
Draft v1

It must be emphasized that this is a draft report that is largely still in outline form, however the Preface, Introduction, Chapters 3, 4, and 9 on Longitudinal Profile and Chapters 5 and 6 on Test Description are partially complete, to varying degrees. This draft is being published on the Web, in time for TRB 2001. There will be additional updates. If interested, be sure to email to request to be notified of additional updates as they are made.

DRAFT Date: January 5, 2001
Prepared By: Phoenix Scientific, Inc.
1790-104 La Costa Meadows
San Marcos, CA 92069
760.471.5396 – Fax: 760.471.5397
email: wherr@phnx-sci.com
Preface

This effort has been driven to a considerable degree by the interest and conviction of Ray Mandli of Mandli Communications. Mandli specializes in Photologging in an integrated GIS environment with GPS referencing. They have had a standing interest in expanding into pavement measurements and have monitored PSI’s progress since our inception in 1992. When in 1999 it was clear that the PPS-2000 had the performance required for a new generation pavement profiling technology, Mandli proposed to Iowa DOT that a PPS-2000 integrated with the Mandli Digilog, such as operated by Iowa DOT, would provide improved operational efficiency and quality of data. Three elements were required to prove out this assertion:

- Application Specific Software for Rut and Ride
- Interface between the PPS-2000 data and the integrated data environment used by the DOT
- Test Results

John Whited of Iowa DOT provided invaluable support, interest and feedback that got the ball rolling on this project which has spanned 2 years.

We are grateful to Don Alexander and Al Bush of the US Army Engineers Waterways Experiment Station. The original two PPS-2000 units were developed under an SBIR contract from WES, and are owned by WES. We have been able to evolve the performance of the hardware and software, continually upgrading both units for WES, because they have made the hardware available to us for this and similar efforts, as permitted by their own inhouse testing schedule.

Mandli has supported the field tests at RPUG 2000 and in Iowa with a Digilog van and personnel and is developing the software for integration of the PPS-2000 data. Tim Caya is the Project Engineer for the PPS-2000 project and Paul Oldenburg is the Software and Civil Engineer who has been instrumental in the data integration.

We are also grateful to the following people and programs for their efforts to supply us with reference data and/or insights into data processing:

- LTPP Program: Monte Symons, Larry Wiser and Jean Sexton
- Fugro BRE: Amy Simpson
- Stantech: Brett Henderson
- Nichols Consulting: Sirous Alavi and others
- CGH Engineers: Gaylord Cumberledge and John Hunt
- Transology: John Darlington
- Piarc: Jim Wambold
- IOWA DOT: Jason Hatfield and Alice Welch

In part because so much support has made this effort possible and also because of our conviction that open disclosure of algorithms is essential for results that can be independently verified and institutionalized by standards such as those created by ASTM, it is the goal of this report, to fully document the algorithms developed and used in this effort.
1 Introduction

1.1 Background

The PPS-2000 Pavement Profile Scanner was originally developed for Rolling Wheel Deflection Measurement. The demanding performance required of the RWD lead to the creation of a sensor which has unparalleled performance with potential for many other applications. We began an effort in 1999 focused on performing tests and developing software to demonstrate the potential of the PPS-2000 to be the basis of the next generation of pavement rut and ride measurement system that would provide improved data at competitive costs with operational improvements:

- High resolution, essentially continuous, transverse profile
- Shoulder condition
- Simultaneous multiple longitudinal profiles from same sensor
- Automatic correction for driver wander
- No hardware outside vehicle envelope
- Hardware mounted high, not impacted by fender bender accidents

1.2 PPS-2000 Description

The core of PSI’s innovative measurement technology is phase-measurement Laser Radar (Ladar) developed with an unprecedented combination of precision, range, and sample rate to meet the demanding requirements of pavement testing from a test vehicle traveling at highway speeds. The static ranging precision is 20 microns (<0.001 inches) rms at a range of 2.1 meters (7 feet) and a sample rate of 1.25 MSPS.
A polygon scanner with 6 sides is used to point the Ladar measurement system at points along a straight line on the pavement, thereby scanning a line and generating the profile along the line 6 times per revolution of the polygon. At 10,000 RPM the system can generate up to 1,000 scans per second. With the scanner mounted 7 feet above the pavement, the ±45° field of view produces a profile 14 feet long.

The orientation of the polygon’s rotational axis determines how the scan lines are positioned on the pavement. The two standard installations are where the rotational axis is orthogonal to the direction of travel. This produces transverse and longitudinal scans as the pavement testing vehicle is driven along in-service roads. Full lane and shoulder coverage is accomplished with no hardware extending beyond the vehicle.

1.3 Project Approach

PSI has developed software to calculate rut indices, longitudinal profile, and IRI from the PPS-2000 scanner data based on industry standard algorithms to the extent possible.

To test this software in a cost effective manner and with independent to compare with, the PPS-2000 was operated on pavements where independent reference data was available. Two separate experimental periods are included.

In 1999 in conjunction with RPUG 1999 in Scotsdale Arizona, testing was performed on in-service LTPP sections on I-10 southwest of Phoenix. In 2000, testing was performed at the NCAT test track in Opelika in conjunction with RPUG 2000 in Auburn Alabama and in Ames Iowa on in-service test sections established by Iowa DOT.
2 Rut Indices – Software Development and Checkout

2.1 Overview

All the rut indices considered by LTPP have been implemented. The implementation was tested by processing over 600 LTPP profiles and comparing the results with that published by LTPP.

2.2 Guidelines

Reference BRE LTPP Report and communication with BRE
Reference Monte Symons interest in 3 and 5 point rut bar for historical correlation

2.3 Software Operation
Procedures

2.4 Algorithm Reference

This section documents the details of the specific algorithms which have been implemented

2.4.1 Positive/Negative Fill Areas

2.4.2 Stringline (3.7m)

2.4.3 Straight Edge (1.8m)

2.4.4 3 and 5 Point

2.5 Export File Format

2.6 S/W Checkout with LTPP Data

Datapav97
3 Longitudinal Profile and IRI from Transverse Scans – Operational Concept

3.1 Current Technology

Longitudinal profile measurement is predominately measured by a technique know as inertial profiling. The techniques was first developed by General Motors and has been refined over the years. The principal is that the distance from a moving test vehicle to the pavement is recorded along with the vertical acceleration experienced by the vertical distance sensor, which is primarily caused when road roughness causes the test vehicle to bounce. The profile is calculated by first double integrating the vertical accelerometer to get the change in elevation of the sensor due to vehicle bounce. This movement is then subtracted from the measured elevation to produce the profile relative to a stable inertial reference, hence the term inertial profiling.

The result is that systems in use today require one non-contact ranging sensor for each longitudinal profile to be produced. Typically, there is just one per wheel path and one in the center as a reference for three point rut processing. This results in a limited statistical sample of the roughness characteristics of the road and makes the results highly dependent upon the path driven by the driver. For example, these systems cannot measure the difference in ride quality for profiles centered in the wheel path (center of the rut) and offset from center on the wall of a rut. Also they cannot measure profiles in multiple wheel paths which may be desirable where truck wheel spacing is wider that car wheel spacing.

Ref ASTM E 1926-98

3.2 Functional Objectives

Obtain required data from a dual purpose sensor which generates transverse profile concurrently.

Produce data with statistical significance by generating a user defined number of longitudinal profiles and associated IRI reading at multiple points across the lane, as defined by the user.
3.3 Operational Concept

Consider that a run with the PPS-2000 oriented transversely and scanning closely spaced transverse profiles provides the data sufficient to map the 3D shape of the pavement. If the points in each successive transverse scan which lie along a specified longitudinal profile are extracted, then they can be processed in the conventional manner, just as if they came from a traditional single point non-scanning laser distance sensor. This idea is illustrated in equation 3-1, where the advantage of the scanner is illustrated. In effect, the PPS-2000 produces the equivalent of 940 discreet sensors. In practical terms one can extract as few as one profile per wheel path or more if it is desired to study variability across the wheel path and thereby have a statistical evaluation of the uniformity if IRI.

3.4 Processing Steps

The following are the primary processing steps required:

- Specify number and transverse position of longitudinal profiles desired
- Generate longitudinal vectors of elevation data from transverse scans
- Double integrate and filter acceleration
- Compute and filter longitudinal profiles
- Compute IRI or other indices of ride
4 Longitudinal Profile and IRI from Transverse Scans – Software Development, Operation and Checkout

4.1 Overview
The software to calculate longitudinal profile and IRI form transverse PPS-2000 scans has been developed and tested

4.2 Background
ASTM specs
World bank report
Spangler patents

4.3 Run Requirements
Operation of the PPS-2000 for longitudinal profile when scanning transversely must consider the requirements presented in this section.

4.3.1 Leadin Data
The run must commence a distance before the desired profile start point equal to or greater than the long wave cutoff to be used in calculation of the longitudinal profile.

4.3.2 Scan spacing
The run should be executed so that scans are spaced between 1-4 inches apart. To potentially be classified as Class I as per ASTM E-950 they must be not more than 1 inch apart.

4.3.3 DMI/TC
There must be a valid DMI/TC signal. The scale factor should be smaller than 2 inches per count, however the software will try to work with lower resolution.
4.4 Run Processing

To compute longitudinal profile(s) from a completed run, follow this procedure.

4.4.1 Start Getdata

Start Getdata and load suitable preferences.

4.4.2 Run File Specification

Longitudinal Profile Calculation is initiated by the file conversion process. This is started by typing Ctrl + O, which displays the standard Getdata File Conversion window, as shown in Figure 4-1. Select all scans or select an inclusion list and specify a range of scans as shown, where the start scan would be the requisite leadin distance from the profile start point and the ending scan would be the run end point. Then click the Longitudinal Profil. button to bring up the Longitudinal Profile Options window shown in Figure 4-2.

4.4.3 Longitudinal Profile Options

Configure the options for the calculation of longitudinal profile.

Profile Specification

The transverse location of the profiles to be calculated, are specified by the following steps:
1. typing the transverse spacing between the imaginary wheel path center lines in the Axle Length” box in inches,
2. typing in the number of profiles desired per wheel path in the No.Profiles.Wheelpath box,
3. typing the spacing between profiles within each wheel path into the Spacing betw. Profiles” box in inches, and finally
4. clicking the Make X-List button to cause these entries to be processed to generate the list of transverse stations (X positions) where profiles will be located. This list can be viewed, one location at a time. In Figure 4-2, the first profile in the left wheel path, L1 is -36 inches. For the parameters shown in Figure 4-2, three profiles located at -36, 0 and 36 inches will be calculated. By clicking and holding the list tab, the list appears as shown in Figure 4-3. By default the program always computes the profile in the center line (X=0). The Make X-List button must be clicked for the input parameters to be processed. After a list is created, it may be edited one cell at a time. Point to the position desired and let up and the value will be displayed in the box to the left, and can then be edited.
Elevation Point Formation Specification

The formation of the transverse points to apply to the longitudinal profile calculation is controlled by the X\_bin interpolation radio buttons. If Off is selected, the scan point nearest to the X-List stations is used. If X\_bins is selected, then the average of all points within a bin of the width specified in Bin width at each Profile” centered about each of the X-List stations is used. If Linear is selected, the value is determined by linear interpolation between the two points on either side of the X-List stations. If Cubic is selected, the value is determined by interpolation between the two points on either side of the X-List stations using a cubic spline fit over 4 points, two to either side of the X-List stations.

Longitudinal Station Specification

The longitudinal profile generated will be referenced to a longitudinal station with an origin (zero value) at the location where the scan number typed into the Section Start (#) box occurred. All scans before the zero station scan will be processed for filter stabilization, however the results are not included in the LP and iri output files. All scans specified after the origin scan at stations up to an including the station typed in Section len(‘) in feet will be processed and recorded in the output files. If scans beyond station Section len(‘) are specified, they will not be processed. The longitudinal profile generated will have a uniform spacing between points, as specified in the Sect.Delta(’) box in feet.

Acceleration Bias

The DO NOT remove acceleration bias check box should not be checked. In the default process, the average acceleration for the run is subtracted from all points before filtering. This is the equivalent of an electrical zeroing or the Zero Velocity Cal button in the Scanner Control Window.

Filtering

At this stage of development, and to provide flexibility to compare to the various filtering approaches in use today, up to three sets of profiles with the three different type of filters can be generated.

No Filtering. To get an unfiltered profile, uncheck the Use Butterworth filter and the Use Boxcar filter checkboxes.

Butterworth Filtering. To obtain profiles filtered by a digital 3rd order IIR bandpass filter, check the Use Butterworth filter check box. For the first filtered set of profiles, the short wave high frequency cutoff is controlled by the value entered into the first LO\_Pass wave len(‘) box in feet and the long wave low frequency cutoff is controlled by the value entered into the first HI\_Pass wave len(‘) box in feet. If the second LO\_Pass wave len(‘) is non-zero, then a second set of profiles are generated with a Butterworth controlled by the second set of LO/HI boxes.

Box Car Short Wave High Frequency Filtering. A third set of profiles may be obtained with a high frequency boxcar filter over a length specified by the value in Boxcar len(“) in inches, by checking the Use Boxcar filter check box. The long wave low frequency cut-off will still be a Butterworth filter. The cutoff will be controlled by the value in the second Butterworth HI\_Pass wave len(‘) box. IF that value is zero or blank, then the first box will be used.
**International Roughness Index (IRI)**

Check the Calculate IRI data file checkbox to obtain an output file containing the IRI for each specified profiles. An output file will be created in the location and with the base name as specified by the Browse button explained below, with the suffix of “.iri” added.

**Unfiltered Acceleration and Elevation Data**

To obtain a data file consisting of just binned elevation data and acceleration which is not interpolated or filtered longitudinally, check the Make “.raw” data file checkbox. An output file will be created in the location and with the base name as specified by the Browse button explained below, with the suffix of “.raw” added. The normal longitudinal profile and iri output files will still be generated.

**TEST Mode output**

Generating the binned elevation points is computationally intensive, particularly at this stage, since all points in each transverse profile are computed before the binned transverse elevations are formed. To obtain an output file based only on the acceleration data, check the Enable TEST mode only checkbox. An output file will be created in the location and with the base name as specified by the Browse button explained below, with the suffix of “.tst” added. The data in this file is not filtered or interpolated longitudinally. This test file was used in debugging the longitudinal value calculations, but has been retained in the package since it may prove useful in the future.

If filtering is selected, the normal longitudinal profile and iri output files will be generated, but since there is no transverse elevation information, there is only one profile at X=0 for each filter selected. If filtering is not selected, a unfiltered profile is generated.

**Browse**

Click the Browse… button to obtain a standard file specification dialog. A default base file name is presented that consists of “LP.” as a prefix to the input file name. Edit the default base file name and directory path as desired and click OK. Filenames have a limit of 31 characters, including any extension.

**Execution**

Click the OK button to start the calculation or click the Cancel button to return to the Scanner Control window. Progress is displayed by the cursor showing a percent value completed.

### 4.5 Output File Formats and Use

All output files are in Excel tab-delimited format.

#### 4.5.1 Longitudinal Profile (LP.basename) File

A sample of the Longitudinal Output file is shown in Figure 4-4. The first column is the longitudinal (Z axis) station in feet. The remaining columns are the longitudinal profiles in inches. There are n*m profile columns where n is the number of profiles specified and m is the number of filters specified. Ex-
cel or other software can then be used to graph the profiles,

![Figure 4-5. Sample LP.basename.iri file.](image)

**4.5.2 IRI (LP.basename.iri) File**

A sample of the IRI output file is shown in Figure 4-5. The organization is identical to the LP file. The first column is the longitudinal (Z axis) station in feet. The remaining columns are the absolute value of the quarter car filtered profile in mm/m. They are not a cumulative average. Since the first profile point is zero, the zeros (in the second row) have been replaced with the average of all the points in that column.

Typically, it is desirable to average IRI over some interval greater than the station step size used to compute IRI. This can be accomplished in Excel as shown by the formula for cell E16 displayed in the formula bar in Figure 4-6. The array LP_iri!C$3:C$1401 refers to the associated IRI output. The variable “pts” refers to the number of points over which to average IRI, cell B3.

![Figure 4-6. Use of index to average IRI.](image)

**4.5.3 Raw Data (LP.basename.raw) File**

A sample of the Raw data output file is shown in Figure 4-7, where:

- “Scan#” is the scan number that is recorded in the data, in this case, adjusted for 16-bit wrap around.

![Figure 4-7. Sample LP.basename.raw file.](image)
• “Z(ft)=nnn” is the longitudinal distance in feet, gotten from the DMI data. The value represents the Z of the “Start Scan” position when found.
• “Accel=nnn” is the vertical acceleration measured in g’s obtained from the housekeeping with each scan. The value is the average over the data collected and has been subtracted from the original data.
• “Vel=nnn” is the vertical velocity measured in inches/second and is obtained integration of the acceleration. The value is an initial condition that is used to allow the Yace to be within a scale suitable for plotting. Since we do not know the initial conditions for vertical velocity and height, a convenient choice is made, and since the height will be filtered, that value will be removed.
• “Yace” is the vertical height measured in inches and is obtained by integration of the vertical velocity. Its initial value is assumed to be zero for convenience.
• “Roll” is the vehicle roll rate measured in degrees/second. It is NOT used in any calculation so far and is displayed to get a sense of the vehicle’s “rocking” motion. If severe (greater than about 5 degrees/sec), then the LP results might be suspect.
• The rest of the columns are measured elevations at the transverse stations that were requested. The units are in inches.

4.5.4 TEST Mode (LP.basename.tst) File

A sample of the Test mode LP.basename.tst output file is shown in Figure 4-8, where:

- “Scan” is the sequential scan number requested.
- “Scan#(ms)” is the internal scan number stored in the housekeeping data with each scan. It represents time measured in milliseconds.
- “Z (in)” is the longitudinal position measured in inches and obtained from the DMI in the housekeeping data.
- “Accel” is the acceleration measured in g’s and obtained from the housekeeping data.
- “TCe” is a tone count increment, an internal variable, and currently not used (=0).
- “Roll” is the roll rate of the vehicle measured in degrees/second and obtained from the housekeeping data. It is NOT used in any calculation so far.
- “Speed” is an instantaneous measure of the speed of the vehicle between changes in the Tone Count value. The units are inches/(microseconds/2). It is used to advance the Z value in scans where the Tone Count is not changing, such as in a slow changing DMI.
- “TC0” is an internal variable with adjust the Tone Count for wrap around (or rollover) because it is stored as a 16-bit integer.
- “TC” is the Tone Count value at the current scan, obtained from the housekeeping data. When adjusted by TC0 and multiplied by a scale factor (inches/tone count), it calculates the distance travelled in the longitudinal direction.
- “Etc-sos” is an internal variable that is used with “Speed” to adjust the Z value. It is obtained from the housekeeping data and has units of microseconds/2.
- “Ah” internal variable not used in current calculations.
4.6 Comparison to other Profiles

4.6.1 Absolute Profiles

To compare either profiles or IRI absolute reference data such as that obtained by Rod and Level Survey, Dipstick or other system, the reference profiles must be filtered by the same algorithms with the same filter cutoffs as used in Getdata. At this time, Getdata has not been programmed to accept an external longitudinal reference. However, Excel spreadsheets originally used to test the filtering and IRI algorithms are available for use to filter and calculate IRI on reference profiles.

Butterworth Filter Spreadsheet

A reference profile can be filtered by the same algorithms implemented in Getdata (except the box car) using the Excel workbook “PSI_Butterworth.xls”, which contains instructions on operation.

IRI of the filtered profile obtained from “PSI_Butterworth.xls” can be calculated using the Excel workbook “PSI_IRI.xls”, which contains instructions on operation.
4.6.2 Other Vehicle mounted Inertial Profiles

Comparison of other vehicle mounted inertial profiles must consider the Classification as per ASTM E-950 used to generate the profiles. Also differences in the profiles can be caused if different filter algorithms and/or break points are employed.

4.7 S/W Checkout

4.7.1 Longitudinal Profile

Bunch of scans of mylar. Have a step in the process where we add a sine wave function to the data as it is extracted from transverse scans, then plot the processed longitudinal profile and confirm result.

4.7.2 IRI

I attached the tests that I did on the spreadsheet version when I developed it. It has 2 versions of the Tri-pulse and the 300ft-sine wave. Now the E1926-98 report claims 2 values for the 300ft case: 0.0222 mm/m and 1.42 in/mi. You can see the 1.42 is incorrect because 0.0222 mm/m * 63.36 (in/ft. / (mm/m)) = 1.406592

Now for the tri-pulse, I agree with the WB#46 paper in detail. But the E1926-98 is not in agreement. My suspicion is that the published code and the run that was made is not in sync. I found that “UNITSC” variable is not defined anywhere that I can see, so some mode was done. Keep in mind that this example uses 0.15m step, and the WB paper uses a 0.25m step.

Coefficients in spreadsheet came from GD log file for various DZ values, and those values were used

DZ into Qtr Car model produces ST array. State Transition Matrix (p40)
(.25m WB)

World Bank and/or ASTM data

Simulated Data Set
5 Test Program Overview

5.1 Overview

To prove out the scanner operation in conjunction with the rut indices calculation software and longitudinal profile data extraction and algorithms developed for this project, the scanner was operated on pavements, for which there was contemporaneous transverse and longitudinal reference data.

The initial testing that produced data that was used for initial software development and validation was when a PPS-2000 was deployed to Phoenix, Arizona for the Road Profile Users Group (RPUG) 1999 meeting on November 1-2, 1999. On the day before and the day after the meetings, the system was operated on I-10 southwest of Phoenix on several LTPP test sections. The assumption was that we could obtain LTPP transverse and longitudinal profile data for use as reference data to evaluate the PPS-2000 performance.

The original plan was to provide a demo in Ames Iowa for the Iowa DOT once the software was operational. However, by the time this activity was scheduled, it was time for RPUG 2000 in Auburn, Alabama. An expanded itinerary was developed that provided for testing at the NCAT test Track in Opelika, as well as tests in Nashville, Tennessee and Ames, Iowa for the respective DOT’s. The original scope called only for a demo to the Iowa DOT. However, since much of the cost is the deployment, once on sight it was agreed that more extensive data collection should be performed.

5.2 1999 Testing

The testing was performed on in-service pavements with no traffic control. The PPS-2000 mounted on the test vehicle (Izuzu Trooper) is shown parked on the shoulder of I-10 westbound near the beginning of LTPP section 47614. The test vehicle was driven round trip from San Diego to Phoenix Arizona with the scanner mounted on it.

Figure 5-1. PPS-2000 on the shoulder of I-10 westbound near the beginning of LTPP section 47614.
5.3 2000 Testing

The PPS-2000 was flown to Madison, Wisconsin where it was installed on a Mandli Digilog van using the same bracket that was developed for the very first field trials of the scanner at Westrack in 1996, when Mandli had volunteered the use of a Digilog van.

The van was driven from Madison to Nashville, Tennessee where testing was performed bidirectionally on a 10 mile stretch of road. The analysis and presentation of those results is outside the scope of this report.

Next the van went to RPUG 2000 in Auburn, Alabama and was operated on the NCAT test track in Opelika. Finally on the return leg to Madison, the van stopped in Ames, Iowa. Testing was performed on 7 of the 8 test sections (1/2 mile long) established by the Iowa DOT for calibration of the automated distress mapping system used there. In addition data was collected on a road behind the DOT that is being mapped in detail by the DOT for realignment, and the system was demonstrated to staff at the DOT.
6 1999 Test Program

6.1 Test Sections

6.1.1 Section 47614

Jointed PCC construction with tining and pronounced oblique transverse joints.

Figure 6-1. Start of LTPP Section 47614.

Figure 6-2. End of LTPP Section 47614
6.1.2 Section 40218

Jointed PCC construction with tining and pronounced oblique transverse joints.

The start of this section was located about midway through PIARC section number 2.

Figure 6-3. Start of LTPP Section 04218

Figure 6-4. End of LTPP Section 40218
6.1.3 Section 41006
Relatively new overlay of AC.

6.2 Summary of Data Collection
The Excel workbook shown in Figure 6-6 lists all the Runs performed as well as the scan numbers corresponding to the start and stop of each section and the TC/DMI scale factor computed for each run. We assumed that each section was precisely marked. After the fact it would have been desirable to have verified the start to end line distance of each site to an accuracy of one inch.

6.3 Reference Data
We did not attempt to obtain reference data until after the testing was performed, based on the assumption that there would be contemporaneous data for all LTPP sections. For the reasons explained below, out of all this effort, what proved useful for analysis, was the transverse results from 41006 and the longitudinal results from 40218

6.3.1 Section 47614 - PCC
We did not collect sufficient leadin data for longitudinal profile calculations so the longitudinal profile reference data was not analyzed. The most recent transverse profile data was over three years old.

6.3.2 Section 40218 - PCC
We did collect sufficient leadin data for longitudinal profile calculations so the longitudinal profile data was obtained from the LTPP Program Office by special request, as the profiles are not routinely published in Datapav. The most recent transverse profile data was over three years old, so the transverse data was not studied.

6.3.3 Section 41006 - AC
We did not collect sufficient leadin data for longitudinal profile calculations so the longitudinal profile reference data was not analyzed. Pasco had just done transverse profile on this section the month before RPUG and we were able to get this data by Spring 2000.
Run Parameters from I-10 Testing in Phoenix, Arizona

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**NOTES**

1 - This run was triggered about 64 feet after the start mark: -63.48

Average 0.85346

Figure 6-6. Summary of 1999 PPS-2000 Test Program Runs
7 2000 Test Program

7.1 NCAT

7.2 Ames, Iowa
8 Rut Indices Experimental Results

8.1 Overview

To prove out the scanner operation in conjunction with the rut indices calculation software developed for this project, the scanner was operated on several types of in-service pavements, for which there was contemporaneous transverse profiles and computed rut indices to serve as control data.

8.2 Arizona LTPP 11/1999

8.2.1 Reference Data

Profiles supplied by CGH Engineers (Pasco) measured 10/1999.

8.2.2 Analysis Methods

8.2.3 Profile Plots

8.2.4 Rut Indices

8.3 Iowa DOT 12/2000

8.3.1 Reference Data

Road and Level data collected by Mandli Communications.

8.3.2 Analysis Methods

8.3.3 Profile Plots

8.3.4 Rut Indices
9 Longitudinal Profile and IRI from Transverse Scans – Field Evaluation

9.1 Overview

To prove out the scanner operation in conjunction with the rut indices calculation software developed for this project, the scanner was operated on several types of in-service pavements, for which there was contemporaneous longitudinal profiles and IRI to serve as control data.

9.2 Test Description

These test were performed concurrently with the tests as described in the section on Rutting. At the time the tests were performed, the requirement to have leadin data for a length equivalent to the longest wavelength of interest was not known. Most of the runs were initiated a minimal distance from the start of the test section. Fortunately LTPP section

9.3 Arizona LTPP Results

Although data was collected on multiple LTPP sections, only the data from section 1006 proved to be useful for longitudinal profile calculation. At the time these experiments were performed, the requirement to collect data over a leadin section of length equal to the long wave cutoff was not understood. Fortunately section 1006 is located in the latter half of a 1,056 foot Piarc section, for which data was collected. Hence albeit by accident we had the requisite leading data for this section.

9.3.1 Analysis Methods

The runs were processed with a 6 inch box car high frequency filter and 100 meter long wave cutoff, for compatibility with LTPP processing.

9.3.2 Profile Plots

Five runs were performed with the PPS- 2000 on 11/3/99 and there were five reference profiles available from LTPP that were collected on section 0218 on 12/8/98 just about 9 months earlier. The left wheel path profiles are plotted in Figure 9-1 and the right wheel path profiles are plotted in Figure 9-2. By inspection it can be seen the profiles measured by LTPP and the PPS-2000 are similar in shape but that there is greater scatter in the PPS-2000 profiles.

In the upper plot of Figure 9-3, the point-by-point average left and right profiles of 5 runs for LTPP and the PPS-2000 have been overlaid. In the lower plot, the left and right wheel paths have been averaged. These plots include the filtered Rod and Level profile furnished by PI-ARC. Since the PIARC section was longer, there was sufficient data to initialize the digital filter.
Figure 9-1. Left wheel path profiles.
Figure 9-2. Right wheel path profiles
Figure 9-3. Plots with LTPP and PPS-2000 profiles overlaid.
9.3.3 Profile Accuracy Statistics

Consideration of the accuracy of these tests is examined by calculating the statistics of the precision and bias. For this LTPP section, the reference data that was available was the LTPP profiles collected by Nichols Consulting using a KJ Law Profilometer. Hence this analysis is the comparison of the results of two inertial profiling devices. As such there is no ASTM standard for this comparison, as ASTM E-950 Classifies the performance of an Inertial Profiling system by comparison with a “true” profile obtain by Dipstick or Rod and Level and filtered indentically to the Inertial Profile.

These tests were not an attempt to establish the Classification of the PPS-2000 under ASTM E-950. This would have required 10 runs and ideally an equal number of true profiles. This activity is planned for the first production unit test program.

Precision

Precision is a measure of how tightly repeat measurements are clustered, or the repeatability of the system. To evaluate this, the standard deviation of the five profiles in each wheel path for both the PPS-2000 and the LTPP/Law data was computed. The results are summarized in Table 9-1. These results are consistent with the qualitative observations of the plots. The PPS-2000 scatter is 98% and 38% greater than the LTPP results in the left and right wheel paths. Considering that this was the first field testing ever performed with the PPS-2000 on in-service roads, these are respectable results. Although the PPS-2000 had scatter greater than the LTPP results, it should be noted that the LTPP results themselves do not qualify as Class I in accordance with ASTM E-950, which specifies a maximum standard deviation of 0.38 mm.

Further it should be noted that driver wander processing has not been implemented and was not applied to these results.

<table>
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<th>Right</th>
<th>ASTM E-950</th>
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<td></td>
<td>PSI</td>
<td>LTPP/Law</td>
<td>PSI</td>
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<td>Standard Deviation, point-by-point (mm)</td>
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<tr>
<td>Average ± Standard Deviation</td>
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<td>0.47±0.22</td>
<td>0.69±0.28</td>
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<tr>
<td>Maximum</td>
<td>2.25</td>
<td>1.31</td>
<td>1.56</td>
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<td>Range (max-min.), point-by-point (mm)</td>
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<tr>
<td>Average ± Standard Deviation</td>
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<td>1.74±0.73</td>
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<td>Maximum</td>
<td>5.51</td>
<td>3.23</td>
<td>4.02</td>
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The frequency and cumulative distributions for the 5 run point-by-point standard deviations are plotted in Figure 9-4 and Figure 9-5.
Figure 9-4. Frequency distribution of the 5 run poin-by-point standard deviations

Figure 9-5. Cumulative distribution of the 5 run poin-by-point standard deviations
Bias

The bias of the PPS-2000 results relative to the LTPP profiles was computed for the difference of the mean profiles of 5 runs of PPS-2000 minus that of the LTPP 5 runs, in each wheel path. The results are summarized in Table 9-2. It is encouraging that even with the increased scatter (lower precision) associated with these first ever in-service tests, the bias error is 23% and 48% below the upper limit to qualify as a Class I system under ASTM E-950.

Table 9-2. Statistics of the Absolute value of the bias of the PPS-2000 mean profile of 5 runs relative to LTPP/KJLaw mean Longitudinal Profile

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<td>Right</td>
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<tr>
<td>Average ± Standard Deviation (mm)</td>
<td>0.97±0.74</td>
<td>0.67±0.57</td>
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<td>Maximum Deviation (mm)</td>
<td>3.86</td>
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The frequency and cumulative distributions of the point-by-point bias of the PPS-2000 relative to LTPP are plotted in Figure 9-6 and Figure 9-7.

Figure 9-6. Frequency Distribution of the magnitude of the deviation of the PPS-2000 mean from the LTPP mean.
9.3.4 Driver Wander

The final production software will look for the pavement lines and attempt to mitigate the effects of driver wander by establishing the transverse data selected as an offset from the line. This data is to be examined to plot the driver wander in these tests. This may explain some of the scatter in these results. Keep in mind that this was the first attempt at testing on inservice roads.

9.3.5 IRI

Results TBD
10 Summary
References