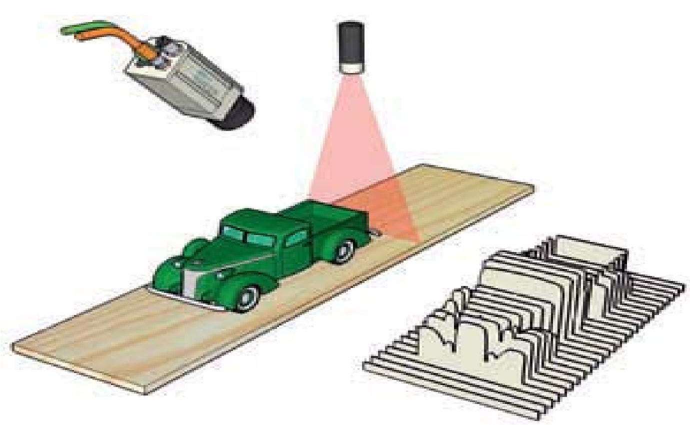
Project Design and Development

The TxDOT VRUT system is based on the principle of laser triangulation 3-D measurement. The laser triangulation 3-D measurement is a widely used technology for high-speed and high-resolution profiling. As shown in Figure 3 a), a thin laser line is projected perpendicularly on top of a target, while a camera views the laser line at an angle. The camera's interpretation of the image is translated by the target profile as shown in Figure 3 b). A triangulation relationship exists between the image pixel shift and the actual height of the target [4]. This relationship can be used to convert each laser line point measured in the image into a vertical height measurement. The height resolution from this relationship can be approximated as:

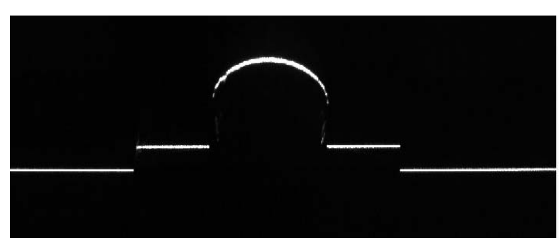
$$\Delta Z = \frac{\Delta X}{\sin(\alpha)}$$

Where:
ΔZ = height resolution in inches.
ΔX is the horizontal pixel resolution in inches. Here $\Delta X = \frac{survey \quad width}{camera \quad pixels}$
α is the angle between the laser plane and the camera optical plane.

The camera used in the VRUT project provides a built-in Center of Gravity Algorithm (CGA). The CGA can detect laser line position at 1/16 of the camera pixel resolution. It gives a final system height resolution sixteen times higher than traditional pixel level laser line detection methods.



a) Laser Triangulation 3-D Profiling from Camera



b) Laser Line Image Caused by Deformation

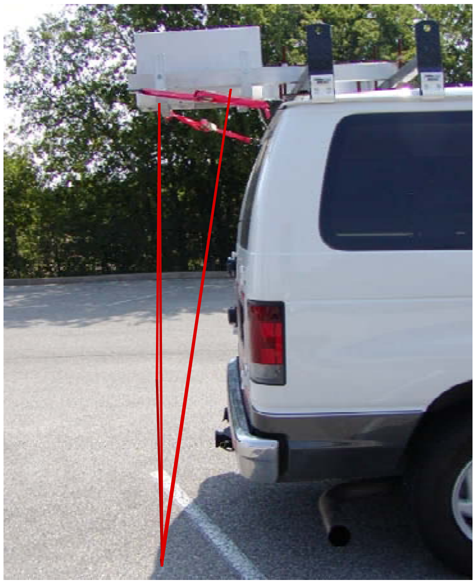
Figure 3. Principles of Laser Triangulation 3-D Measurement.

Each profile from the laser triangulation measurement is a single trace of transverse contour. Multiple profiles taken at a given travel distance produce a 3-D image frame of the target, as shown in Figure 3 a). When the system is used for pavement surface surveying, it provides a complete 3-D model of the roadway.

In the TxDOT VRUT system, a high-power infrared laser line projector is mounted 84 inches above and perpendicular to the pavement surface. The laser projector illuminates the pavement with a 14-foot long, 0.0787-inch wide laser line across the lane, as shown in Figure 4. The camera captures the laser line from a horizontal distance of 17.5 inches. With a pre-calibrated laser triangulation algorithm, this pixel shift can be converted to a height measurement. In a traditional laser and digital camera laser triangulation design, the camera captures each image frame and sends it back to the host computer for processing. The host computer detects each pixel location along the entire laser line and then converts these pixel locations using a series of trigonometry calculations. The measurement speed is limited by the camera speed, image data transfer rate from the camera to the host computer, and image processing speed of the host computer. The 3-D camera used in the TxDOT VRUT system can perform a majority of the image processing and find the laser line locations inside the camera. Because only processed pixel location data is sent to the host computer, the data volume is only a fraction of the full image frame data volume. Since the frame rate is largely limited by the bandwidth of the camera to host computer interface, the 3-D camera can operate at a much higher scan rate.

Using the current hardware setup and CGA processing, VRUT can provide a height resolution of 0.0335 inches while covering a 14-foot lane width.

a) VRUT Back View with Laser Line Drawing



b) VRUT Side View with Laser-Camera Triangle

Figure 4. TxDOT VRUT System.

1. Hardware Design

VRUT hardware consists of a high-speed 3-D camera, a high power infrared laser line projector, a control unit (host computer), and various electronics that control camera speed and implement laser safety protocols, as shown in Figure 5. During normal operation, the control unit receives a vehicle speed signal from a Distance Measurement Instrument (DMI). The control unit generates a camera line signal, which triggers the camera to capture a full profile on a 1-inch interval setting. The transverse profile consists of a set of depth data for elevation change and a line of laser line intensity data for the reflectivity or brightness of the pavement surface. Multiple profiles are accumulated along the travel direction inside the camera to form an image frame. The control unit adjusts the camera exposure time to control the amount of time the camera sensor is exposed to the laser beam for each frame-capturing moment. The control unit also adjusts the laser output power to obtain the best image quality regardless of pavement surface types.

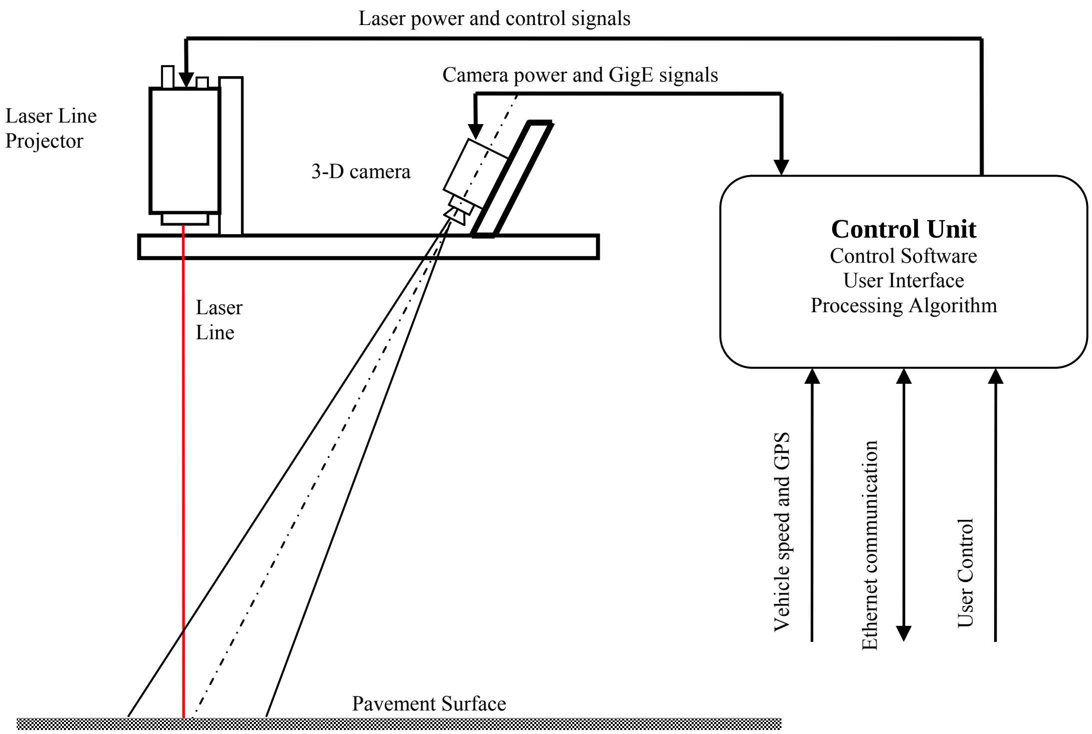


Figure 5. VRUT System Hardware Diagram.

VRUT has two operation modes. One mode is used for network level survey, and the other is used for project level data collection. In the network level survey mode, all image data is processed in real time while the vehicle travels on the roadway. The camera speed is adjusted to capture one profile per inch of travel. Twelve raw range profiles are averaged to provide a 1-foot average profile. This 1-foot average profile is then filtered to a smooth transverse profile for rut measurement. No raw image data will be saved while operating in this mode. If project level data collection mode is used to collect data, all raw image data can be saved to the hard disk and can be post processed after the runs are completed. Users can increase the speed of the profile sampling to equal 1/4 inch per sample; however, if the sampling speed is set at a higher rate, the maximum allowable vehicle speed will be reduced. When collecting data at the default setting of 1 inch per profile, a 1-mile raw data sample will require approximately 250 MB of hard disk space.

VRUT currently supports the TxDOT PMIS data format and is fully compliant with the TxDOT VAMOS Ethernet communication protocol [6]. VRUT includes a number of data types as defined by the TxDOT pf99 data format. The data types include the rut statistic summary, detailed rut depth and volume information for every foot of survey distance, and additional information, such as lane width, image quality, and pavement edge condition. VRUT reports this data in the predetermined summary interval of 1/10 mile, as defined in TxDOT PMIS data collection protocol.

2. Laser Safety

VRUT uses a seven watt infrared laser line projector, which is a regulated class IV diode laser in the state of Texas, for the laser triangulation measurement. When the raw laser goes through the line generator lens, it is converted into a 90 degree fan angle continuous line beam, which is then rated as a class IIIB laser on the pavement surface. Laser hazard analysis conducted by Laser Professionals Inc. [5] concluded that vision damage by reflective laser light can occur only if the beam reflects from a 100% return mirror, and a person is within 1 foot of the mirror surface. Additionally, the person must look into the reflected laser beam on the ground at exactly the same angle for more than 10 seconds with a fully dilated pupil. This is very unlikely to occur during data collection, since the laser source is moving above 10 mph before being activated; however, intra beam vision damage can occur within a 10-foot distance from the laser source if the beam enters a fully dilated eye at the same angle for 10 seconds. This situation is very rare but possible for operators who conduct system calibrations while the laser is on and the vehicle is parked. TxDOT has developed a laser safety program for using its regulated laser on its data collection equipment. A set of safety measures are implemented, with safety devices on equipment and personal protection, for operators to minimize this hazard.

VRUT laser safety controls are designed for protecting the traveling public and operators in the following situations: system calibrations and routine checks while the vehicle is not moving and the laser has to be active; when the vehicle stops in traffic; and in the event the vehicle becomes involved in an accident. There are a number of system design rules that have been established for all these safety concerns.

- In normal VRUT operational mode, the laser switches off automatically if the vehicle speed falls below 10 mph. Because the laser beam is moving at this speed on a non-mirrored pavement surface, no beam will focus on exactly the same point into an eye pupil for more than 10 seconds.

- In calibration mode, only trained operators with a valid software access password can enable the laser without vehicle DMI input. Protective eyewear must also be used by every operator in this mode.
- Perimeter detection sensors are installed near the laser beam to detect objects within a 3-foot proximity to the laser beam and turn off the laser if activated.
- A crash sensor is installed on the housing vehicle. In the event that an impact is detected, this sensor removes power from the laser. The power will not be reactivated after the crash.
- The user must intentionally start the laser every time the equipment is started. The laser does not activate by default, even if the laser key is left in the ON position after shutdown.

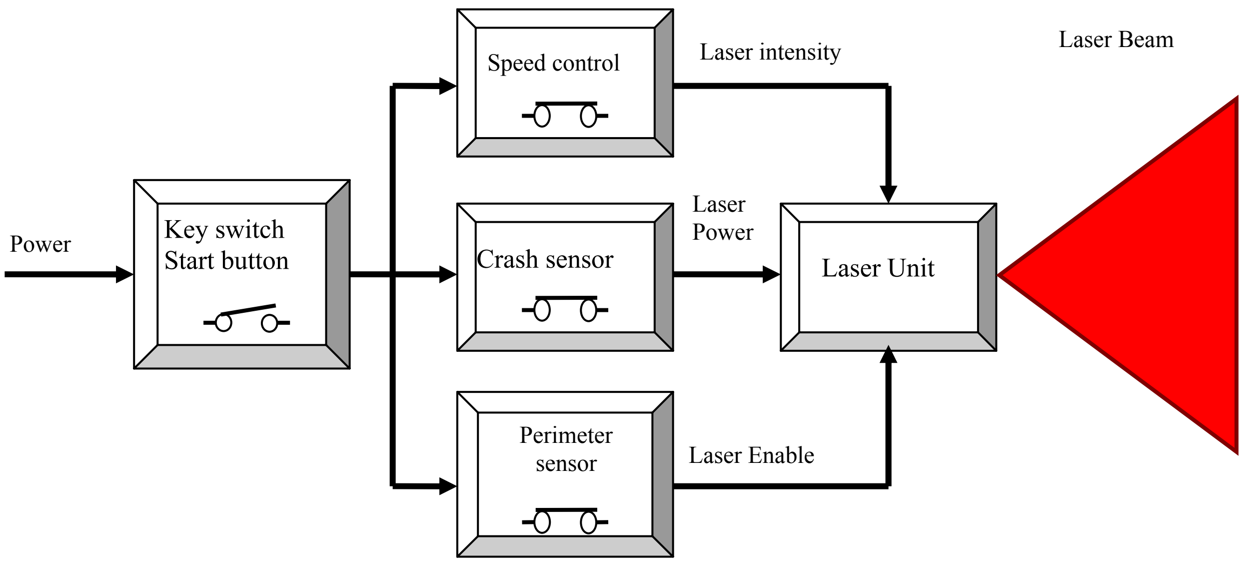


Figure 6. Laser Safety Implementation.

Figure 6 shows the VRUT laser safety implementation block diagram. When both the Emergency Off button (EMO) and the user activated key switch are turned on, the power to the laser unit is enabled. The laser enable and laser intensity signals then control the laser beam. When the perimeter detection sensor is inactive or no object is detected near the laser path, the laser unit will activate. Initially, the laser light is emitted at a low power level. VRUT controls laser intensity or laser power level through a speed control device. Laser intensity can be set from zero output to maximum output. If the vehicle speed is below 10 mph, VRUT will set the laser output to zero, and no laser radiates onto the pavement surface. At any speed above 10 mph, the laser will operate at maximum output. Only authorized operators can override this speed protection by entering a unique software password, which allows the laser to operate in calibration mode and during system troubleshooting.

3. System Software

The TxDOT team developed its own custom software package for this project. The package includes an operation control and user interface module, which controls the camera and laser and the other sensors and devices. The data acquisition module transfers 3-D range and intensity data from the camera to the system memory. The intensity image-processing module checks image quality and controls the camera exposure time. The range image detects the lane stripe for determining the rut boundary and checks for sealed cracks. The range image-processing module detects the pavement edge, edge drop-off, roadside vegetation, and curbs on both sides of the image. The purpose of these detection processes is to eliminate non-rut objects in the transverse profile and to limit the rut processing area to the correct lane width. The rut measurement module checks wheel path locations and then positions a virtual 6-foot straightedge bar on top of the profile for each wheel path. Rut depths are measured based on the maximum deviation from the virtual straightedge bars to the profile lines on the wheel path. The area between the straightedge bar and profile line is reported as rut volume information. Ethernet data and the command communication module are used to control VRUT from the VAMOS computer and to receive commands from VAMOS for operation and survey parameters. All commands and data types are defined in TxDOT's pf99 communication protocol. Figure 7 graphically depicts the exchange of data between the different parts of the system.

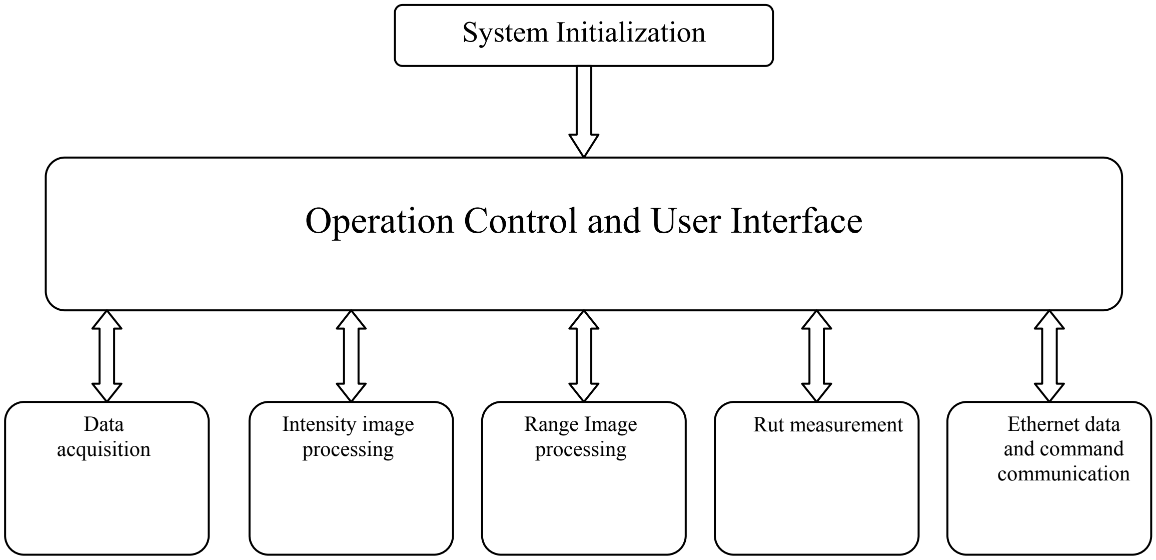
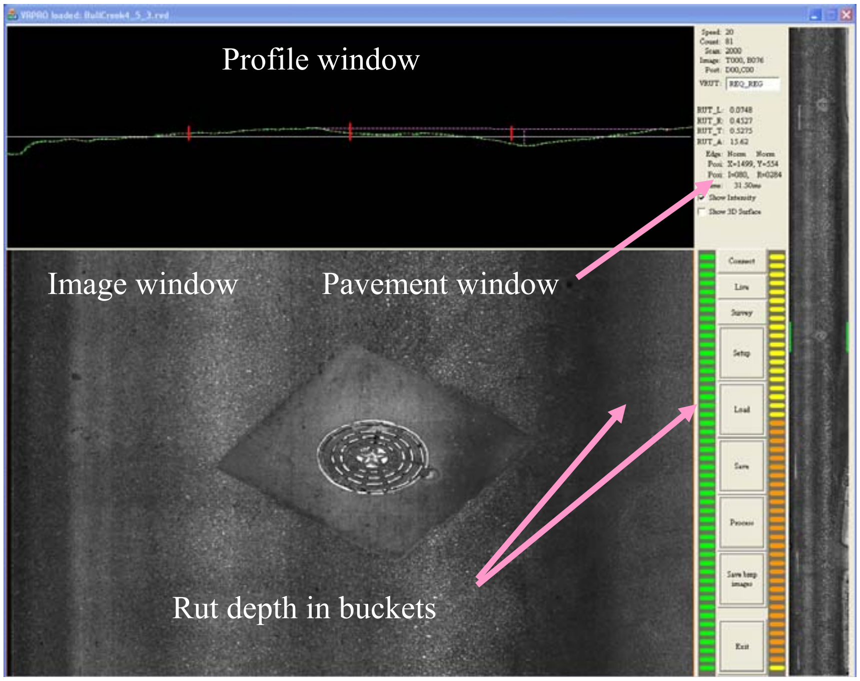
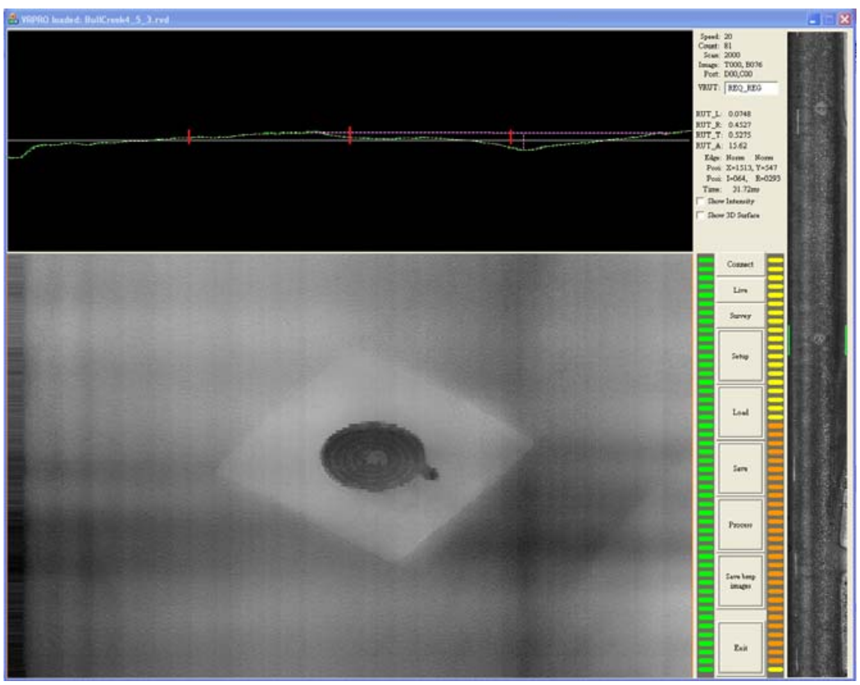


Figure 7. VRUT Software Modules.

Figure 8 shows screen captures of the VRUT user interface. The interface consists of a profile window, an image window, a pavement window, rut bucket bar, parameter displays, and user controls. The image window displays the intensity image with lane stripe mark locations and other detected features. The user may also choose to display a range image or a 3-D pavement image in this window. The profile window displays an average profile for the entire image frame, which covers a 48-foot long pavement section. The user can choose a 1-foot long average profile or a single scan profile by clicking the mouse in the image window at a desired location. The pavement window displays a 200-foot long compressed pavement image and provides the user a broad view of the surveyed roadway. Users can scroll this window along 1 mile of saved data, either from live camera view or reloaded from a saved raw data file on disk. TxDOT's pf99 protocol divides the rut data into buckets, which are defined as: no rut for rut depth from zero to 1/4 inch; shallow rut for rut depth from 1/4 inch to 1/2 inch; deep rut for rut depth from 1/2 inch to 1 inch; severe rut for rut depth from 1 inch to 2 inches; and failure rut for rut depth larger than 2 inches. The rut bucket display bar on the right side shows the left and right rut depths using an easy-to-interpret color coding system.



a) intensity image display



b) Range image display

Figure 8. VRUT User Interface.

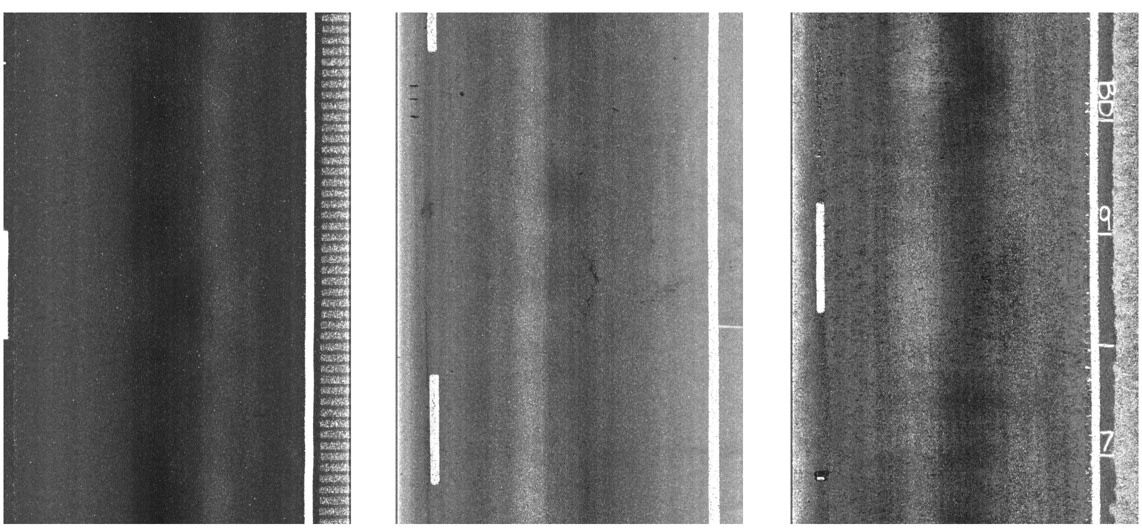
The user controls allow the user to save a single frame data file or create a video stream file of raw image data captured during data collection. Both files are in a specially defined format with all image and range data included. Only the VRUT software can recognize these files and reload them for offline processing at a later date. The parameter display area shows survey information, network connectivity, and measured rut data. Users can move the mouse inside the image window to get readings of depth and image brightness for any location within the image window.

System Capabilities

1. Pavement Surface Image

The 3-D camera used in the VRUT project is a multifunctional camera capable of measuring range data and linescan style brightness (intensity) data concurrently. In the VRUT rut measurement system, each individual measurement or scanned profile includes a full 1536-point depth profile ranging ±8 inches with a depth resolution of 0.0295 inches and a full intensity profile of surface brightness ranging from 0 to 255 pixel grayscale values. Scans are temporarily stored in the camera's internal memory and accumulated one after another. When the 48-foot travel interval is complete, the camera sends 576 scans as a range image frame and an intensity image frame. The intensity image is useful for surface feature detection because it presents the same information as the visual appearance of pavement surface. Since the scope of the VRUT project is concentrated on rut measurement, the intensity image is currently only processed for lane stripe and sealed crack detection. Other detection capability features may be possible in the future.

Figure 9 shows examples of intensity images from the VRUT system. Since the intensity image presents a downward visual view of the pavement surface, it mainly provides information on surface characteristics such as lane stripes, surface paints, and sealed cracks.



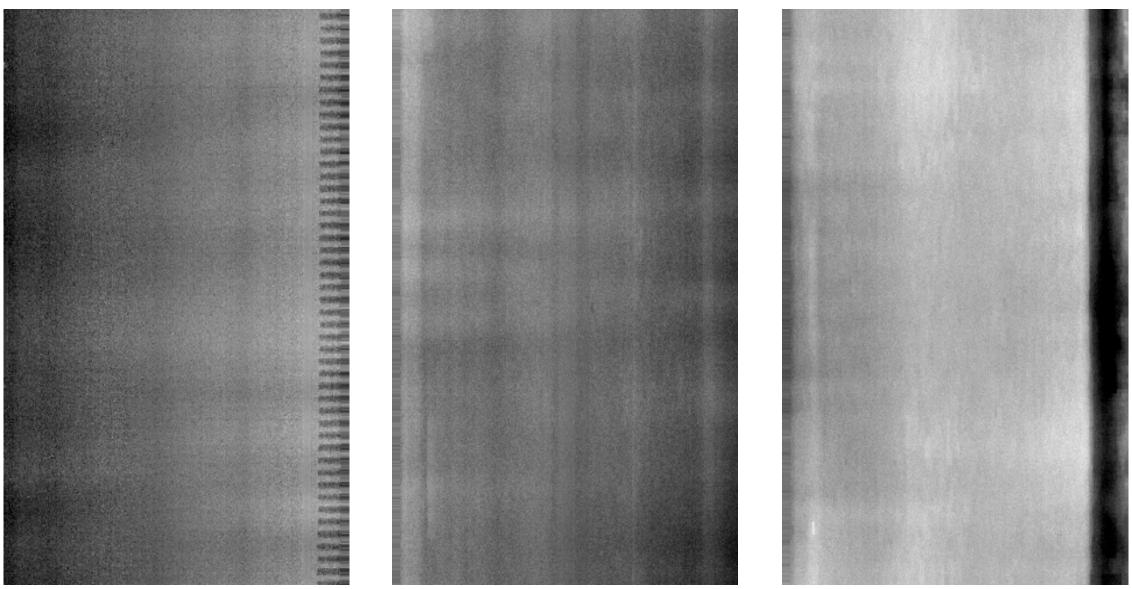
a) Rumble Strip b) Normal Traffic Lane c) Edge and Grass

Figure 9. Sample 48 Foot by 14 Foot Intensity Images for Lane Stripe Detection.

2. Range Image

The range image (depth image) represents the elevation changes on the pavement surface and contains the most important information used for rut measurements. The range image is also used to detect the pavement edge, roadside vegetation, curbs, and other lane width limitation information. The detection of these features plus the lane stripe detection from intensity images can help to determine the available lane width and increase the reliability of the rut measurement.

Figure 10 shows some examples of the range image. The dark area indicates a surface area with low elevation, and the bright area indicates surface areas with higher elevation. Range images provide clear information on depth related features such as edge drop-off and rumble strips.



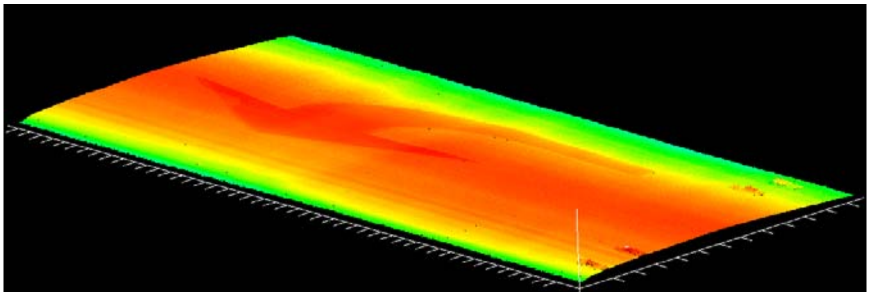
a) Rumble strip b) Normal traffic lane c) Edge and grass

Figure 10. Sample 48 Foot by 14 Foot Range Images.

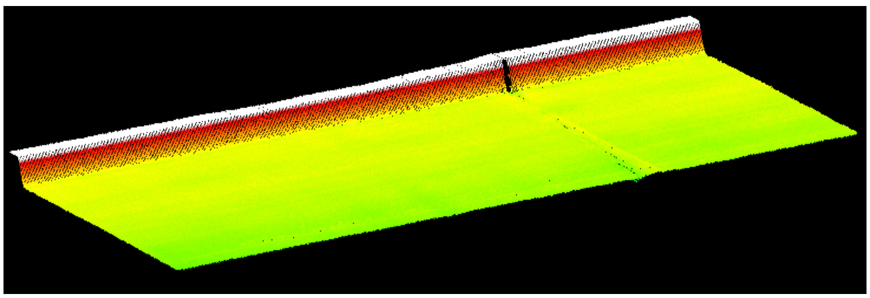
3. 3-D Pavement Display

VRUT is also capable of 3-D data presentation. It provides a rainbow color display on a 3-D pavement surface. The rainbow color display uses color difference to display the depth change of each image pixel in a 3-D image map. Figure 11 shows some examples of 3-D surface views. The resolution of the

VRUT depth measurement is high enough that pavement marking, road reflectors, pavement joints, and curbs can all be differentiated in the range images.



a) Rainbow Color Display of Left Turn Pavement Marking

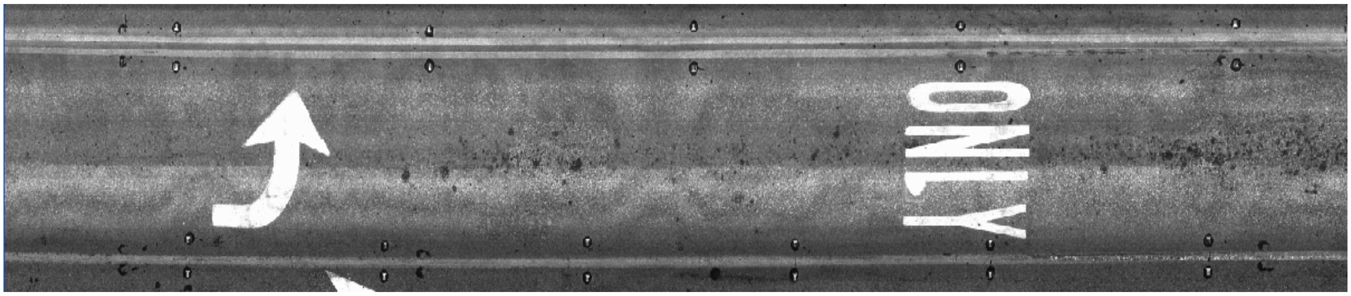


b) Rainbow Color Display of Bridge Joint and Left Side Curb

Figure 11. 3-D View of Pavement Surface.

4. Pavement View

The pavement view display provides a broad view of the pavement surface in 200-foot long increments, as shown in Figure 12. VRUT can store a 1-mile long raw data file captured either directly from the 3-D camera or reloaded from a saved video stream file in its memory. This allows users to view the pavement condition in 200-foot long increments through a compressed low-resolution image. When users scroll the pavement view window over the 1-mile long pavement data, all other display windows are synchronized to update respectively. The profile and image windows show the high-resolution profile and image of a 48-foot section in the center of the pavement view display.



a) Intensity Image View

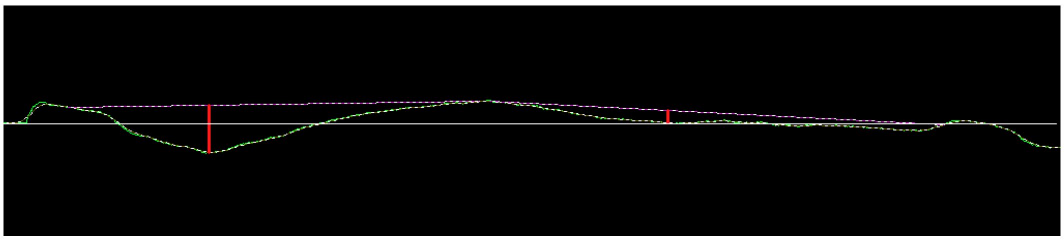

b) Range Image View

Figure 12. Pavement View over 200-Foot Long Road.

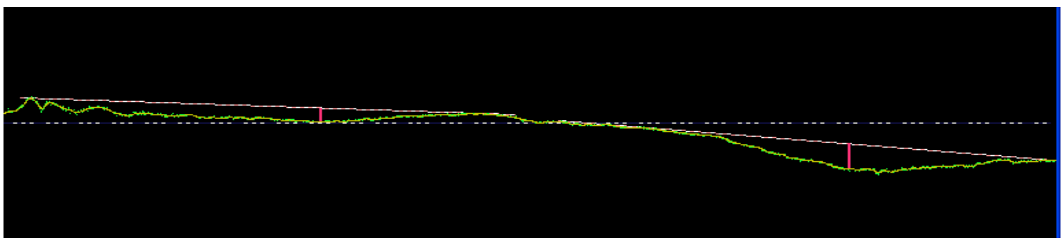
5. Rut Measurement and Display

Producing accurate and reliable rut measurement is the main goal for this project. VRUT uses a separate window to display graphics of the transverse profile and rut measurement for both wheel paths. Rut depth and volume are displayed numerically in the parameter display area. Rut locations and two virtual straightedge bars are drawn on the profile window. Figure 13 shows examples of rut measurements on a wide highway and a narrow farm to market road. Some of these are from smooth asphalt concrete pavement (ACP) while others are from a seal coat surface consisting of different sizes of aggregate. Due to the filtering effect of averaging twelve sample profiles representing a 1-foot long pavement section for rut measurement, aggregate size does not affect the accuracy of the VRUT system. In most cases, aggregate noise is a significant source of inaccuracy for point sensor-based measurement systems and single transverse profile based rut devices. Because aggregate size on coarse surfaces is comparable or larger than shallow rut depth thresholds, defined as 1/4 inch, a single data reading from a point sensor or a single profile may experience a severe noise issue. Road test results show that VRUT consistently provides accurate rut measurement on different pavement surfaces, including coarse aggregate surfaces such as a Grade 3 seal coat.

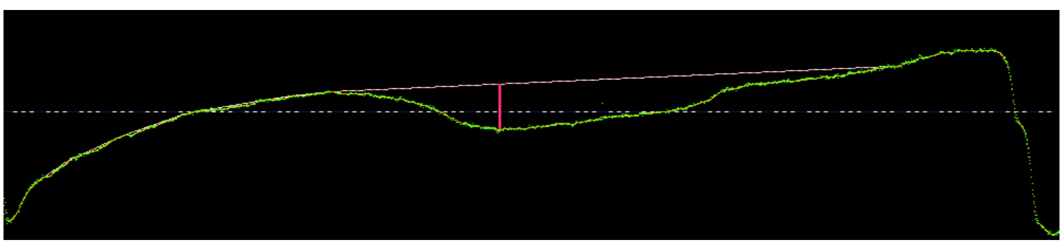
Figure 13 shows that, in reality, transverse profiles do not always exist in the regular shape required by a point sensor-based rut measurement method. For practical reasons, a rut measurement system must be able to adapt to various road profiles and must be flexible enough to eliminate any non-rut related road structures or objects. The lane detection and rut search algorithm implemented in VRUT can allocate rut depth in the correct place and measure the rut depth appropriately.



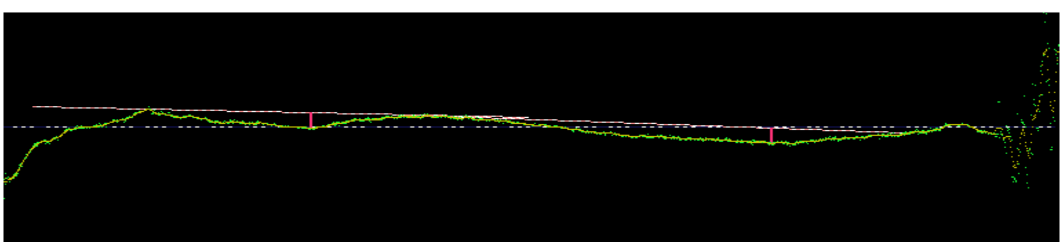
a) Severe Rut on ACP Smooth Texture Surface



b) Deep Rut on Grade 3 Seal Coat Rough Texture Surface



c) Severe Rut on a Narrow County Road with Edge Drop-Off



d) Shallow Rut on a Narrow County Road with Tall Roadside Grass

Figure 13. Rut Measurement from Transverse Profile on Different Roads.

The rut window displays only one sample profile at a time, so the user can not obtain a broad view of the rut depth distribution along the 48-foot pavement section in this single image frame. In order to allow for a broad view of the rutting encountered in a section, a color coded rut bucket bar, as shown in Figure 8, is designed to display rut measurements for each longitudinal foot, with a different color representing the different rut bucket categories of no rut, shallow rut, deep rut, severe rut, and failure rut, respectively. This display is available in both real-time operation and offline processing mode. The user can click the mouse in the image window near the rut bucket bar to change the profile window display and read the rut values.

System Calibration

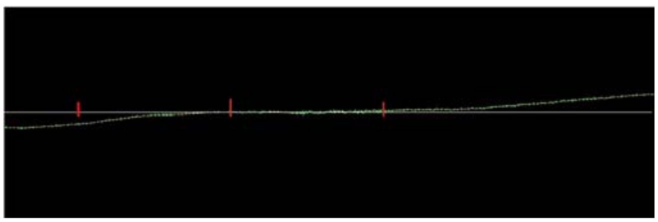
VRUT is an optical image-based measurement system. Its optical string consists of a laser line projector, a wide-angle lens, and a 3-D camera. Laser line straightness, lens distortion, and misalignment of the camera and the laser line may introduce errors into the profile data. To minimize these errors, the system must be calibrated after installation.

System calibration consists of two steps: a laser line calibration and a laser triangulation calibration. The laser line calibration is designed to minimize the lenses optical distortion, camera and laser misalignment, and hardware variation. The laser line calibration uses a 14-foot long reference bar, which is placed under the laser line projector path to provide a reference, as shown in Figure 14 a). The camera captures a raw profile measurement from the un-calibrated laser line with all distortions and errors appearing in the image, as shown in Figure 14 c). This raw laser line image represents the system's quality and is saved as a raw data correction reference. In the real data collection mode, the system uses the raw laser line data as a lookup table. Each element in the table will be subtracted from the corresponding real-time measurement to minimize the variation of system installation. An example of a corrected profile is shown in Figure 14 d).

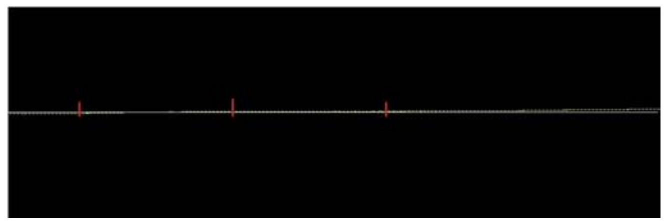
After the laser line calibration, each profile data point in pixel value will be converted to a depth measurement in inches or millimeters through a laser triangulation algorithm. The accuracy of this conversion depends on a number of factors such as camera magnification, the angle between the camera optical plane and the laser line plane, and the angle of the laser and the camera to the pavement surface. Some of these factors may induce errors to the originally specified system design and triangulation formula. These errors must be corrected or minimized with a procedure of laser triangulation calibration. The laser triangulation calibration is conducted with a designed calibration object, as shown in Figure 14 b). The object is a four-step symmetric block, with steps 2 inches high and all of equal width. The system will compare measured data to the actual dimensions of this block and create a correction table to the laser triangulation formula. After this two-step calibration, the system will load two lookup tables at start up each time and apply them to the raw measured data of each transverse profile. Test results from artificial objects with known dimensions show that the calibration eliminates most system errors from an installed unit.

a) Laser Line Calibration

b) Laser triangulation calibration



c) Original Laser Line Image



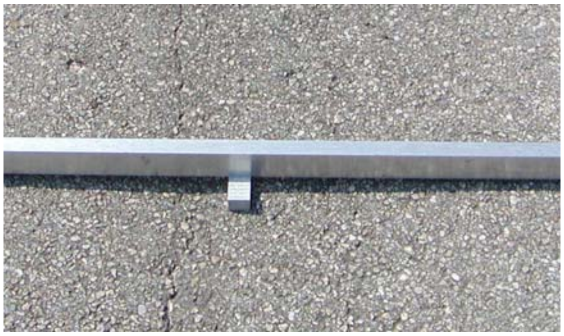
d) Calibrated Laser Line Image

Figure 14. System Calibration.

Field Tests and Verification

As defined in ASTM E1703, manual straightedge rut measurement is a widely accepted standard rut measurement method. Data from manual rut measurement could therefore be used as a reference to the ground truth for any automated instrument evaluation [8]. After laboratory testing and calibration, the VRUT data must be compared to manual rut measurement for accuracy. To evaluate the VRUT system in its normal data collection condition, the system should run at its normal operational speed to collect comparison data.

a) Rut Block with 1/16 Inch Steps



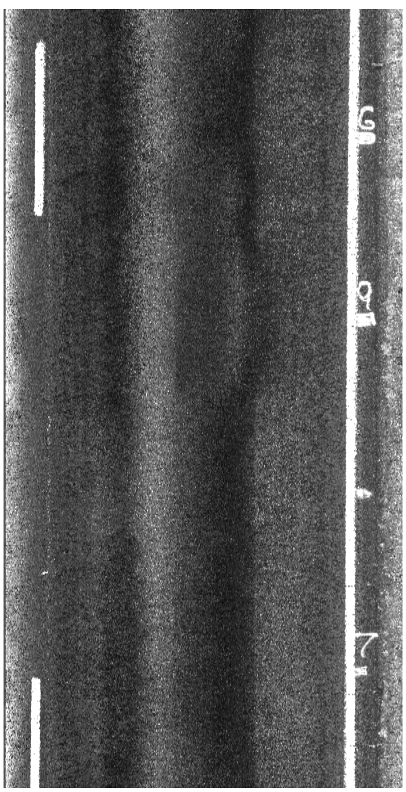
b) Rut Depth Reading with Straightedge

c) Manual Reading and Position Mark

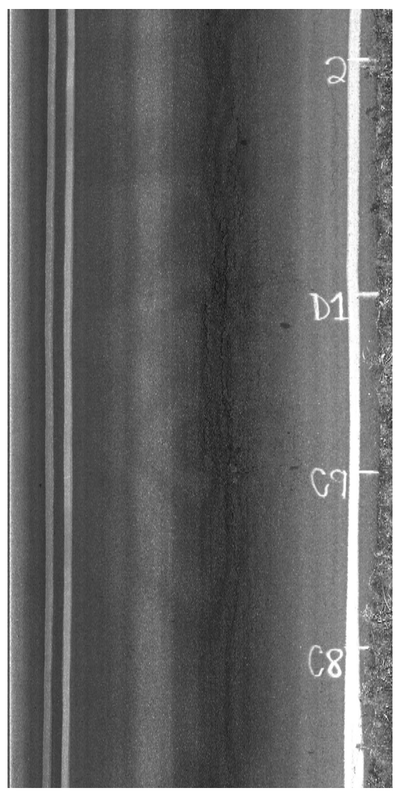
Figure 15. Manual Rut Measurement.

After pavement test sections are selected, manual straightedge rut data is collected on both wheel paths. Figure 15 a) shows a rut measurement block used for large-scale manual data collection. The block has sixteen steps at 1/16 inch increments. As shown in Figure 15 b), the data collector inserts the block under the straightedge bar at the maximum rut location and reads the smallest mark on top of the block. The mark reading provides a rut depth measurement at 1/16 inch. Compared to a traditional ruler rut measurement, this block provides a much quicker and more repeatable result. After each manual measurement, the location of the straightedge is marked with a paint line and a unique reference number, as shown in Figure 15 c). When the manual survey of a test section is complete, the VRUT system scans the section at the posted speed limit and saves all raw image data to a stream file. Some sections were scanned three times for repeatability analysis. Repeatability data is presented and analyzed later in this report. Later, the image data sets are loaded into the VRUT program for offline processing using the same processing algorithm as the real time operation.

Figure 16 shows an example of a reloaded 48-foot long pavement image. The operator can move the mouse to a marked rut location and double click the left mouse button to get left and right rut measurements in inches. Each VRUT stream data file contains 1 mile of raw image data. After all information in the frame is processed, the user can proceed to next frame.



a) Coarse Seal Coat Pavement



b) Smooth ACP

Figure 16. Marked Manual Rut Measurement Section.

Data Analysis

The TxDOT team has collected over six thousand manual rut data measurement points from different pavement test sections. These sections include four county roads and two major highways, smooth ACP and coarse seal coat surfaces, and road widths ranging from 8 to 12 feet wide. Table 1 shows a partial data result from ACP and seal coat pavement sections. In the table, VRUT provides a continuous rut depth measurement and manual rut provides a discrete rut depth measurement at 1/16 inch steps. Since the rut block is pushed under the straightedge to accomplish the step reading, it tends to underestimate rut depth by a maximum error of 1/16 inch. In Table 1, if a measured rut depth is smaller than 1/16 inch, VRUT will set that reading to zero to avoid aggregate noise.

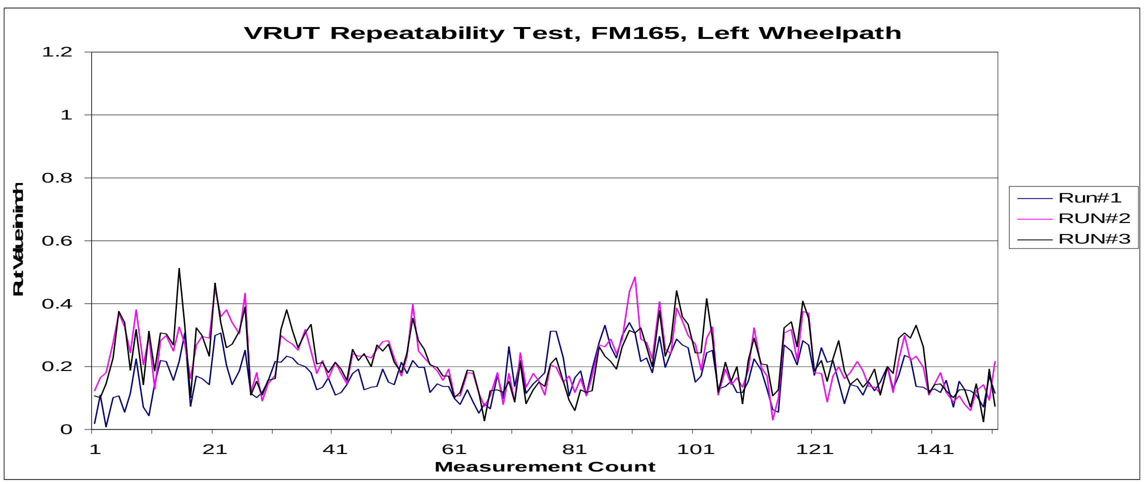
Table 1. Examples of Manual and VRUT Rut Comparison Data.

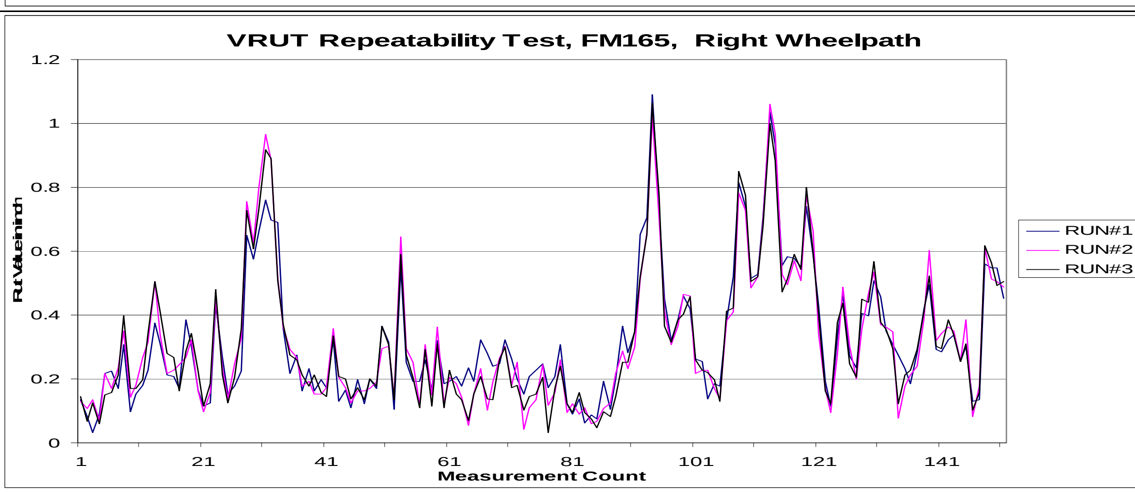
Manual and 3-D Rut Comparison 1/19/2009										
		Left		Right			Left		Right	
Index	Mark	Manual	3-D Rut	Manual	3-D Rut	Mark	Manual	3-D Rut	Manual	3-D Rut
1	A1	0	0	0.0625	0.126	P1	0.25	0.102	1.0625	0.724
2	A2	0	0	0.5625	0.5	P2	0.1875	0.343	0.4375	0.389
3	A3	0	0	0.4375	0.453	P3	0.25	0.24	0.375	0.37
4	A4	0	0	0.25	0.252	P4	0.3125	0.102	1.0625	0.866
5	A5	0	0	0.25	0.291	P5	0.25	0.161	0.375	0.331
6	A6	0	0.103	0.25	0.272	P6	0.25	0.201	0.375	0.228
7	A7	0.125	0	0.25	0.268	P7	0.625	0.567	0.75	0.59
8	A8	0	0	0.375	0.362	P8	0.5	0.448	0.375	0.187
9	A9	0	0	0.75	0.657	P9	0.3125	0.189	0.3125	0.264
10	B1	0	0	1.5625	1.38	Q1	0.25	0.149	0.375	
11	B2	0	0.083	1.5625	1.38	Q2	0.25	0.213	0.5	0.279
12	B3	0	0.083	0.3125	0.272	Q3	0.125	0	0.25	0.126
13	B4	0	0	0.125	0.055	Q4	0.25	0.142	0.25	0.122
14	B5	0	0.09	1.0625	1.024	Q5	0.1875	0.185	0.1875	0.118
15	B6	0.25	0.213	0.125	0.126	Q6		0.122	0.3125	0.197
16	B7	0.25	0.146	0	0	Q7	0.25	0.283	0.25	0.204
17	B8	0	0	0.375	0.24	Q8	0.3125	0.307	0.25	0.204
18	B9	0	0	1.0625	1.091	Q9	0.25	0.35	0.0625	0.165
19	C1	0	0	0.1875	0.177	R1	0.1875	0.181	0.1875	0.122

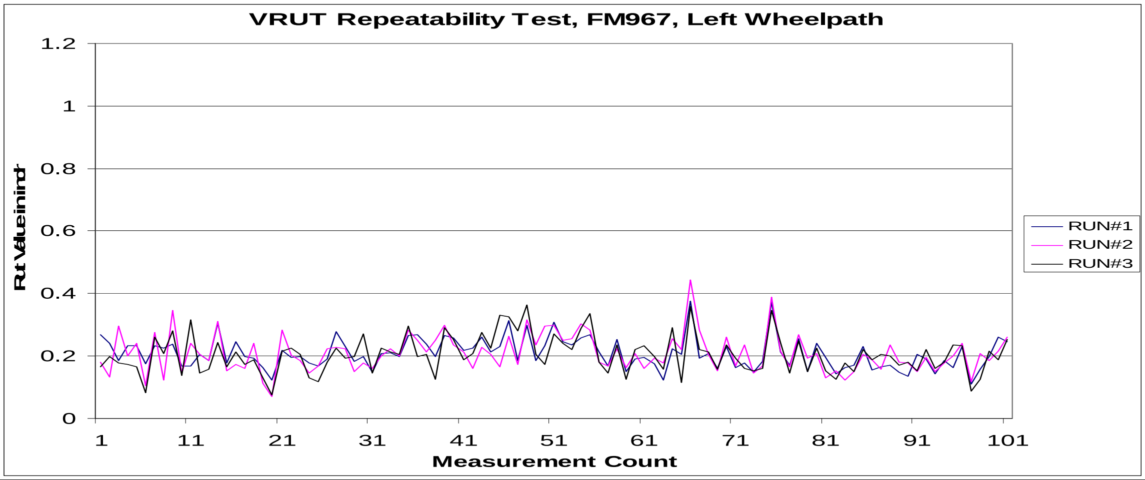
Manual and 3-D Rut Comparison 1/19/2009										
		Left		Right			Left		Right	
Index	Mark	Manual	3-D Rut	Manual	3-D Rut	Mark	Manual	3-D Rut	Manual	3-D Rut
20	C2	0	0	0.5625	0.353	R2	0.25	0.285	0.125	0.188
21	C3	0.125	0.161	0.3125	0.295	R3	0.125	0.484	0.3125	0.224
22	C4	0.625	0.579	0.375	0.217	R4	0.1875	0.122	0.125	0.287
23	C5	0.75	0.689	0.5	0.433	R5	0.1875	0.146	0.25	0.173
24	C6	0.1255	0.118	0.3125	0.24	R6	0.1875	0.146	0.25	0.173
25	C7	0	0	0.5	0.453	R7	0.1875	0.098	0.1875	0.169
26	C8	0	0	0.875	0.822	R8	0.125	0.087	0.25	0.146
27	C9	0	0.091	1.875	1.735	R9	0.125	0.122	0.3125	0.236
28	D1	0	0	1.875	1.716	S1	0.25	0.173	0.1872	0.24
29	D2	0	0	0.6875	0.677	S2	0.1875	0.212	0.0625	0.188
30	D3	0	0	0.625	0.567	S3	0.1875	0.259	0.125	0.295
31	D4	0	0	0.625	0.543	S4	0.1875		0.125	0.196
32	D5	0	0	0.375	0.354	S5	0.125	0.22	0.25	0.177
33	D6	0	0	0.125	0.118	S6	0.125	0.216	0.125	0.11
34	D7	0	0	0	0.173	S7	0.0625	0.196	0.1875	0.106
35	D8	0	0	0.1875	0.177	S8		0.106	0.125	0.118
36	D9	0.0625	0.078	0.125	0.149	S9	0.125	0.197	0.125	0.118
37	E1	0	0	0.375	0.37	T1	0.1875	0.248	0.0625	0.177
38	E2	0	0	0.0625	0.067	T2	0.125	0.133	0.25	0.248
39	E3	0	0	0.1875	0.161	T3	0.125	0.157	0.125	0.126
40	E4	0	0	0.25	0.213	T4	0.125	0.169	0.125	0.149
41	E6	0.125	0.275	0.125	0.271	T5	0.1875	0.165	0.125	0.102
42	E7	0.0625	0.102	0.0625	0.106	T6	0.125	0.201	0.1875	0.187
43	E8	0	0	0.1875	0.193	T7	0.1875	0.259	0.25	0.291
44	E9	0	0	0.125	0.126	T8	0.1875	0.173	0.1875	0.228
45	F1	0.0625	0.094	0.1875	0.275	T9	0.1875	0.169	0.25	0.134
46	F2	0	0.11	0.25	0.24	U1	0.1875	0.185	0.125	0.212
47	F3	0	0.146	0.25	0.193	U2	0.25	0.224	0.125	0.232
48	F4	0	0.114	0.1875	0.181	U3	0.0625	0.149	0.125	0.232
49	F5	0.0625	0.125	0.4375	0.445	U4	0.125	0.165	0.1875	0.283
50	F6	0	0.256	0.125	0.129	U5	0.125	0.149	0.4375	0.409

1. Repeatability Test

VRUT data were collected three times on some test sections. The data from these three runs were processed to evaluate VRUT repeatability. There are two factors that affect data correlation and stability during multiple runs. Vehicle wander while driving down the lane changes the course of actual data collection. As a result, the 3-D camera may pick up transverse profiles differently each time. Since the VRUT rut algorithm is designed to find the correct rut location over a 14-foot wide profile, it should be able to tolerate a certain degree of profile shift, but its real performance will be evaluated in this repeatability test. In addition, VRUT was manually started during the test, so each processed 1-foot profile may cover a slightly different longitudinal distance for each run; VRUT may not process exactly the same foot image for rut data. As a rut is a general longitudinal depression along the wheel path, this slight distance offset should not cause significant errors for a rut measurement system.







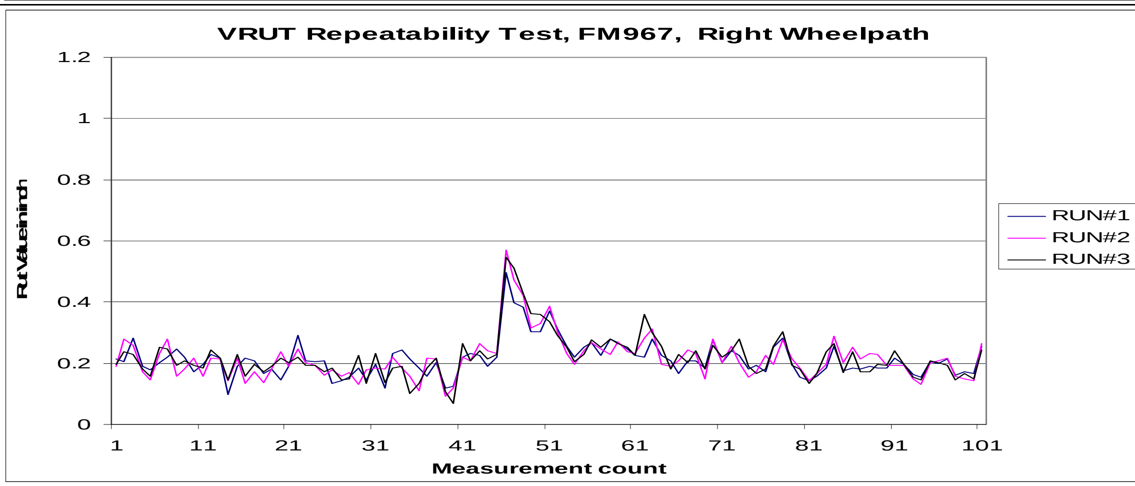


Figure 17. VRUT Repeatability Test.

Figure 17 shows some repeatability data from two test sections. Both of the sections are seal coat pavements, but the section of FM967 has a larger aggregate size. Table 2 gives the square value R^2 of correlation factors between each run for the two repeatability test sections. This R^2 value represents the fraction of the variation in one data series that may be explained by the other data series, or how close the two data series are from the same measurement. Its value varies from 0 to 1, from no relationship to perfect fit between two data series.

Where $R = \dfrac{\sum (x-\bar{x})(y-\bar{y})}{\sqrt{\sum (x-\bar{x})^2 \sum (y-\bar{y})^2}}$

x,y are the data arrays of two different test runs, and $\bar{x}, \bar{y}$ are the means of data x,y.

There are 1/2 to 1 inch ruts found on the right wheel path. VRUT shows a high repeatability and high data correlation for repeated runs on the right wheel path. Note that there is no major rut measured in the left wheel path. Most data from this area falls below 1/4 inch. These small depth changes do not necessarily represent the longitudinal depression of the pavement surface but could be some random surface changes attributed to the presence or absence of especially large seal coat aggregates. TxDOT PMIS protocol defines 1/4 inch as the threshold for minimum rut data. A depth measurement below 1/4 inch is not counted as a rut.

Table 2. Correlation Between Repeatability Tests.

VRUT Repeatability Test, R^2						
	Left Wheel Path					
	FM165			**FM967**		
	RUN #1	**RUN #2**	**RUN #3**	**RUN #1**	**RUN #2**	**RUN #2**
RUN #1		0.616	0.612		0.732	0.684
RUN #2			0.858			0.712
RUN #3						
	Right Wheel Path					
	FM165			**FM967**		
	RUN #1	**RUN #2**	**RUN #3**	**RUN #1**	**RUN #2**	**RUN #3**
RUN #1		0.953	0.984		0.856	0.910
RUN #2			0.957			0.867
RUN #3						

Test results show that VRUT can precisely repeat itself in real rut measurements. It gives consistent true rut measurements on repeated runs.

2. Manual and VRUT Comparison Test

Figure 18 shows manual and VRUT data comparison tests on smooth ACP. Manda Road is a 9-foot wide county road with edge drop-off and roadside vegetation. The VRUT lane width detection algorithm can detect the center lane stripe and the right side edge location and provides the correct rut measurement. Because there is less aggregate noise on a smooth ACP, VRUT rut results show very high correlation to manual rut data.

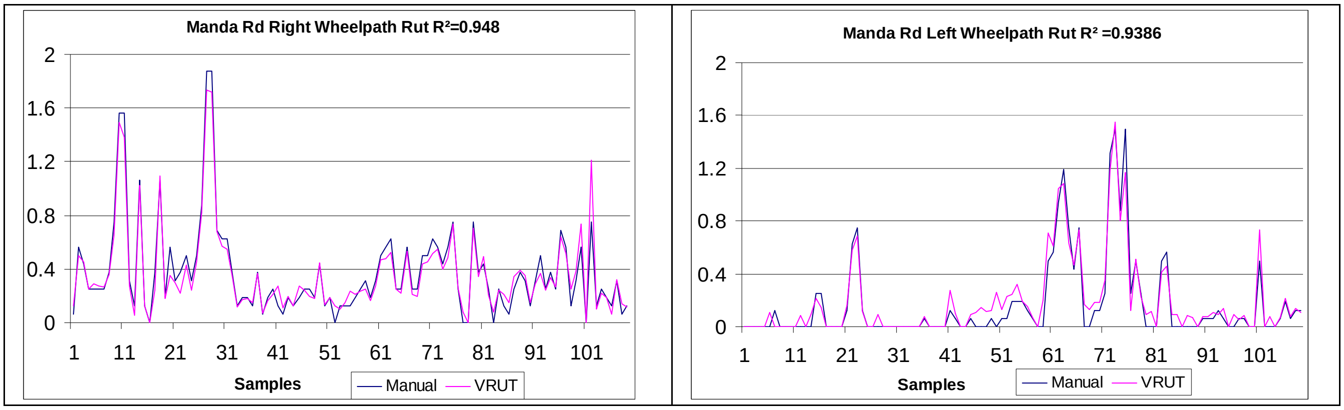


Figure 18. Manual and VRUT Comparison on ACP Smooth Pavement.

Figure 19 provides another example of manual and VRUT rut data comparison. This test was conducted on US183 and US290, both major highways. The test sections were 12 feet wide, with large aggregate surface types. A total of four thousands pairs of manual rut data were collected over 6 miles.

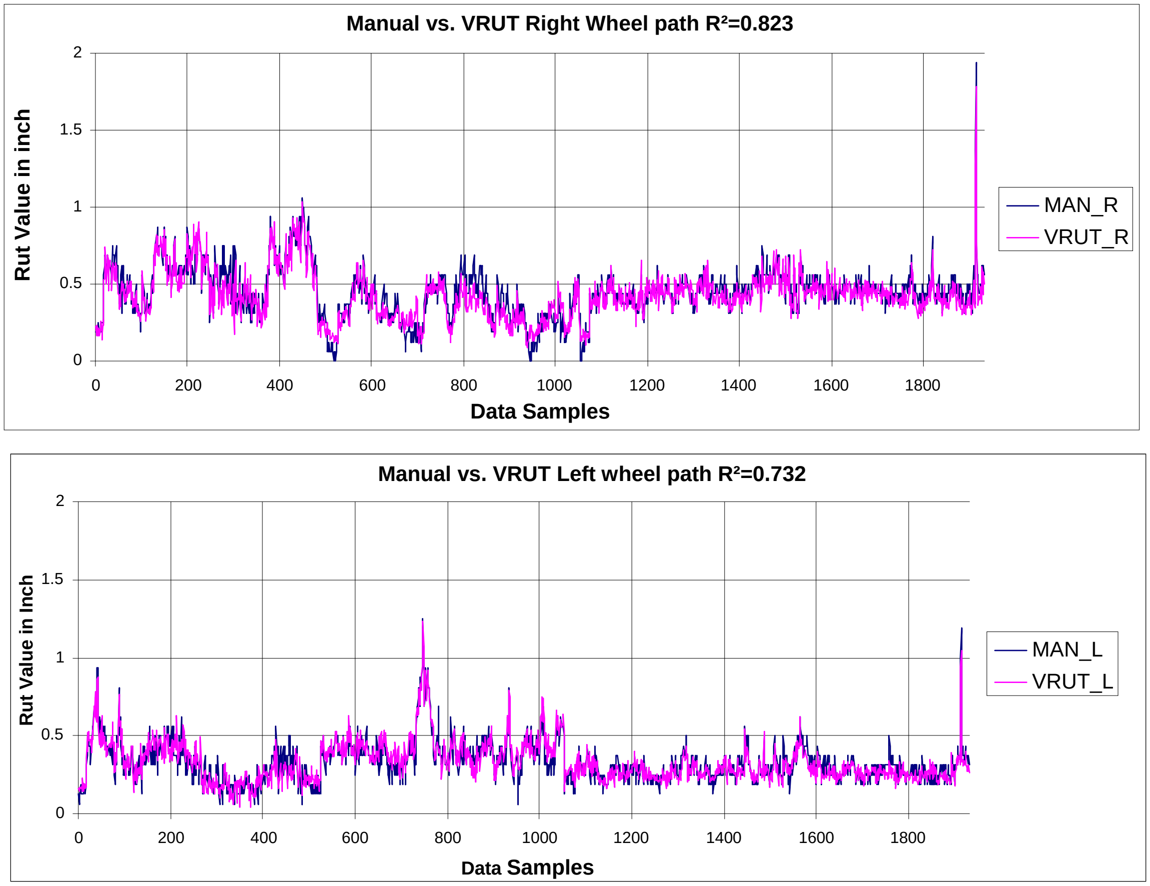
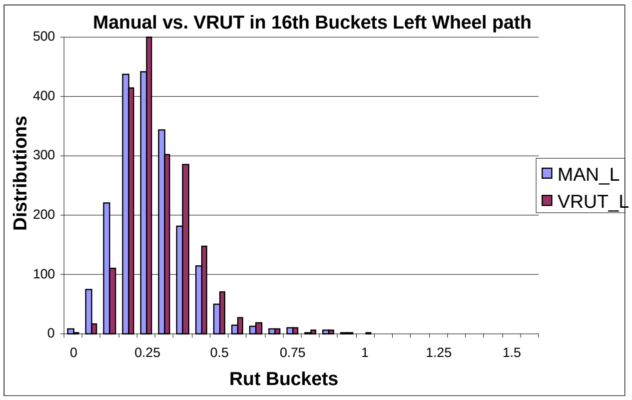


Figure 19. Manual and VRUT Rut Data Comparison.

To match with the 1/16 inch increment used by manual rut measurement, VRUT data is rounded to a 1/16 inch increment for direct comparison. Figure 20 shows the rut count number in each 1/16 inch bucket. These charts illustrate how closely the manual rut data and VRUT rut data correlate. Comparing the left wheel path bucket and right wheel path bucket, the more rutted right wheel path shows a higher correlation between manual rut data and VRUT rut data.



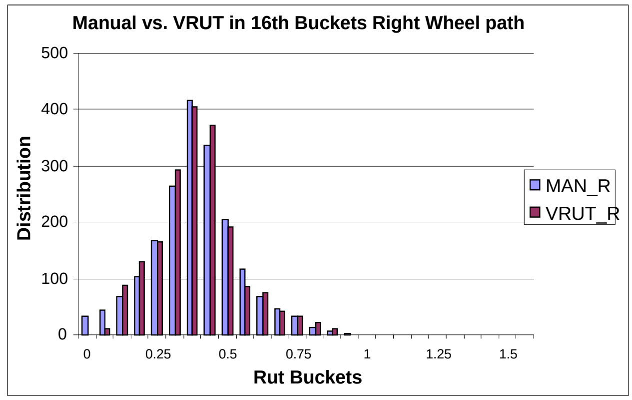


Figure 20. Manual and VRUT Rut Data Comparison in Sixteenth Bucket.

A t-test is used on manual and VRUT rut data in Figure 19 to analyze their agreement. In the Microsoft Excel Analysis ToolPak, the Two-Sample T-Test analysis tool tests for equality of the population means underlying each sample. Using this tool, we can compare analytical results obtained with two different methods of rut measurement in order to confirm whether the methods provide similar analytical results or not.

Table 3. Statistical Test on Manual and VRUT Data.

Two Sample T-Test Alpha=0.01				
	Left Wheel Path Rut		**Right Wheel Path Rut**	
	Manual	**VRUT**	**Manual**	**VRUT**
Mean	0.3610	0.3404	0.4380	0.3816
Variance	0.0226	0.0222	0.0398	0.0347

Two Sample T-Test Alpha=0.01				
	Left Wheel Path Rut		Right Wheel Path Rut	
	Manual	VRUT	Manual	VRUT
Observations	1074	1074	1074	1074
Pooled Variance	0.0224		0.0372	
Hypothesized Mean Difference	0.0250		0.0560	
Degree of Freedom	2146		2146	
T-Stat	-0.6817		0.4398	
P(T<=t) two-tail	0.4955		0.9683	
T-Critical two-tail	2.8099		2.5781	

Table 3 shows the t-test results from data in Figure 19. The test is conducted at a 99% confidence level (Alpha=0.01). On both wheel paths, since t-stat values are much smaller than t-critical two-tail values, there is no statistically significant difference between VRUT and the manual rut data.

Summary

A research team in TxDOT's Construction Division, Materials and Pavement Section has successfully developed a new rut measurement system based on 3-D surface inspection technology that can provide accurate rut measurement from continuous transverse profiles. When used on the TxDOT PMIS data collection system, it adds a new node called VRUT—a high-speed, multifunctional device capable of capturing high-resolution 14-foot wide range images and intensity images at speeds from 10 to 70 mph. VRUT can detect lane stripes, pavement edges, curbs, and roadside vegetation and can identify the actual wheel paths for correct rut measurement. It provides not only accurate rut depths for the left and right wheel paths, but also volume information for the rutted area.

VRUT produces consistent rut measurement during multiple runs on the same pavement test section. It also provides stable depth values on different types of pavement, ranging from smooth ACP surfaces to coarse Grade 3 seal coat surfaces, from 8-foot wide narrow roads to 12-foot wide major highways. A comparison study of VRUT rut data to manual straightedge rut data from a number of massive data collection experiments shows that VRUT results are highly correlated to the manual rut measurements. As the manual straightedge rut measurement is a widely trusted, standard true rut measurement method, the study shows that VRUT as a fully automated rut system can produce close results to the ground truth in various pavement conditions.

The goal of this project has been focused on rut measurement. Considering the capability of the 3-D camera system, a comprehensive system can be expected in the near future that will be capable of identifying multiple distresses.

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