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16. Abstract
During Research Project 0-4479-01, a methodology for establishing bump detection using inertial profile measurements was developed. During this project, the method was further refined and compared with the current bump detection method used in TxDOT's Ride Quality program and with results from profilograph simulations based on profiles measured on numerous projects across the Texas. A large sample of sections where the Template Analysis Procedure (TAP) identified bumps was also verified using reference profiles from the Walking Profiler.

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VERIFICATION OF THE BUMP DETECTION METHODOLOGY USING INERTIAL PROFILE MEASUREMENTS

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BACKGROUND AND OBJECTIVES

INTRODUCTION

The Texas Department of Transportation (TxDOT) started implementing its new ride quality specification in 2002. This specification requires the use of inertial profilers in lieu of profilographs for quality assurance testing of surface smoothness on new construction and rehabilitation projects. The profilograph-based ride specification that it replaced includes criteria on both section-wide and localized roughness. Although a method is currently used to evaluate localized roughness, its assessment, and that of section-wide roughness, is based on different criteria. The new ride specification identifies defects based on an allowable difference between the average measured profile and its moving average, and assesses section-wide roughness using the international roughness index (IRI). While both criteria are correlated to user perception of ride quality as measured by the present serviceability index, PSI is not presently used to establish the need for corrections. Also, the improvements in PSI resulting from corrections are neither evaluated nor predicted in the new ride specification. Thus, TxDOT initiated Project 0-4479 to investigate the application of its new ride equation for detecting defects in a smoothness specification.

The method developed from Project 0-4479 uses bump templates to scan measured profiles for the occurrence of localized defects. This method is referred to as the Template Analysis Procedure (TAP). TAP finds bumps and dips by cross-correlating bump templates with the measured profile of a section under evaluation. This process yields a set of correlation statistics that indicates how closely a particular area in the section follows the different templates. TAP then compares the absolute value of each statistic to a threshold. Where the specified threshold is exceeded, a bump or dip is recorded at that location depending on whether the correlation is positive or negative, respectively. The magnitude of the bump or dip is then determined from the profile of the section at the located point.

During Project 5-4479-01 this method has been further refined and compared with the current bump detection method used in TxDOT's Ride Quality program and with results from profilograph simulations based on profiles measured on numerous projects across the Texas. A large sample of sections where TAP identified bumps was also verified using reference profiles from the Walking Profiler (WP). This and other results in accordance with the project objectives are provided in this report.

SUMMARY OF WORK PERFORMED AND RECOMMENDATIONS

The TAP method was used on 10 state projects. Each project would typically contain several miles of pavements thus providing a large sample of asphalt and concrete pavements in Texas. A separate analysis was performed for each individual bump identified by TAP and was verified with the Walking Profiler. Results of these analyses for each project are presented in Figures 1 through 6. For each figure, the bumps identified by TAP are noted. Each bump identified by TAP that researchers were able to verify with the Walking Profiler is also noted. In some cases where the bump identified by TAP was not verified by the WP, the grade change recorded by the WP was too great to see something as small as a 150 mil bump. Therefore, the bump/dip identified by TAP may actually be present in the surface but the data from the WP may have been inconclusive.

Using the inertial profile data for each project, a Ride Quality analysis and a profilograph simulation were performed for each wheel path. The Ride Quality program uses an average of the profiles in each wheel path; therefore, researchers altered the inertial profile data files such that a Ride Quality analysis could be obtained for each wheel path. For example, to obtain a Ride Quality analysis of the left wheel path, the column of profile data for the right lane was deleted and replaced with the left wheel path. Therefore, when the Ride Quality program obtained an average for the wheel paths, both columns of data were of the left wheel path profile. The bumps/dips identified from the Ride Quality and profilograph simulations are shown for each of the summary charts (Figures 7 through 25).

In a number of cases, more bumps were found using TAP than found using the Ride Quality or profilograph simulation methods. Also, there were many cases where TAP found less than either of the two methods. Similarly, the Ride Quality and profilograph simulation methods did not always find the same bumps. This is not surprising since the three methods are completely different. For example, the Ride Quality method looks for variations greater than 150 mils from a 25-foot running average. Recall that TAP is not applied unless the NSI readings are less than a specific value, in this case, 4.0.

It was noted that the TAP method seemed to give more bumps on asphalt pavements than on concrete, although this could have been the samples used. TAP is related to how people would rate a road based on the eight wavelengths of one through eight meters used in the NSI model. As a result, TAP may be less sensitive to a one-foot bump than a three-foot bump. The TAP method does not respond well to joints since these would typically be less than one foot. On the other hand, if bad joints result in a surface profile with wavelengths that are multiples of the spacing between these joints, and if these wavelengths range between one to eight meters, TAP should pick these rough areas. Improvements to the method could be made by applying additional templates with widths from one to twenty-five feet and more height variations.

Four additional points and recommendations should be noted:

- The report includes many comparisons between the TAP and the method in the ride quality program. The methods are based on two completely different concepts. The TAP program is based on a prediction of how the public would rate the pavement ride. It is unlikely that the TAP method would replace the current method until much more usage. It should be used for awhile in conjunction with the current method in ride quality program in order to gain more acceptance by TxDOT engineers. It is hoped that TxDOT will code the TAP method into ride quality as it can provide an indicator of how bumps actually affect ride.

- Originally, a pilot implementation of the proposed modified ride specification program was planned. Due in part to the time required in the acceptance of the current Ride Quality procedure, the Implementation Director proposed an alternative implementation plan that would provide more useful data for TxDOT engineers and which could be used to assess the impact of changing from the existing Ride Quality bump template to the

TAP procedure. The Implementation Director presented this implementation plan in the June 2006 RMC meeting. The specific recommendations provided to the RMC and discussed were: (1) TxDOT will modify the Ride Quality program to include TAP; (2) save FY06 raw profile data over the highway network; (3) report new SI in addition to the current SI and IRI for the entire highway network in FY06; (4) report localized roughness over the network in terms of the existing Ride Quality template and TAP; and (5) conduct a bump panel study to verify predictions of NSIs and threshold used TAP from profiles measured from sections with known bumps.

- The NSI program was modified to account for a much wider set of field and PMIS data. UTA provided TxDOT with a revised version of NSI. Following Project 5-4479 and using the modified NSI version and the IRI program, IRI and NSI were computed for 1,550,288 sections of 0.1 mile each, using 26 districts from profiles obtained during the 1996 PMIS data collection as recommended in the previous section. A summary of the comparisons of IRI with NSI are illustrated in the appendix.

- It is recommended that TxDOT consider implementing TAP as an additional reporting option for Ride Quality. This would require TxDOT to include the TAP software with the existing program. For this purpose, researchers provided TxDOT with a copy of the TAP software so that TxDOT can include this method of bump detection in the Ride Quality program. No changes are required in the current Item 585 smoothness specification to implement the product from this project. It was decided near the end of the project to provide an integrated program with easily identifiable functions that could be used by the TxDOT contractor responsible for developing and maintaining the Ride Quality program for integrating the template analysis code into a TAP module within Ride Quality. A compiled version of the Matlab program with an execute module was provided so that TxDOT engineers could begin using the program until the Ride Quality program was modified.

PROGRAM REFINEMENTS FOR TAP IMPLEMENTATION

For implementation of the TAP bump identification procedure, bumps are located which affects user perception of ride as predicted by the NSI model. A number of changes were made to the original program defined in the TAP procedure. The first change was to increase the scope of the bump finder and threshold detection programs to handle more test profiles. Additionally, the bump detection and reporting method in TAP was modified to provide both bump height and bump width. An example of the bump report from the Bump Finder program on one of the projects used in the implementation project on US 77 K6 lane near Waco is illustrated in Table 1. From the bump report shown, the user can examine the profile within the interval where the bump is reported to further investigate the area where the bump is found. If there are overlapping bumps, the beginning of the first bump to the end of the last overlapping bump is defined as the bump width. Similar inspections of the bumps reported with Ride Quality and from profilograph simulations of measured profiles are presented in the next section. A large sample of bumps reported by the template analysis procedure was also investigated using reference profiles from the Walking Profiler. Visual inspections of both the actual pavement and the measured reference profiles were made by project personnel during the course of this investigation.

Table 1. Example of TAP Bump Report (US 77 Waco, K6).

Left Wheel Path

Section (0.1 mi)	Begin (feet)	End (feet)	Length (feet)	Bump Height (mils)	NSI
9	5013	5040	26	193	3.67
23	12461	12526	65	280	3.25
28	15162	15205	44	238	3.59

Right Wheel Path

Section (0.1 mi)	Begin (feet)	End (feet)	Length (feet)	Bump Height (mils)	NSI
4	2257	2298	40	155	3.82
9	4931	4975	44	185	3.67
23	12465	12525	61	253	3.25
25	13646	13689	43	579	3.52
28	15152	15178	26	158	3.59

EVALUATION OF FIELD DATA

Verification of the TAP was performed by assessing if each bump identified by TAP was discernible by the measurements obtained from the walking profiler. For example, TAP identified a 26-foot long bump from the inertial profile data on US 77 (Figure 1) in the left wheel path (LWP) from 8 to 34 feet. Researchers performed a walking profile measurement in the same location and graphed the data as shown in Figure 2. The inertial profile data are filtered and therefore do not appear exactly the same as the walking profile data which show absolute changes in elevation. Based on the profile shown in Figure 2, researchers can agree with TAP that there is a bump between 8 and 34 feet.

In the next example, TAP identified a 16-foot long dip from the inertial profile data in Corrigan on US 287 (Figure 3) in the right wheel path (RWP) from 1430 to 1446 feet. The walking profile measurement also shows an obvious dip in the same location as shown in Figure 4.

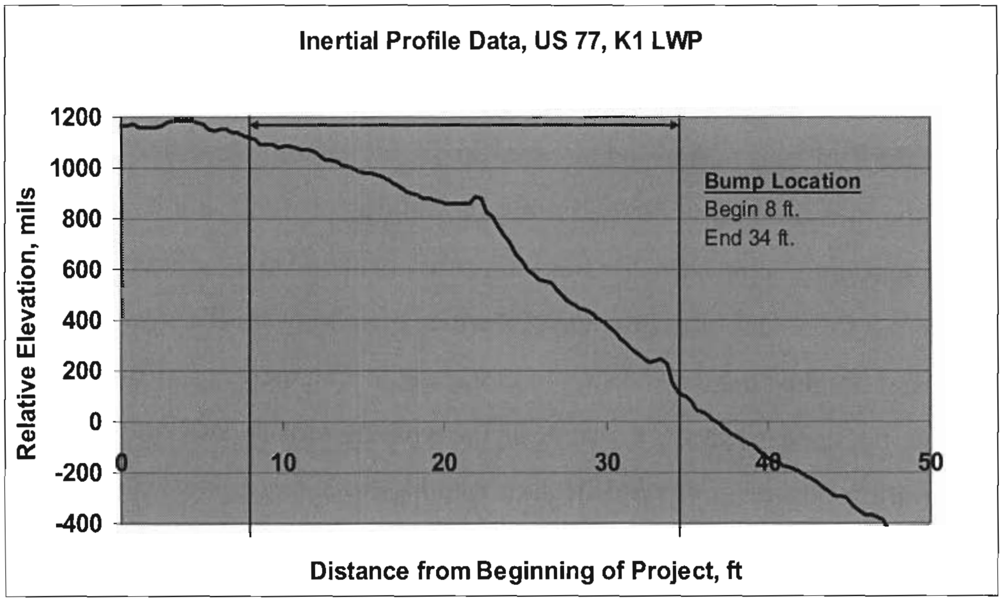

Figure 1. Inertial Profile Data from US 77 in Waco, Left Wheel Path of K1.

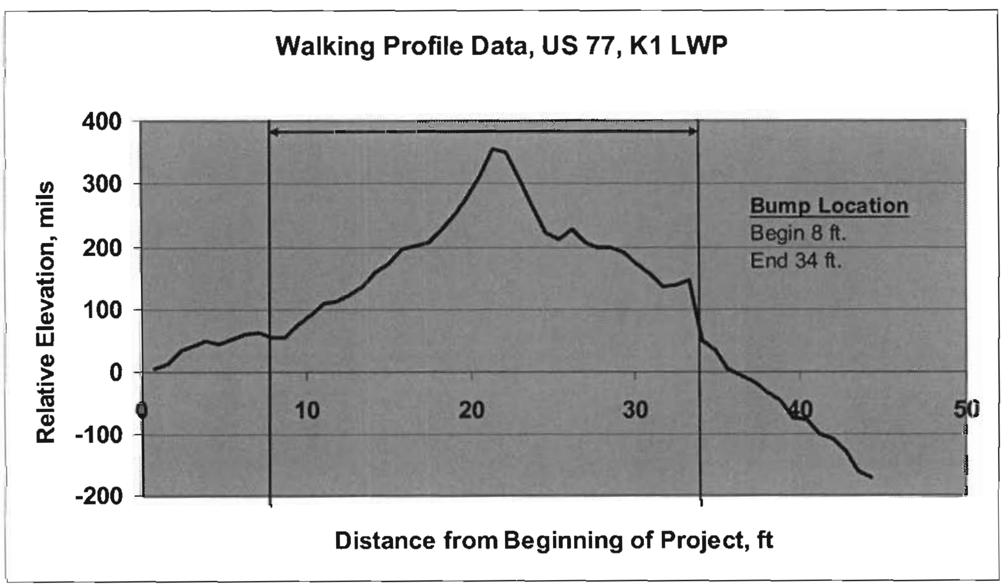

Figure 2. Walking Profile Data from US 77 in Waco, Left Wheel Path of K1.

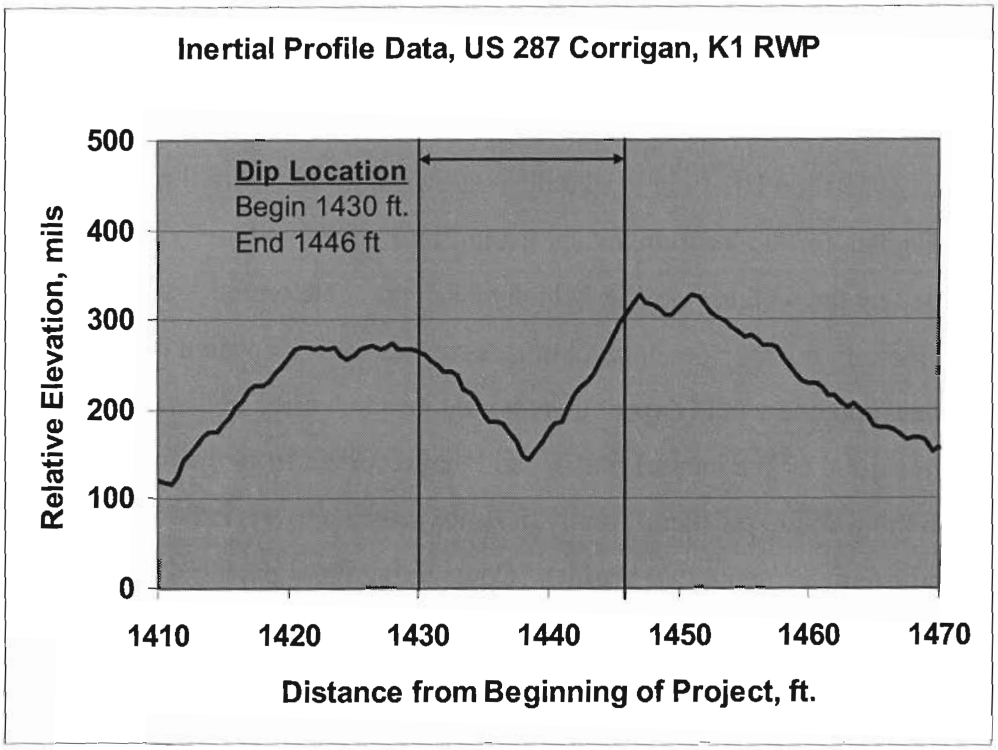

Figure 3. Inertial Profile Data from US 287 in Corrigan, Right Wheel Path of K1.

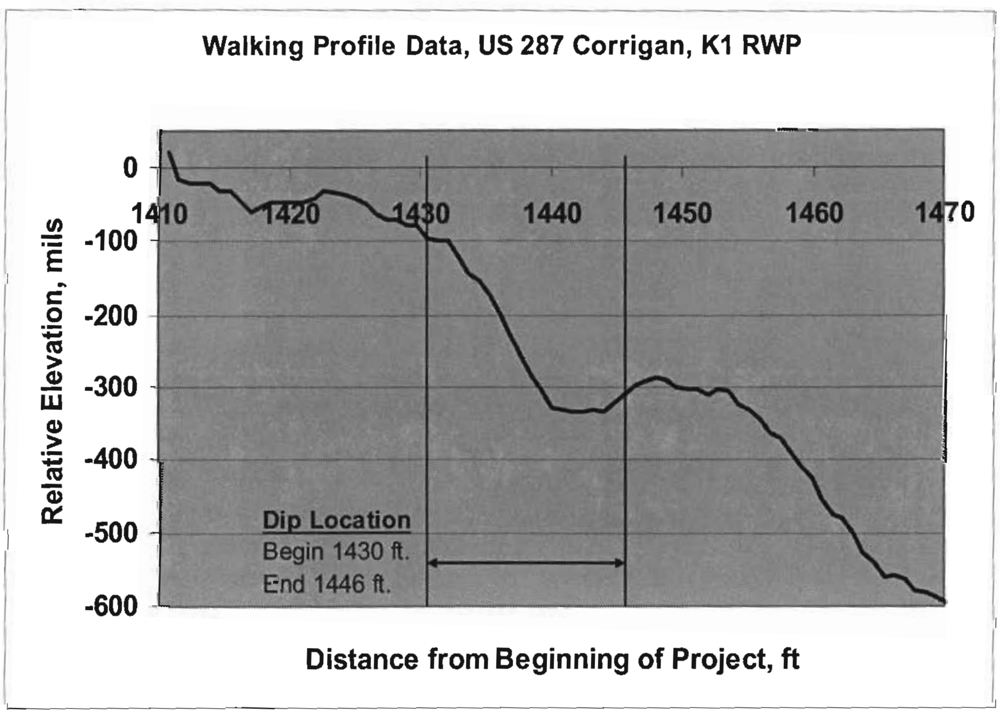

Figure 4. Walking Profile Data from US 287 in Corrigan, Right Wheel Path of K1.

In the previous two examples, the bump and dip, respectively, were easily verified in a visual evaluation of the walking profile data. In some cases though, bump or dip verification is more difficult (or less obvious) as shown in the following example. TAP identified a 7-foot long dip from 3148 ft to 3155 ft on US 79 in Rockdale as shown from the inertial profile data in Figure 5. Walking profile data for the location are shown in Figure 6. Note that there is a significant grade change recorded by the walking profiler which makes the scale on the y-axis very large for attempting to identify bumps. Secondly, bump locations were identified in the field using a measuring wheel and one would expect there would be some error in distance measurement between that recorded by the inertial profiler and that recorded from the measuring wheel that was used with the walking profiler. Finally, it is not possible to track the walking profiler in exactly the same path as the inertial profiler. Considering these potential sources of error, researchers concluded for this case that there is a dip/defect present in the pavement surface identified in Figure 6 which corresponds closely to the location identified by TAP.

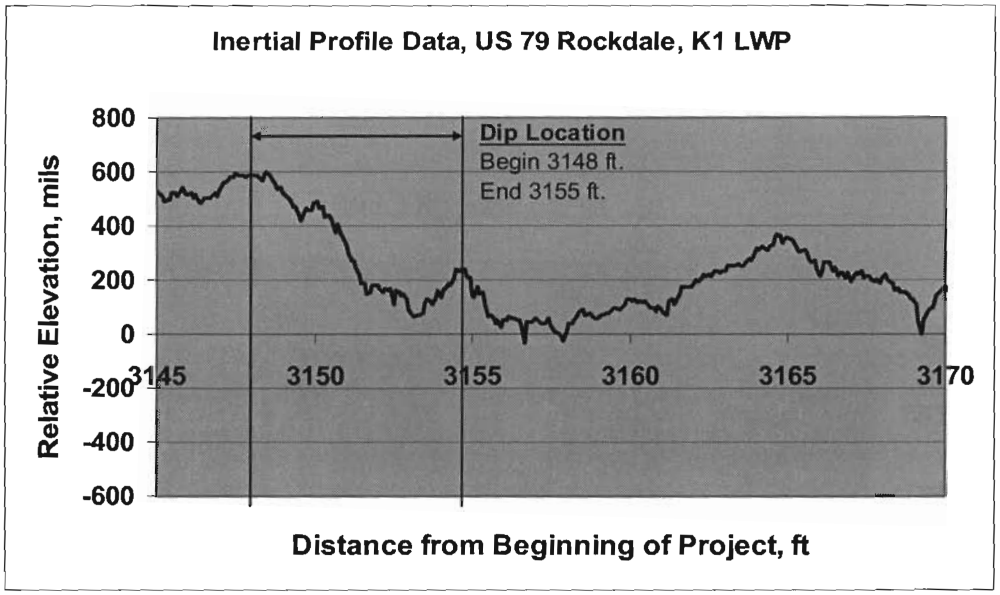

Figure 5. Inertial Profile Data from US 79 in Rockdale, Left Wheel Path of K1.

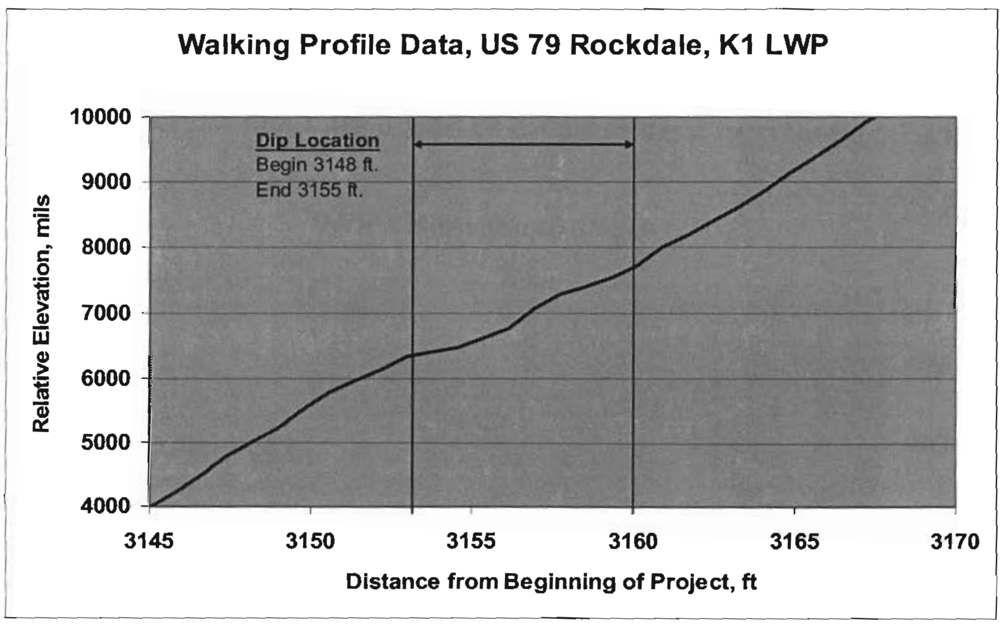

Figure 6. Walking Profile Data from US 79 in Rockdale, Left Wheel Path of K1.

For the following summaries of the results, four sets of data are represented. The Walking Profiler (WP), Template Analysis Procedure, Ride Quality (RQ), and Profilograph Simulation (PS) are displayed on each of the following graphs.

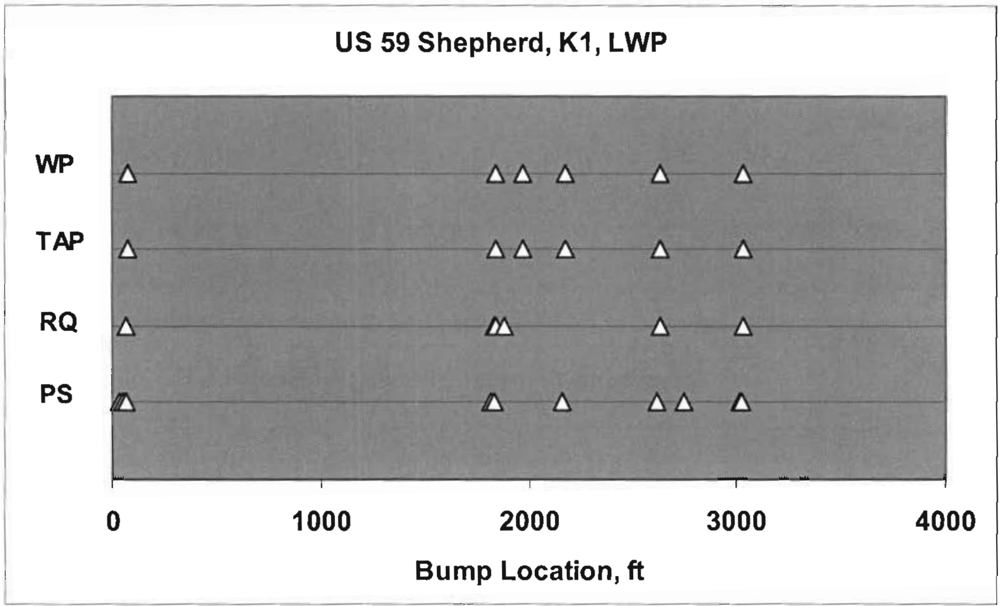

Figure 7. Summary of Results for US 59 Shepherd, Lane K1, Left Wheel Path.

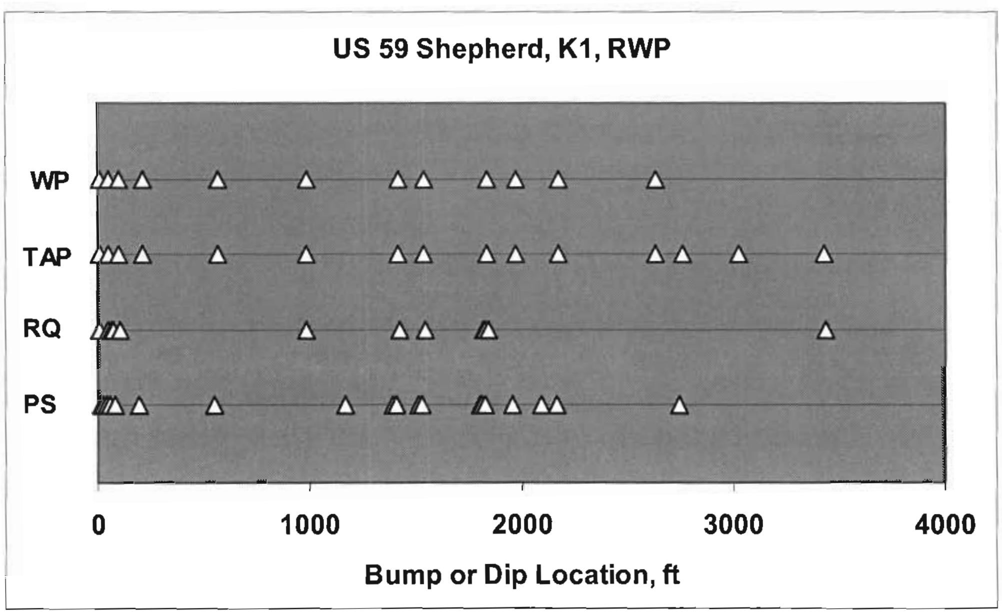

Figure 8. Summary of Walking Profile for US 59 Shepherd, Lane K1, Right Wheel Path.

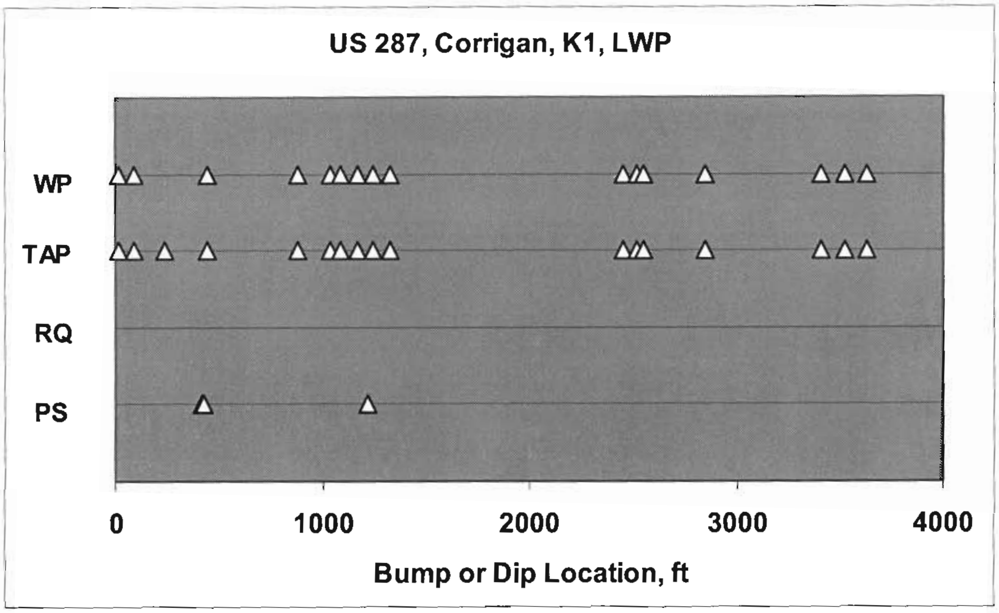

Figure 9. Summary of Results for US 287, Corrigan, Lane K1, Left Wheel Path.

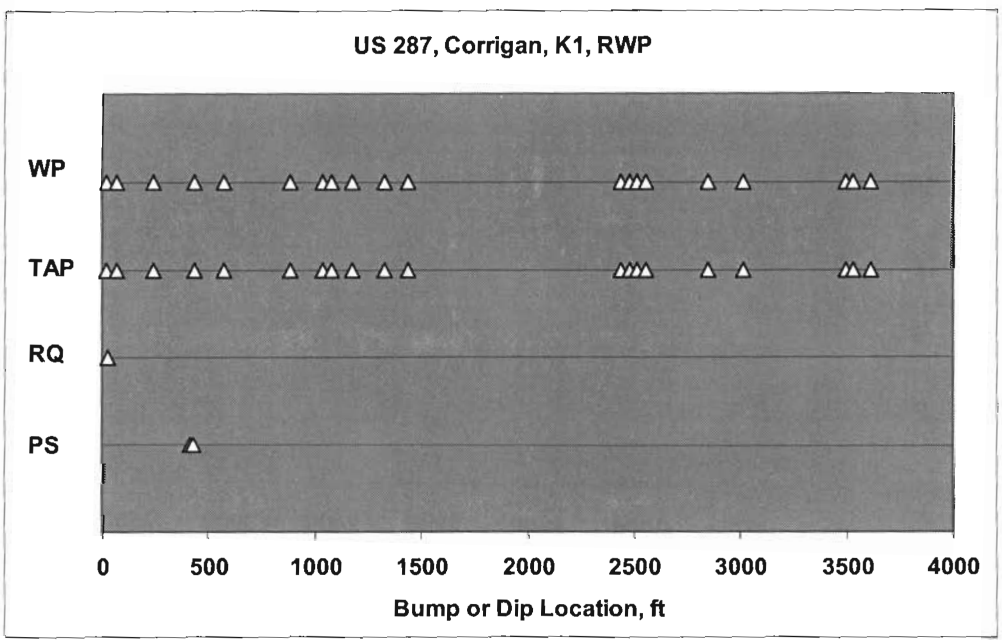

Figure 10. Summary of Results for US 287, Corrigan, Lane K1, Right Wheel Path.

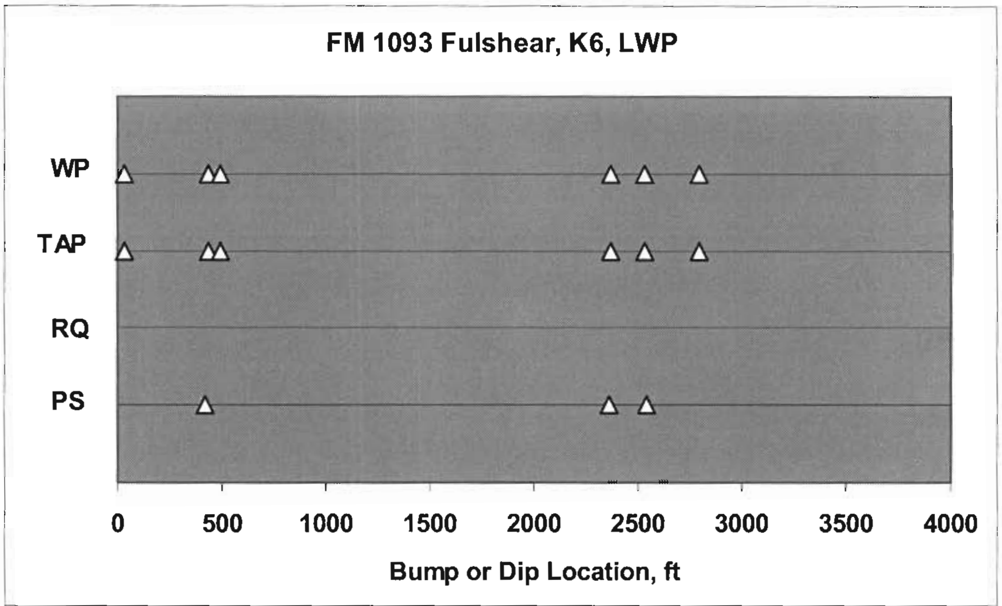

Figure 11. Summary of Results for FM 1093, Fulshear, Lane K6, Left Wheel Path.

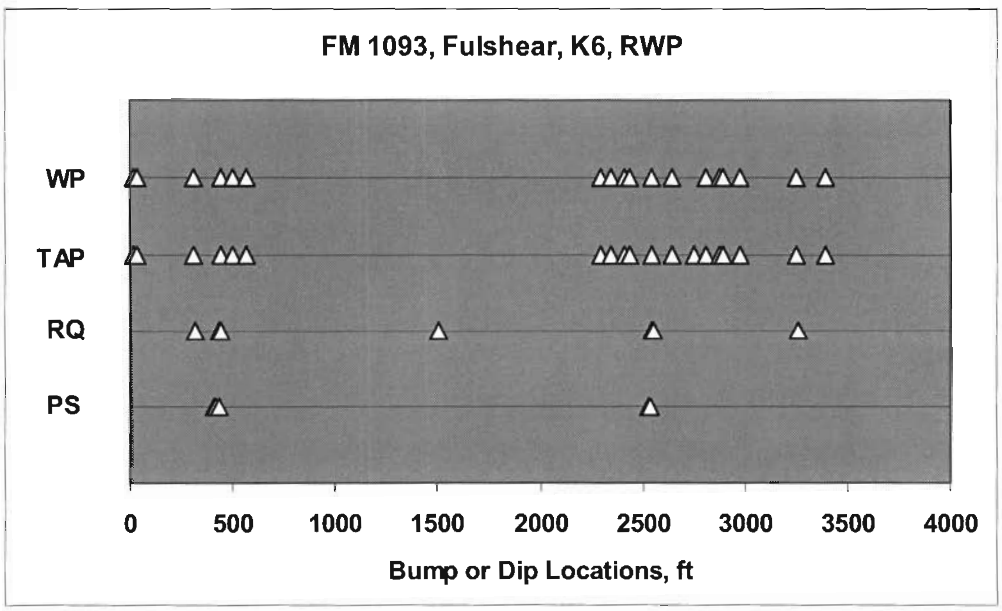

Figure 12. Summary of Results for FM 1093, Fulshear, Lane K6, Right Wheel Path

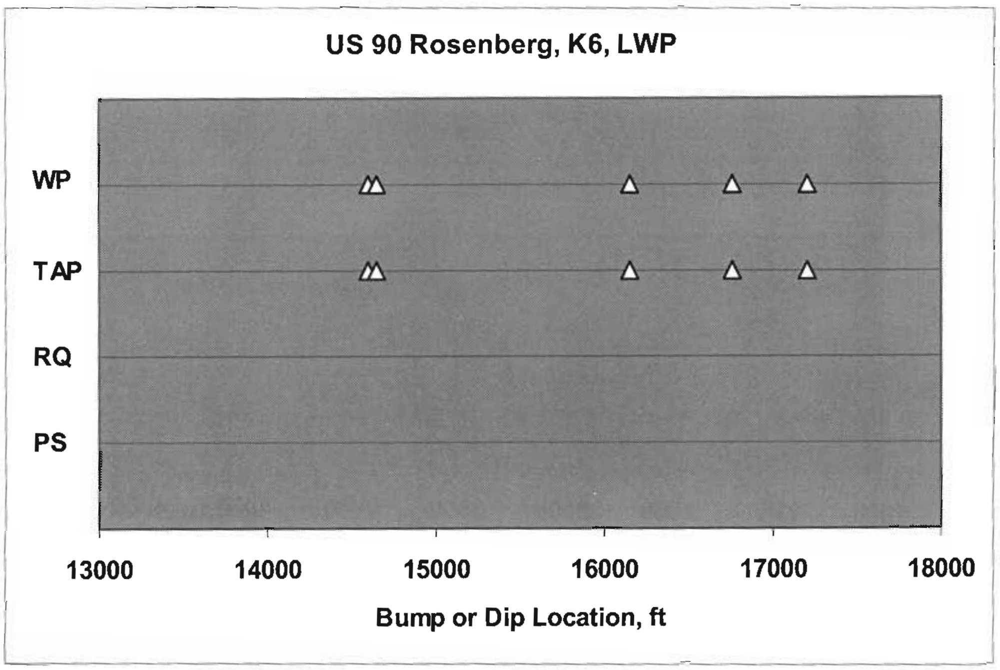

Figure 13. Summary of Results for US 90, Rosenberg, Lane K6, Left Wheel Path.

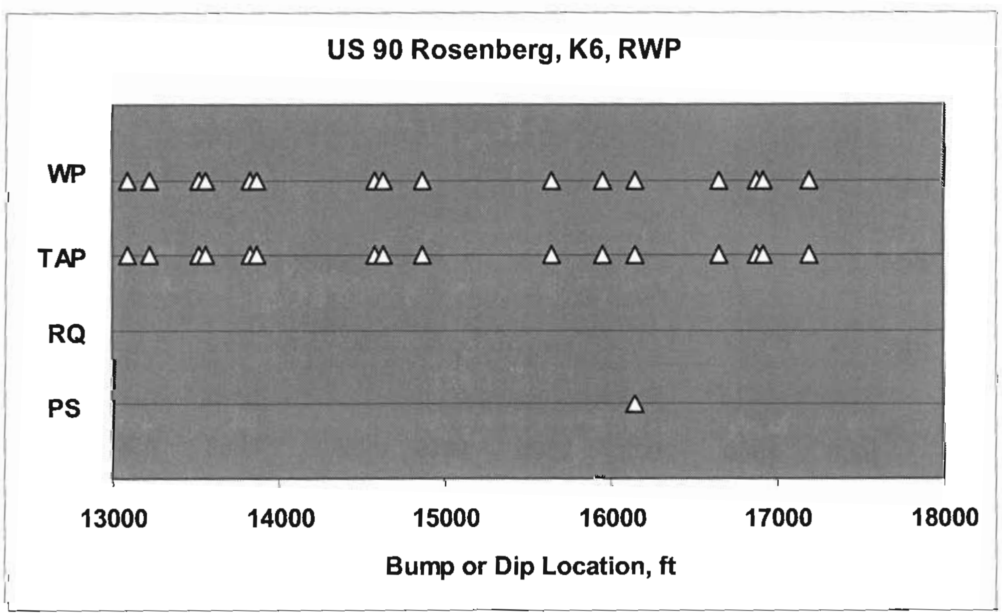

Figure 14. Summary of Results for US 90, Rosenberg, Lane K6, Right Wheel Path

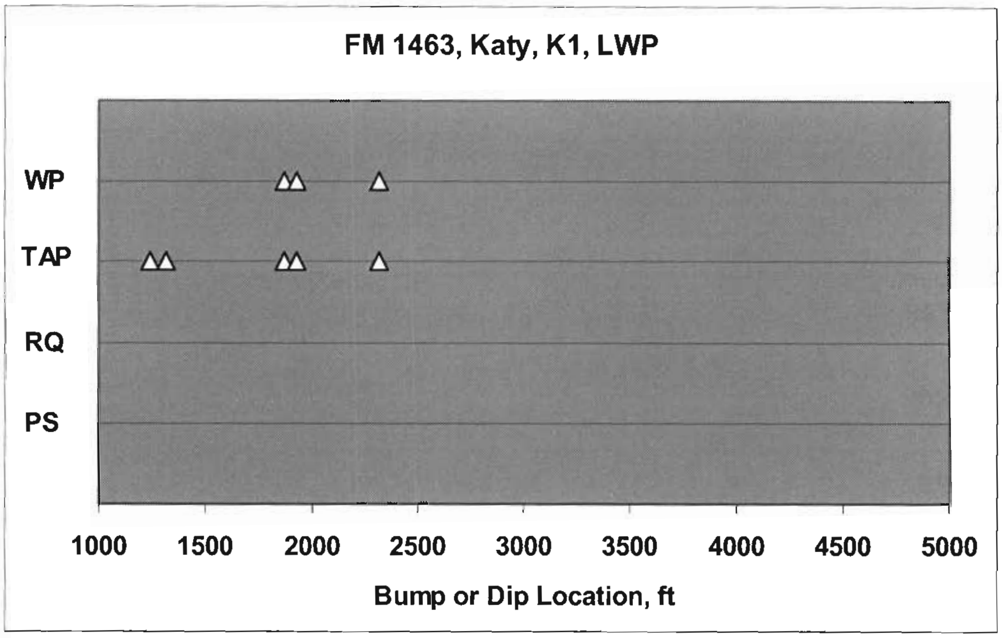

Figure 15. Summary of Results for FM 1463, Katy, Lane K1, Left Wheel Path.

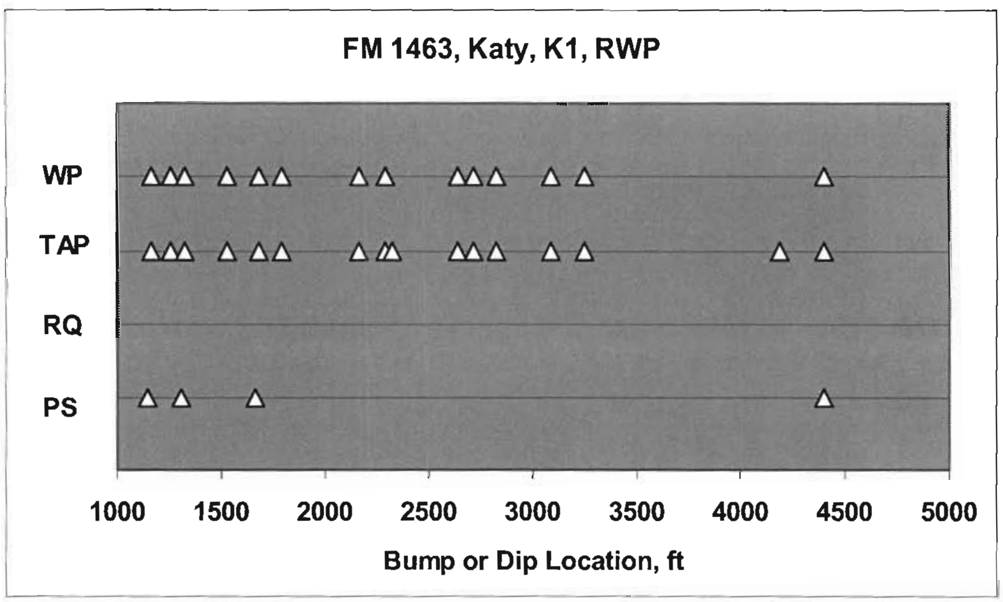

Figure 16. Summary of Results for FM 1463, Katy, Lane K1, Right Wheel Path.

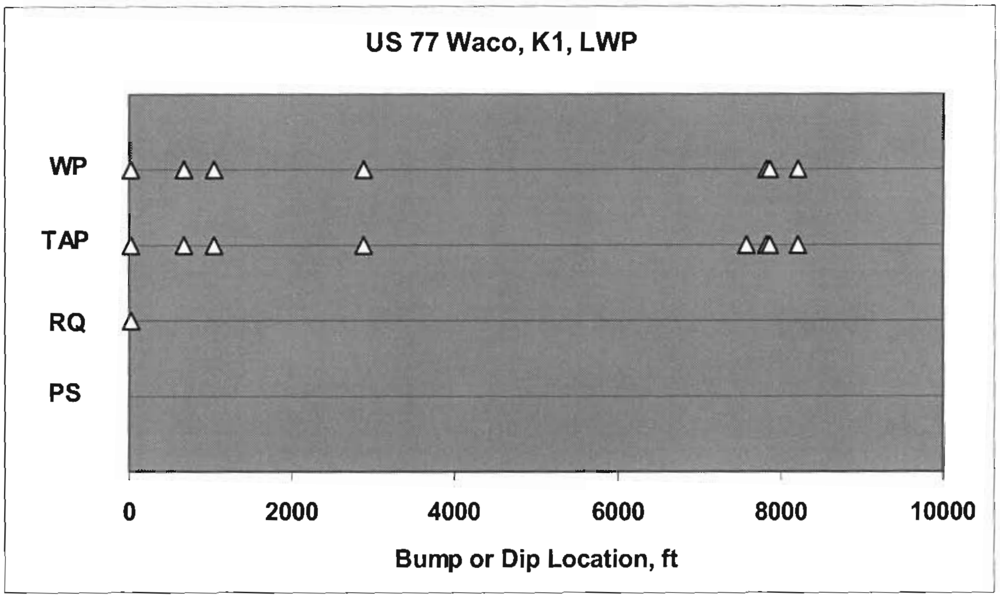

Figure 17. Summary of Results for US 77, Waco, Lane K1, Left Wheel Path.

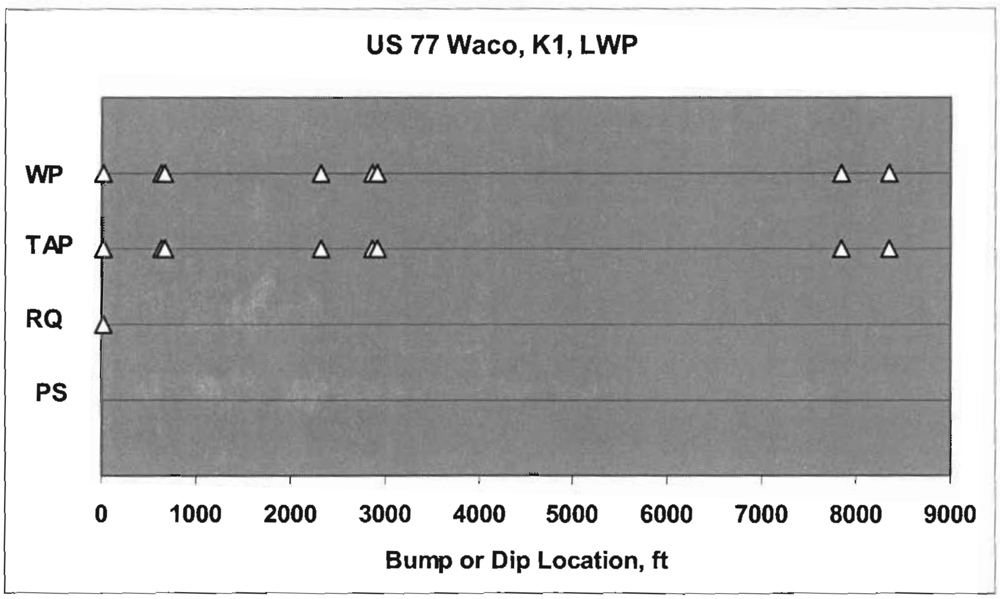

Figure 18. Summary of Results for US 77, Waco, Lane K1, Right Wheel Path.

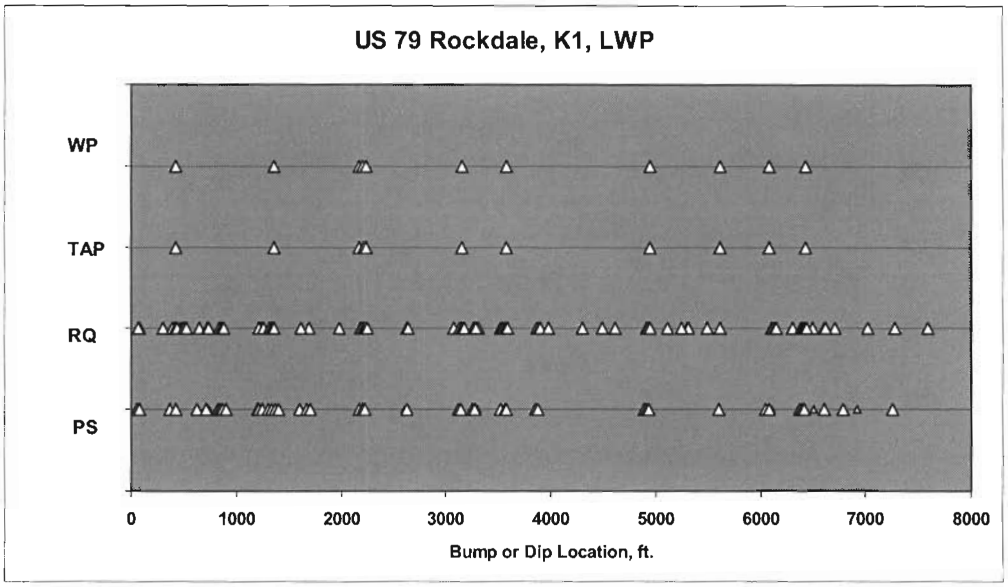

Figure 19. Summary of Results for US 79, Rockdale, Lane K1, Left Wheel Path.

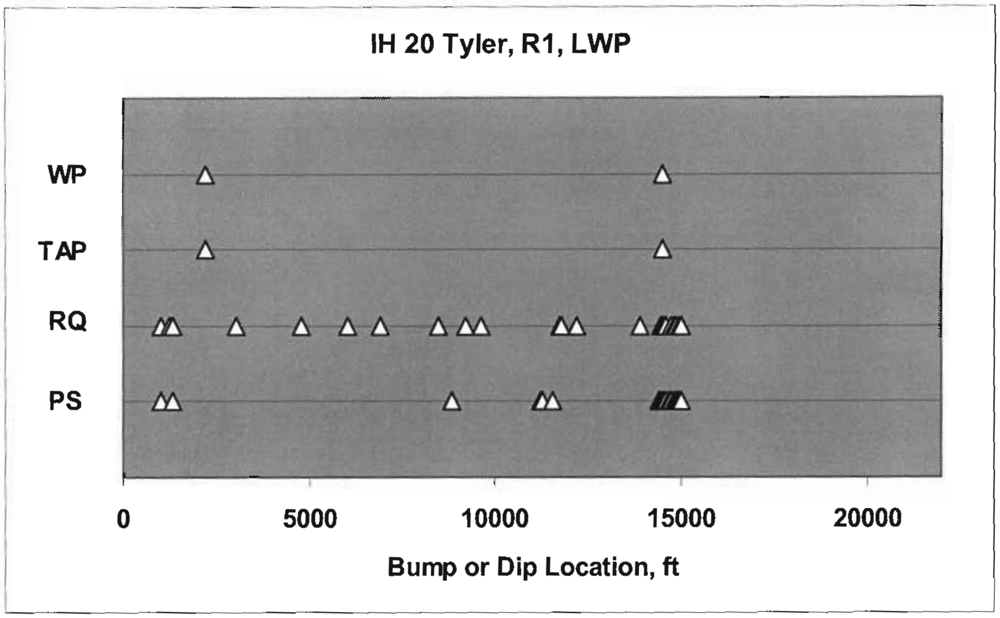

Figure 20. Summary of Results for IH 20, Tyler, Lane R1, Left Wheel Path.

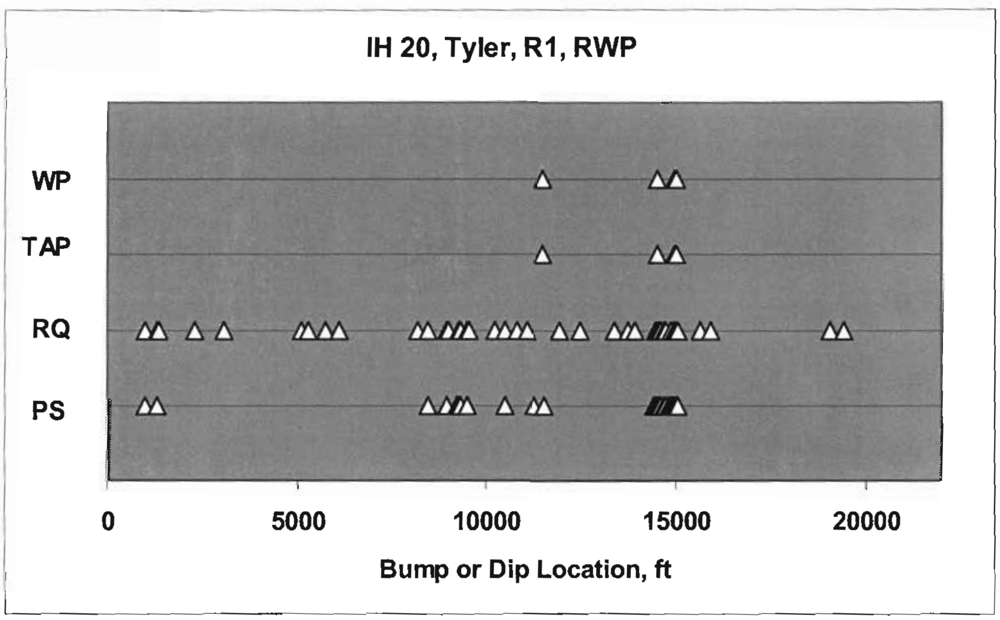

Figure 21. Summary of Results for IH 20, Tyler, Lane R1, Right Wheel Path.

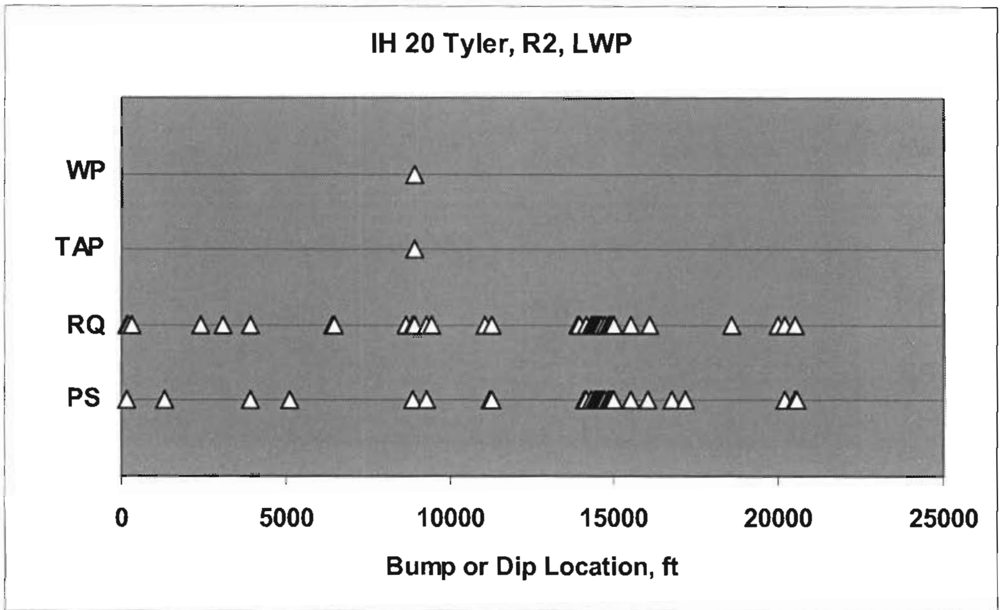

Figure 22. Summary of Results for IH 20, Tyler, Lane R2, Left Wheel Path.

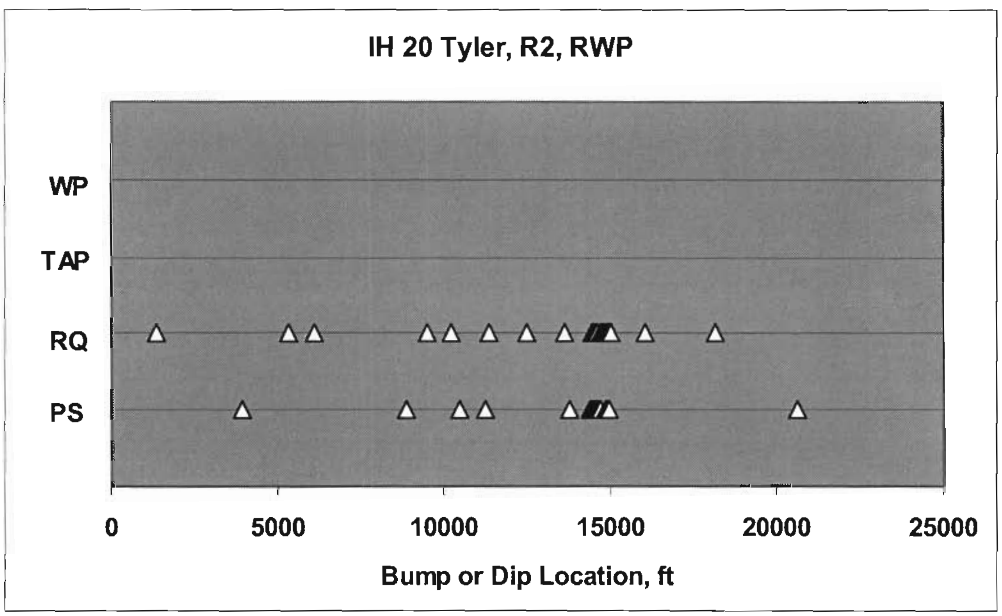

Figure 23. Summary of Results for IH 20, Tyler, Lane R2, Right Wheel Path.

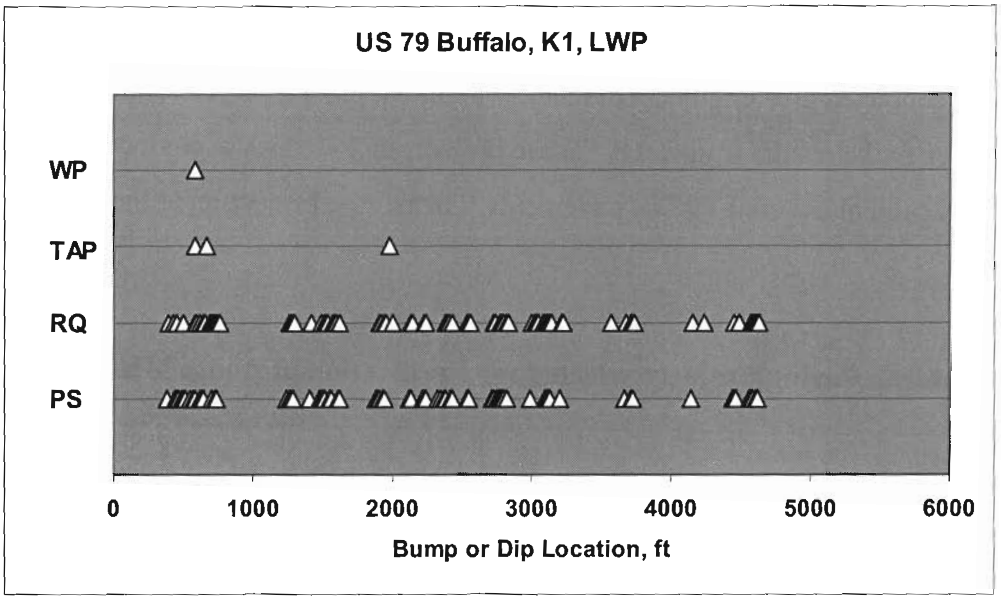

Figure 24. Summary of Results for US 79, Buffalo, Lane K1, Left Wheel Path.

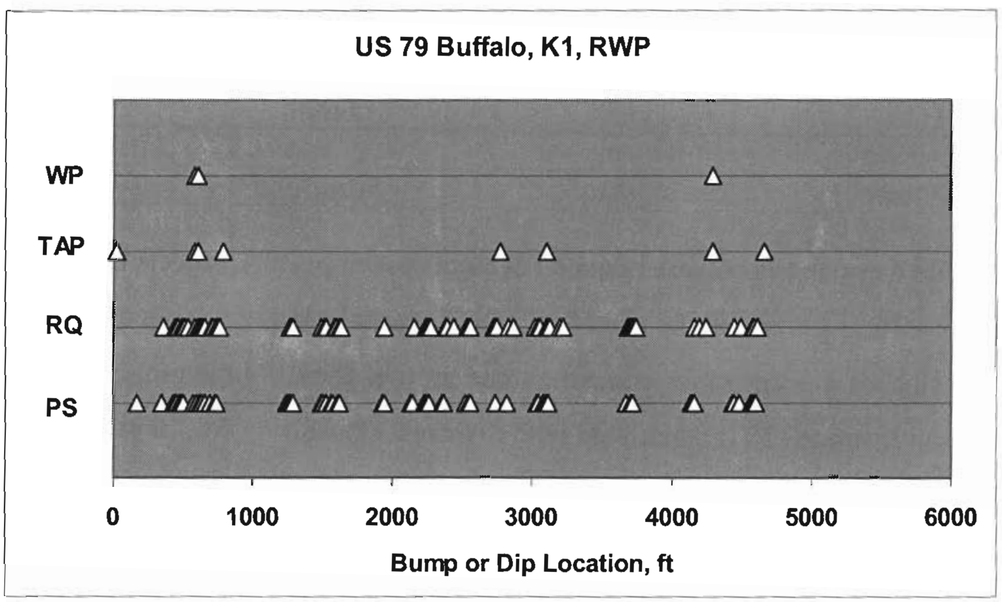

Figure 25. Summary of Results for US 79, Buffalo, Lane K1, Right Wheel Path.

FURTHER FIELD VERIFICATIONS OF TAP

Researchers contacted area engineers to identify potential paving projects, and selected ten projects to verify the results from TAP. These projects included six asphalt concrete (AC) and four Portland cement concrete (PCC) pavements. The paving project locations are shown in Table 2.

Table 2. Paving Projects Selected for Verification of Bump Methodology.

Highway and City	District	County	Pavement Type
US 59 Shepherd	Lufkin	San Jacinto	AC
US 287 Corrigan	Lufkin	Polk	AC
FM 1093 Fulshear	Houston	Fort Bend	AC
US 90 Rosenberg	Houston	Fort Bend	AC
FM 1463 Katy	Houston	Fort Bend	AC
US 77 Waco	Waco	McLennan	AC
US 79 Rockdale	Bryan	Milam	PCC
IH 20 Tyler	Tyler	Smith	PCC
US 79 Buffalo	Bryan	Leon	PCC
FM 1093 Katy	Houston	Fort Bend	PCC

Inertial profile measurements were made on each of the ten paving projects listed in Table 2. Scheduling conflicts prevented the use of a TxDOT inertial profiler to collect the data, particularly since it was desirable to use the same profiler for all of the projects. Thus, Texas Transportation Institute (TTI) contracted with Dynatest Consulting Inc. to perform all of the inertial profile testing (Figure 26). Prior to data collection, the Dynatest profiler was verified by TTI at the Ride/Rut Facility.

Researchers analyzed all of the inertial profile data with the TAP which identified bumps greater in height than 150 mils and their locations. TAP was subsequently refined to only reports bumps greater than 150 mils. Researchers then scheduled traffic control with the local maintenance offices and performed walking profile measurements with the equipment shown in Figure 27 in the pavement locations where bumps were identified by TAP.

Figure 26. Dynatest Consulting Inc. Preparing to Collect Inertial Profile Data on US 77 in Waco.

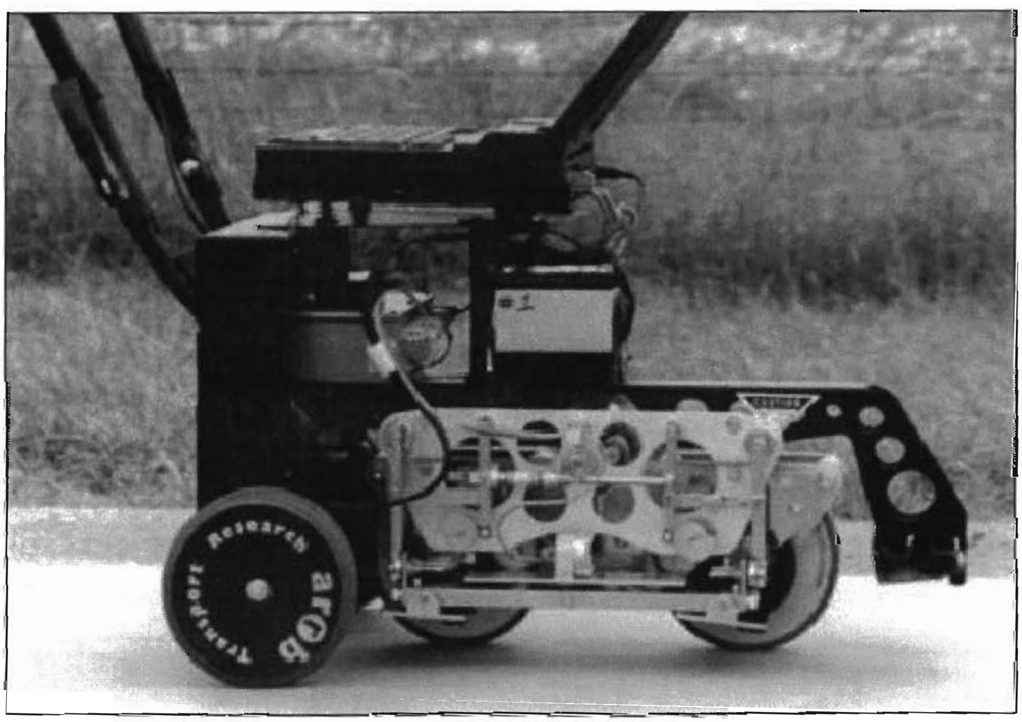

Figure 27. TTI's Walking Profiler Used to Verify Bumps Identified from the TAP Analysis of the Inertial Profile Data.

APPENDIX:
COMPARISONS OF NSI AND IRI ON 2006 PMIS DATA

Several corrections to NSI had been previously made because of the data set ranges that would occasionally result in a bad NSI number. The original NSI equation given below could result in NSI readings that were imaginary or greater than 5.0.

$$\text{PSI} = 5\, e^{-\sqrt{\alpha P}}$$

Where: PSI denotes the predicted PSR and αP can be described below as,

$$\alpha P = \alpha_1 P_1 + \alpha_2 P_2 + \ldots + \alpha_8 P_8$$

and where each P term represents a power spectrum for each frequency component. The set of α coefficients are derived from the regression analysis.

To account for these cases, the equation was modified so that the square root of the P values was first obtained before computing the sum of the products and provisions made to insure the result would not be negative. During Project 5-4479, an additional correction was needed in computing the Fourier components to account for the different data spacing of the profiles collected by non-TxDOT profilers. The original regression was then rerun with the new model to compute the model coefficients with the original 4901 project data. UTA provided TxDOT with a revised version of NSI. Using this version and the IRI program, the IRI and NSI were computed for 1,510,294, 0.1 mile sections from 25 Districts from profiles obtained during the 1996 PMIS data collection. Recall that the larger the IRI the rougher the section and the smaller the NSI number. In order to better compare the relationships between IRI and NSI or SI, the IRI readings were converted from inches per mile to mm per meter. Previous rating sessions have shown that an estimate of the associated SI (for IRI values greater than 1) can be expressed as SI = 6 – IRI. This estimate is useful in sorting through the large amount of data. About 2 percent of the data were bad because of urban traffic, start ups, stopping, and other urban traffic conditions. It also could reflect some operator or equipment errors. The IRI, NSI, and SI readings were computed from all profiles including these areas. The real time IRI and SI reports that are provided to PMIS automatically discard these areas. Thus, when re-computing the IRI and SI readings from the complete set many readings are bad. Roads with an IRI of 6 or greater or SI (or NSI) readings 0.5 or less typically reflect these cases, or at least are not values that should be obtained on the state's highway network. The data were filtered so that only those sections with IRI and the corresponding NSI values within these two ranges were included. The results are given for all sections in Table 3. Figure 28 provides the resulting plots for District 19 for SI versus NSI for the cases where IRI is 6 or less. Figure 29 provide a plot of IRI versus NSI only for the cases where NSI is greater than 0.5 and IRI is less than 6. Similar plots were computed for all districts. The additional plots were not included due to the additional space but illustrate the similar cluster patterns.

Table 3. IRI and NSI Comparisons

District	Count	(IRI < 6)	(NSI > 0.5)	(IRI<6 & NSI>0.5)	(IRI<6 & NSI>0.5) / Count
Dist1.txt	67038	66224	66775	66029	**0.9849**
Dist2.txt	66472	64255	65152	63308	**0.9524**
Dist3.txt	58841	58015	58512	57787	**0.9821**
Dist4.txt	79656	79255	79523	79156	**0.9937**
Dist5.txt	110852	109671	110301	109287	**0.9859**
Dist6.txt	74127	73548	73910	73420	**0.9905**
Dist7.txt	64098	63669	63909	63572	**0.9918**
Dist8.txt	76816	75883	76414	75615	**0.9844**
Dist9.txt	68751	67371	68126	66987	**0.9743**
Dist10.txt	74279	72881	73686	72439	**0.9752**
Dist11.txt	37616	37244	37504	37179	**0.9884**
Dist12.txt	67639	63929	65362	62274	**0.9207**
Dist13.txt	67572	66776	67347	66624	**0.9860**
Dist14.txt	43769	42927	43346	42613	**0.9736**
Dist15.txt	71758	70822	71306	70464	**0.9820**
Dist16.txt	62020	61384	61854	61258	**0.9877**
Dist17.txt	67247	66644	67084	66528	**0.9893**
Dist18.txt	72790	70896	71866	70204	**0.9645**
Dist19.txt	20434	20410	20422	20400	**0.9983**
Dist20.txt	43207	42754	43023	42616	**0.9863**
Dist21.txt	45229	43987	44680	43549	**0.9629**
Dist22.txt	47672	47332	47555	47267	**0.9915**
Dist23.txt	55128	54833	55026	54764	**0.9934**
Dist24.txt	40953	40311	40802	40195	**0.9815**
Dist25.txt	26330	26247	26317	26237	**0.9965**
Total	1510294	1487268	1499802	1479772	

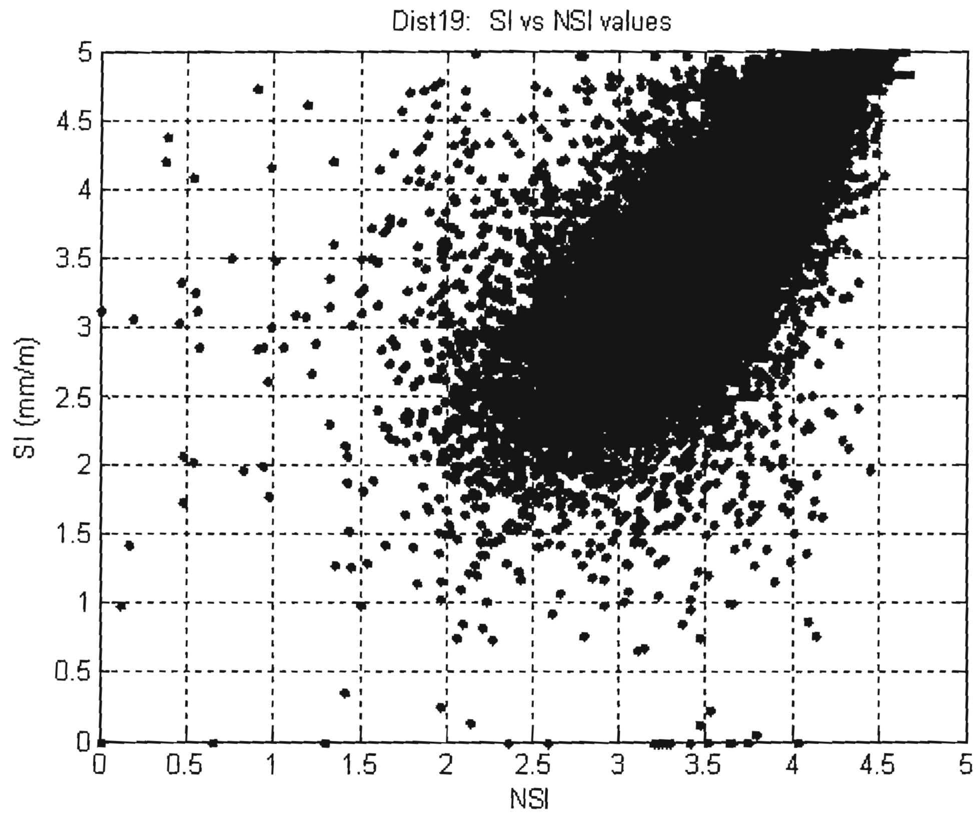

Figure 28. SI vs NSI for IRI Less Than 6 for District 19.

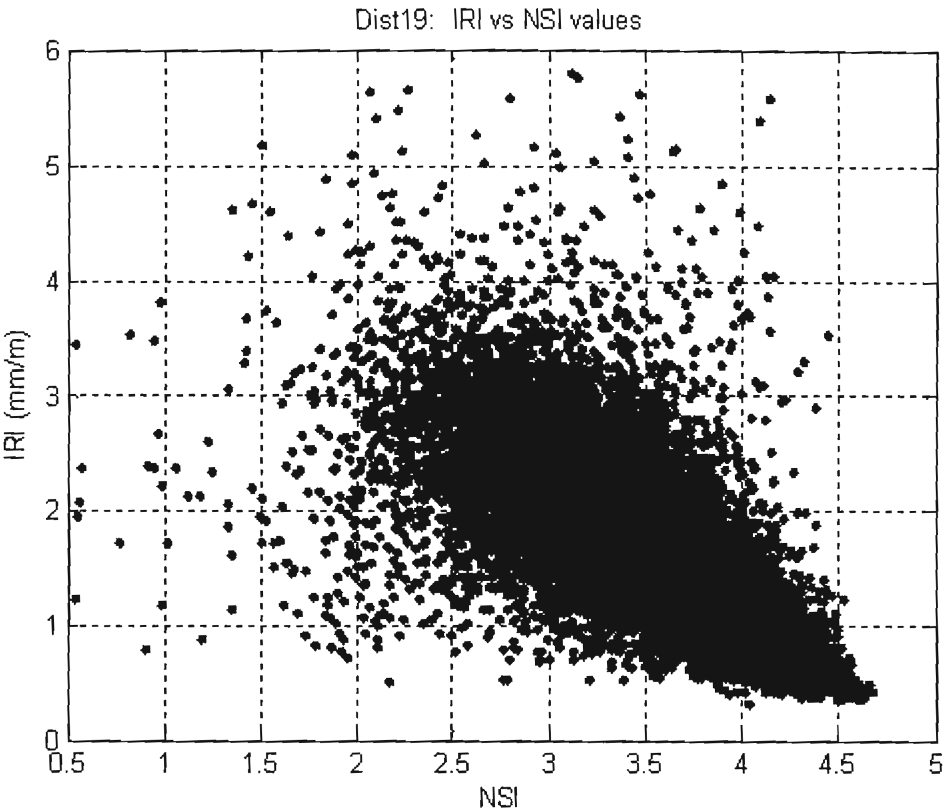

Figure 29. IRI vs NSI for District 19.