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TRANSITION FROM MANUAL TO AUTOMATIC RUTTING MEASUREMENTS: Effect on Pavement Serviceability Index Values

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TRANSITION FROM MANUAL TO AUTOMATIC RUTTING MEASUREMENTS: EFFECT ON PAVEMENT SERVICEABILITY INDEX VALUES

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PREFACE

The research reported herein aimed to develop a procedure or protocol to transition from using rutting ratings from manual surveys to using automated rut depth measurements for calculating the New Mexico Department of Transportation's (NMDOT) Pavement Serviceability Index (PSI). One recommended approach and an alternative procedure are presented. One of the main motivations of NMDOT to implement this change was to increase the safety of distress survey crews and the traveling public by eliminating the need for performing manual rut depth measurements in the roadway during the annual manual surveys. The NMDOT was also interested in avoiding duplication of efforts resulting from collecting rut depth data by two different methods.

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ABSTRACT

The Pavement Serviceability Index (PSI) is used by New Mexico Department of Transportation (NMDOT) to express the serviceability level of a pavement section at the network level. The PSI is calculated with distress ratings (including rutting) and roughness data. Currently, rut depth data collected with two NMDOT-owned 3-point profilometers are not used as an input in the calculation of PSI values. The main goal of this project was to develop and recommend a procedure to substitute automated rut depth for rutting ratings from manual surveys. For planning and reporting purposes, it is important for NMDOT to maintain the consistency of the methods and data used to calculate PSI values and to document any change implemented so that comparisons of current and past conditions and performance evaluations of the network can be made. The transition from using manual survey ratings to automated rut depth measurements should introduce the smallest possible difference in the calculated PSI values and the overall condition rating of the highway network. Three procedures or approaches are presented and discussed. Regression analyses were applied to the rut depth and PSI data. Recommended Approach A proposed preserving the current PSI formulation and factors and converting the automated rut depth data into equivalent rutting ratings. Alternative Approach B proposed minor modifications to the PSI formulation. A third approach (Approach C) was considered and evaluated, but was not recommended. Results of the statistical tests performed on the data and results are also presented. The ratings from manual surveys and automated rut depth data were compared with detailed measurements of transverse profiles to evaluate the data from these two methods. This report includes an implementation plan for the recommended and alternative approaches.

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Additionally, Robert S. Young provided background and historical information on the use of the rut depth and distress data to determine pavement condition indexes, pavement serviceability index and distress data of previous years, and contact information of key personnel as needed throughout the duration of the project. Tito T. Medina provided the available automated rut depth and roughness data files, information about measurement procedures and NMDOT equipment, and information about issues related to the data quality. Shahzad Shah and Mark Gallegos assisted in transferring data files and accessing computer codes used to compute the pavement serviceability index, and provided information about the data formats.

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INTRODUCTION

The Pavement Serviceability Index (PSI) is used by New Mexico Department of Transportation (NMDOT) to express the serviceability level of a pavement section at the network level. The PSI is calculated with distress ratings (including rutting) and automated roughness data. Currently, the rut depth data collected by NMDOT using two 3-point profilometers are not used to calculate PSI values or in any other pavement condition index. These automated rut depth data are collected simultaneously with roughness data. The main goal of this project was to develop and recommend a procedure to replace rutting ratings from manual surveys with automated rut depth data for the calculation of the NMDOT's PSI.

For planning and reporting purposes, it is important for NMDOT to maintain the consistency of the methods and data used to calculate PSI values and to document any change implemented so that comparisons of current and past conditions and performance evaluations of the pavement network can be made. The transition from using rutting ratings from manual surveys to automated rut depth data should introduce the smallest possible error in the calculated PSI values and the overall condition rating of the highway network.

This report includes a summary of the literature review of information relevant to the project and the results and observations of a survey of 22 State Departments of Transportation (DOTs). This survey focused on learning about the state of practice in these agencies regarding rutting measurements and data collection and use. The report also describes the comparisons of rutting ratings from manual surveys and automated rut depth data with detailed measurements of transverse profiles to evaluate the data from these two methods. Finally, the results of the regression analyses applied to the rut depth and PSI data are presented and discussed. In addition, this report includes an implementation plan for recommendations of the project.

LITERATURE REVIEW

RUTTING – DEFINITIONS AND CAUSES

A rut is a longitudinal depression that can occur on the surface of flexible pavements (also called asphalt pavements) along the wheelpaths. Ruts are permanent deformations of the pavement structure (1). Uplift, or shoving, might occur along the sides of the rut. Rutting is considered a critical distress in flexible pavements because it can represent a serious safety hazard for drivers (2) and is frequently associated with other important pavement distresses. Ruts filled with water can cause vehicle hydroplaning; rutting can also be hazardous because ruts tend to pull a vehicle towards the rut path as it is steered across the rut. The transverse profile of a rutted pavement can take different shapes or geometries; however, rutting is generally illustrated as in Figure 1.

Some negligible rutting may occur in hot mix asphalt (HMA) surfaces due to densification under continuous traffic loads after the initial compaction during construction. Some of the possible causes of excessive rutting include (3):

- Permanent deformation in any of the pavement layers or subgrade, generally due to consolidation, poor compaction, or lateral movement of the materials due to traffic loads.
- Heavy loading on saturated unstable granular base and subbase during spring thaw periods.

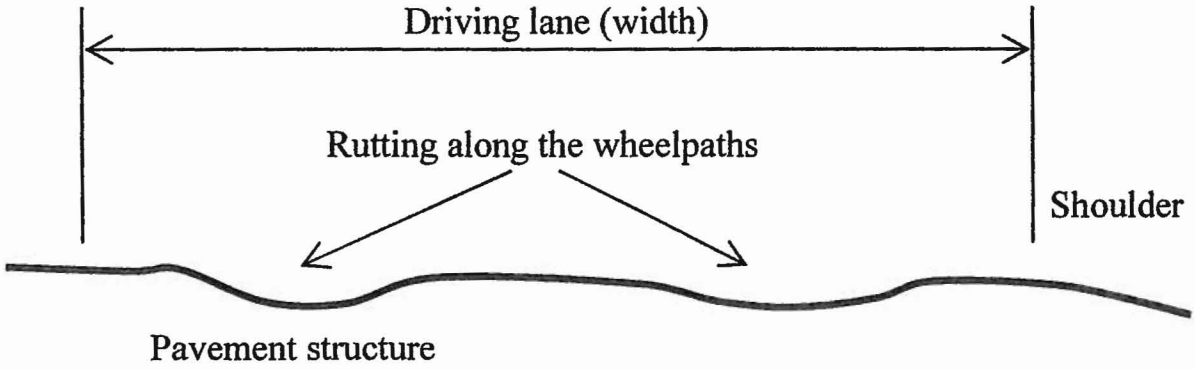


FIGURE 1 Illustration of a Typical Transverse Profile of a Rutted Pavement (not Drawn to Scale)

- Plastic movement of the asphalt mix due to high temperature (hot weather), inadequate compaction during construction, low binder viscosity or high asphalt content, excessive filler material or too many rounded particles in the coarse and fine aggregates of the HMA, inadequate lateral support from unstable shoulder materials, or permanent deformation of an overstressed subgrade.

The plastic deformation in the HMA layer, generally due to improper mix design, is the most common cause of rutting, especially in routes with heavy traffic loads and high tire pressures (4).

RUT DEPTH DATA AND MEASUREMENTS

Definitions of Rut Depth

Rut depth has been defined differently depending on the method or equipment used to measure or rate it. Rut depth is the vertical distance (or depth) from a straightedge or rut bar, laid transversely across the wheelpath, to the pavement surface (Figure 2). Note that this definition does not require that the straightedge or rut bar be positioned horizontally on the pavement surface. The rut depth is generally measured approximately in the center of the rut or depression. The characteristics of a straightedge may vary with the user, agency or country.

Rut Depth Measurements

Depending on the method or technique used to measure the rut depth, the distress of rutting may be expressed in area of the pavement (in square feet or square meters) affected by a given severity level of rut depth (3). The *Distress Identification Manual for the Long-Term Pavement Performance (LTPP) Program* (5) recommends taking a record of rut depth measurements instead of severity levels. The LTPP Program also recommends measuring rutting with a 1.2 m straightedge to the nearest millimeter at 15.25 m (50 ft) intervals for each wheelpath for sections of the Specific Pavement Studies (SPS).

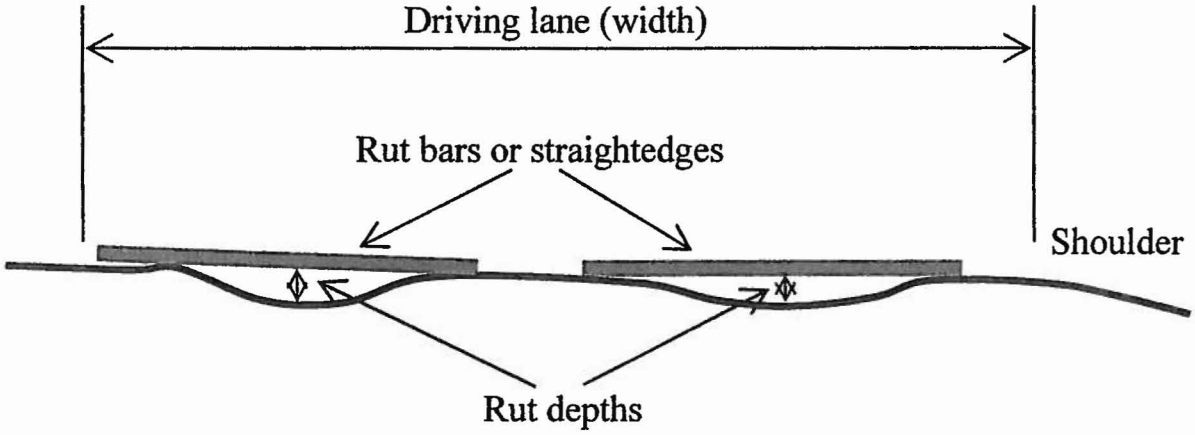


FIGURE 2 Illustration of Rut Depth as Measured with Rut Bars or Straightedges (not Drawn to Scale)

The distress due to rutting can be expressed as a deterministic value of the rut depth or as a rating of the severity and extent in a sample unit. Rut depth measurements can be made manually and automatically. Automated rut depth measurements can be done using profilers with sensors, generally mounted in vans. Manually operated profilers can also be used in smaller scale measurement projects or for calibration of more sophisticated or expensive equipment.

Manual Rut Depth Measurements

A standardized procedure to manually measure rut depth is described in detail in ASTM "*Standard Test Method for Measuring Rut-Depth of Pavement Surfaces Using a Straightedge*" (6). This standard recommends using a 1.83 m (6 ft) long straightedge (but other lengths are possible) and a gauge graduated to at least 1 mm (1/16 in.) for the rut depth measurements. According to this standard, the straightedge should be placed across the rut, perpendicular to the traffic direction, so that it rests on the pavement surface and makes contact on both sides of the rut. Sliding the straightedge along its length should not change the contact points or create a pivot point. To measure the rut depth, the measurement gauge (or ruler) should be placed between the two contact points, perpendicular to the plane formed by the bottom of the straightedge, and making contact with the pavement surface (Figure 3). The rut depth is the greatest distance measured between the bottom of the straightedge and the pavement surface.

Rut Depth Ratings

The levels of severity and extent or density of rutting in a test section have been defined differently by various agencies. An agency should decide whether to rate the extent of the predominant or the highest severity or to rate the extent of each level of severity for a given distress type. Agencies must also decide whether to estimate or measure and record the extent using either finite values or ranges of values (7). For example, the British Columbia Ministry of Transportation and Infrastructure of Canada (8) defines three severity levels: low severity level when the rut depth is less than 10 mm, moderate severity level when the rut depth is between 10 and 20 mm, and high severity level when the rut depth is greater than 20 mm. The density of

TABLE 1 Density (or Extent) Levels for Rutting According to the British Columbia Ministry of Transportation and Infrastructure of Canada (8).

Level	Description	Percent Length Affected
1	Few	< 10%
2	Intermittent	10 to 20%
3	Frequent	20 to 50%
4	Extensive	50 to 80%
5	Throughout	80 to 100%

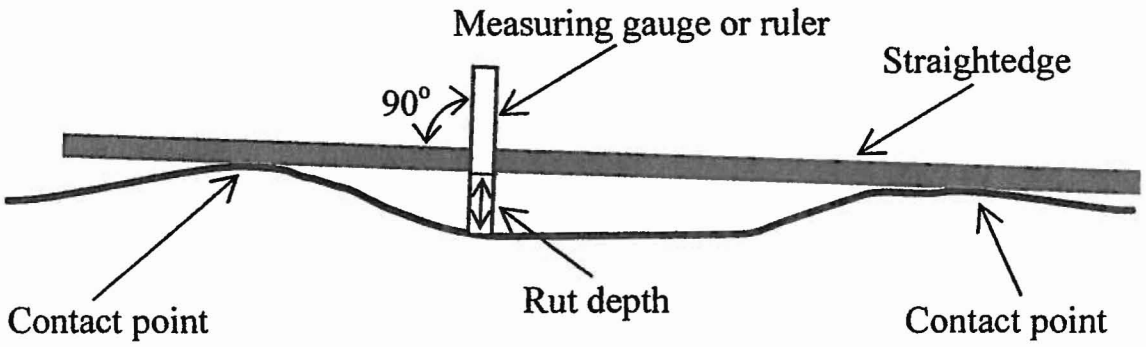


FIGURE 3 Manual Rut Depth Measurement According to the Standard ASTM E1703/E1703M-95 (not Drawn to Scale)

rutting is defined by this agency as the percent length of the two wheelpaths in the test section affected by a given density level of rutting. This agency defines five density levels as shown in Table 1.

The 1999 "*Pavement Surface Condition Manual*" of the Washington Department of Transportation (7) describes the severity as the average rut depth in the wheelpath for the section or sample. In this manual, the severity levels are: low when the average rut depth is between 0.25 and 0.5 in., medium when it is between 0.5 and 0.75 in., and high for average rut depth greater than 0.75 in.

Rut Depth Ratings from Manual Surveys in New Mexico

Since 2001 and to the time of publication of this report, NMDOT collects data for eight types of distress in flexible pavements, including raveling and weathering, bleeding, rutting and shoving, longitudinal cracking, transverse cracking, alligator cracking, edge cracking, and patching. Note that raveling and weathering are rated as a single distress type; likewise, rutting and shoving are also rated as one distress type. These data are collected during manual (walk) surveys and do not include deterministic measurements. These distress ratings are meant to be used as part of the pavement condition assessment at the network level. These distress data are in the form of

severity and extent ratings according to the NMDOT's Distress Evaluation Charts for Flexible Pavements (Appendix A).

For rating the distress of rutting and shoving, the current NMDOT protocol requires that the rut depth be visually assessed by the rater with a 1.2 m (4 ft) long straightedge or rut bar (e.g., 4 ft oak bar or aluminum level) on both wheelpaths (Figures 4 and 5). The procedure includes the following steps:

1. Facing incoming traffic, the rater walks into the driving lane and places the rut bar on the pavement surface and slides it back and forth across the rut, perpendicular to the direction of the traffic. This is done while holding the rut bar in the middle portion with the working hand.
2. The rater visually identifies the point of greatest rut depth.
3. The rater slides the fingers that hold the bar down until making slight contact with the pavement surface.
4. Maintaining the relative position of the fingers and the rut bar, the rater lightly presses the bar against the hand and lifts the bar to observe the distance between the bottom of the bar and the tip of the finger that made contact with the pavement. This indicates the rut depth.
5. The rater quickly estimates whether the rut depth is less than 0.25 in., between 0.25 and 0.5 in., between 0.5 and 1.0 in., or greater than 1.0 in.

These steps are immediately repeated in the adjacent wheelpath. A rut-bar check is done in the two wheelpaths in approximately 10 to 15 seconds. The estimated rut depths are not recorded. While evaluating a test section , the rater keeps track of the range in which the greatest estimated rut depths lie and uses this information to assess the severity and extent ratings for rutting and shoving based on the NMDOT's Distress Evaluation Charts for Flexible Pavements (Appendix A).

The NMDOT protocol requires that the rut-bar checks be done in 6 to 9 locations (both wheelpaths) throughout the test section or sample unit, if conditions are safe. The rater should visually identify the locations of greatest rut depth in the test section to perform the rut-bar

FIGURE 4 New Mexico State University (NMSU) Engineering Student Doing a Rut-Bar Check in Manual Surveys for NMDOT (NMSU Photo by Darren Phillips)

FIGURE 5 Rut-Bar Check with a 4 ft Aluminum Level in Manual Surveys in New Mexico (NMSU Photo by Darren Phillips)

checks. The traffic is not stopped or controlled during these manual surveys. A reduced number of rut-bar checks or windshield surveys are acceptable in locations that do not offer safe conditions for the rater and travelling public. In the NMDOT Pavement Distress Evaluation Program, the test sections are 161 m (0.1 mile) long.

The possible values of severity and extent ratings are 0, 1, 2 and 3. The criteria to rate the severity and extent of rutting and shoving are given in the NMDOT's Distress Evaluation Charts for Flexible Pavements (Appendix A). The possible severity ratings for rutting and shoving and the corresponding criteria of rut depth are:

- Rating = 0: Rut depth less than 0.25 in.
- Rating = 1 (Low severity): Rut depth between 0.25 in. and 0.5 in.
- Rating = 2 (Medium severity): Rut depth between 0.5 in. and 1.0 in.
- Rating = 3 (High severity): Rut depth greater than 1.0 in.

The possible extent ratings and the corresponding criteria of percent area of the test section that exhibits a given severity level of rutting and shoving are:

- Rating = 0: Severity rating for rutting and shoving is 0.
- Rating = 1 (Low extent): From 1% to 30% of the test section.
- Rating = 2 (Medium extent): From 31% to 60% of the test section.
- Rating = 3 (High extent): 61% of the test section or more.

When the greatest rut depth in a test section is less than 0.25 in., the severity and extent for the distress of rutting and shoving are rated as zero. In the current NMDOT's distress rating protocol, the severity rating "rules" or controls the extent rating. This means that the extent rating is assessed based on the area of the sample unit that shows the highest severity rating for the given distress type.

Manually Operated Profiler

The Face Company Dipstick® profiler can be used when the amount of pavement profiles needed is relatively small or to calibrate more sophisticated or expensive profilers. It can be used for transverse and longitudinal pavement profiles. The Face Company Dipstick® profiler is manually operated and generally requires two people for data collection, an operator and a data recorder. It consists of a pendulum-type inclinometer inside a case supported by two feet located 305 mm (12 in.) apart at the two ends of the instrument (9). Two digital displays read the relative elevations of the feet with respect to each other. The operator places the Dipstick® at the end of a pre-marked transverse profile for the first reading. Subsequent readings are recorded sequentially as the operator moves the instrument along the section alternately pivoting the instrument about each foot.

Software analysis provides a profile accurate to ± 0.0127 mm (± 0.0005 in.) (9). The total accumulated error due to the procedure and equipment using the Dipstick® is established by a closed loop survey, which consists of performing forward-and-return runs along the transverse profile and calculating the error. Instruments such as the Dipstick® are generally used to measure a profile for calibration of more complex instruments (5).

For all LTPP sections except for SPS sections, the LTPP Program recommends to measure the transverse profile with a Dipstick® profiler at 15.24 m (50 ft) intervals. The protocol for Dipstick® profile measurements is described in the report by J. S. Miller and W. Y. Bellinger (5). However, profile measurements on General Pavement Studies (GPS) and SPS sites that cannot be obtained using the LTPP profiler should be done using the Dipstick® (5).

Sensor Profilers

More sophisticated profiling systems use either contact sensors or non-contact sensors and are generally mounted in vans. The newer systems are non-contact type and use probes or transducers, with either acoustic (ultrasonic) or light (laser) sensors, to measure differences in the pavement surface. Some systems combine different types of sensors for simultaneous measurements of profiles, one for each wheelpath and one for the center lane. These profiles are used to calculate (by computer) a mathematical measure of roughness and an estimate of rutting at specified intervals along the roadway.

COMPARISONS OF MANUAL AND AUTOMATED RUT DEPTH MEASUREMENTS – PRIOR STUDIES

Most common profilometers are equipped with 3, 5 or more infrared or laser sensors for measuring longitudinal and transverse profiles. A survey reported by the National Cooperative Highway Research Program (NCHRP) indicated that 46 agencies (states, Canadian provinces, or FHWA) that responded the survey collected automated rut depth measurements, generally simultaneously with roughness data (10). A few US states reported that they collected or received automated rut depth data but they did not use it. This was the case of NMDOT. At the time of this NCHRP survey, 16 agencies used 3-sensor profilers, 16 agencies used 5-sensor profilers, and 14 agencies used equipment with more than 5 sensors, generally 31 sensors (10). In practice, few agencies actually used all the sensors available in 37-sensor profilers (10).

Few systematic studies have been done to compare manual and rut depth measurements or to determine the accuracy of automated or electronic rutting measurements. One of the most comprehensive projects for this purpose was carried out in New Zealand (1). An important conclusion of this study was that the measurement error (bias) increases as the number of sensors increases. However, the greater the number of sensors, the greater the probability of locating the high and low points, so the lower the error (1). In addition, profilometer rut depth measurements always underestimate the true rut depth (up to about 15%) because of the equally spaced sensor configurations in the profilometers (1). For the measured rut depth to correspond to the actual rut depth, the sensors would need to record the high and low points in each wheelpath. This is impossible for sensors installed at discrete intervals.

The 3-sensor profiler, or 3-point method, has received considerable criticism (2, 10) for not providing repeatable and accurate rut depth measurements. An LTPP study showed that calculations of rut depth from 3-point and 5-point rut bars do not necessarily provide accurate rut depth data compared with the wire-line method or model, and concluded that a year-to-year consistency may be difficult to obtain due to the high variability of these measurements (2). The ASSHTO provisional standard (11) requires a minimum of 5 sensors. However, some studies show that at least 9 sensors are needed for accuracy. For example, a study in Texas compared rut depths determined at ten sites with a 5-sensor and 9-sensor profilometers with rut depths measured manually using 1.2 m and 1.8 m long straightedges and a Dipstick® (12). This instrument was also used to collect transverse profile data. The correlation between rut depths determined from a 5-sensor rut bar and manual measurements was 0.4. This very low value indicates that 5-sensor rut bars or less may not be accurate enough for rutting, and that a minimum of 9 sensors would be required for measuring rutting with sufficient accuracy for pavement management. The sensor configuration, the lateral placement of the vehicle, and the transverse location of the rut bar have considerable influences on the accuracy of the measurements and rut depth calculations (2, 13).

NMDOT'S PAVEMENT DATA COLLECTION

The NMDOT's Annual Pavement Evaluation Program collects pavement distress, rutting and roughness data along highways and interstate routes throughout New Mexico. Distress and rutting ratings are collected in manual (walk) surveys in approximately 15,500 test sections. Two 3-point profilometers are used to obtain roughness and rutting data in selected National Highway System (NHS) and non-NHS routes throughout the state. Over 97% of the state-maintained pavements in New Mexico are asphalt pavements.

PAVEMENT DISTRESS AND RUTTING RATINGS

The NMDOT has systematically collected pavement distress data for pavement management purposes since the 1980s. Until 2000, the NMDOT's manual surveys consisted of rating 24 distress types in flexible (asphalt) pavements and 17 distress types in rigid (concrete) pavements. In 2001, NMDOT did not collect distress data, revised the distress rating protocol, and consolidated the distresses of flexible and rigid pavements into 8 distress types each. The NMDOT resumed distress data collection in 2002; the NMDOT's "*Distress Evaluation Chart for Flexible Pavements*" used since 2002 to the present is shown in Appendix A. Since 2006, university students from New Mexico State University (NMSU) and the University of New

Mexico (UNM) have worked as raters in the manual distress surveys to evaluate pavement distresses (including rutting) for NMDOT in approximately 15,500 test sections along highways and non-highway routes throughout New Mexico.

The test sections are 161 m (0.1 mile) long, generally starting or ending at each highway milepost, and are spaced at 1.6 km (1 mile) intervals. The survey crews are composed of two raters. A crew travels to the assigned location or milepost and drives the vehicle off the shoulder to a safe parking position, with the vehicle emergency flash lights, strobe and light bar turned on. After safely parking, the raters get out of the vehicle with the equipment and materials necessary for the evaluation and safety and walk 161 m (0.1 mile) along the roadway (or on the shoulder when possible) starting at the milepost marker when the test section is in the positive direction or ending at the milepost marker when the test section is in the negative direction. The crew performs a preliminary evaluation by observing the conditions of the pavement surface and identifying the types of distresses present.

Sometimes the location of the test sections has to be adjusted and moved 161 m to 323 m (0.1 to 0.2 miles) forward or backward, at the discretion of the raters, when unsafe or hazardous conditions exist or due to the presence of a bridge or ramp within the length of the test section to be evaluated. Once the raters arrive to the end of the test section, one of them starts the evaluation (by rating the severity and extent of each distress type) and the other watches for traffic and potential hazards on the road, while both walk back toward the starting point and their vehicle. When road conditions are safe, crews make manual rut measurements in each pavement section using a rut bar or straightedge (Figure 6).

FIGURE 6 Two NMSU Engineering Students Doing Distress Rating Manual Surveys for NMDOT (NMSU Photo by Darren Phillips)

AUTOMATED RUT DEPTH AND ROUGHNESS

The Pavement Evaluation Section of NMDOT collects automated data of pavement roughness and rut depth in interstate and other highway routes in New Mexico. In the 1980s, NMDOT used

a Tech West Photo Log to measure pavement roughness (14). From 1991, roughness and rutting data were collected with an Automatic Road Analyzer (ARAN) van. In 2000, NMDOT started measuring roughness and rutting data with a K. J. Law Dynatest T6600 High Speed Profilometer mounted on a van (Figure 7). A second T6600 Profilometer and van were acquired in 2003 for the data collection activities (14). Roughness data are collected according to the "*Standard Practice for Determination of International Roughness Index (IRI) to Quality Roughness of Pavements*" (15). This equipment uses three infrared displacement sensors and two precision accelerometers. The sensors are set at 68 in. The rut depth data are stored in "raw data" files at user-defined intervals, such as 0.5, 1, 2 or 3 ft. Using the raw data, the rut depth is currently averaged and reported every 161 m (0.1 mile).

FIGURE 7 One of the Two NMDOT-Owned Ford E350 Vans with Mounted K. J. Law Dynatest T6600 Inertial High Speed Profilometers (14)

NMDOT'S PAVEMENT SERVICEABILITY INDEX (PSI)

The NMDOT uses the Pavement Serviceability Index (PSI) as a measure of the pavement condition, for both flexible and rigid pavements. This index ranges from 0 (very poor condition) to 5 (very good condition). (Even though the equations presented in this section apply to rigid and flexible pavements, the focus of this research is in flexible pavements.) The NMDOT's PSI is currently calculated from pavement roughness data and distress ratings (including rutting), through one of the following empirical expressions:

$$PSI = 0.041666\,X, \quad \text{if } X \leq 60 \tag{1}$$

or

$$PSI = [0.0625(X - 60)] + 2.4999, \quad \text{if } X > 60 \tag{2}$$

where X is given by

$$X = 100 - \left[\frac{0.6(\mathrm{IRI} - 25) + (0.4\mathrm{DR})}{2.9} \right] \tag{3}$$

where IRI is the International Roughness Index and DR is the Distress Rate defined as

$$\mathrm{DR} = \sum_{i=1}^{n} \left[(\text{Severity Rating}_i)(\text{Extent Factor}_i)(\text{Weight Factor}_i) \right] = \sum_{i=1}^{n} (\mathrm{DR}_i) \tag{4}$$

in which i denotes one of the eight types of distresses of flexible or rigid pavements ($n = 8$), and DR_i is the component of the distress rate (DR) value corresponding to the distress type i for a given pavement section. The factors for the extent ratings are given in Table 2. The weight factors used in Equation 4 for flexible pavements are given in Table 3 (14). Note that "rutting and shoving" is the distress type with the third highest weight factor in Equation 4 for the calculation of PSI values. The extent factors and weight factors for the eight distress types rated by NMDOT at the time of the publication of this report are provided in Appendix B.

TABLE 2 Factors for Extent Ratings for Flexible Pavements.

Extent Rating for Rutting and Shoving	Factor
0	0
1	0.5
2	0.8
3	1.0

TABLE 3 Weight Factors for Distresses in Flexible Pavements (14).

Distress Type	Weight Factor
Raveling and Weathering	3
Bleeding	2
Rutting and Shoving	14
Longitudinal Cracking	20
Transverse Cracking	12
Alligator Cracking	25
Edge Cracks	3
Patching	2

The NMDOT ranks the condition of the highway pavements in New Mexico based on the calculated PSI values (Table 4). The higher the PSI value, the better the pavement condition. The NMDOT considers that interstate highways with PSI lower than 3.0 are in deficient condition and those with PSI of 3.0 or greater are in non-deficient condition. For non-interstate highways, the limiting PSI value between deficient and non-deficient conditions is 2.5. Pavement sections that are unpaved or for which data are missing are assumed to be deficient (14).

Another pavement condition index calculated and reported by NMDOT is the Ride Quality Index (RQI). The values of RQI range from 0 to 5; a higher RQI value indicates a smoother pavement (14). The RQI is calculated as

$$RQI = 5\exp^{(-0.004104\ IRI)} \tag{5}$$

A number of different regression equations to calculate pavement condition or serviceability indices used by other agencies (3, 16, 17, 18) can be found in the literature.

TABLE 4 NMDOT's Ranking of Pavement Condition Based on PSI Values at the Network Level (14).

New Mexico PSI Range	Pavement Condition		
	Condition Ranking	Interstate Highways	Non-Interstate Highways
$4.0 \leq PSI \leq 5.0$	Very Good	Non-deficient	Non-deficient
$3.0 \leq PSI < 4.0$	Good	Non-deficient	Non-deficient
$2.5 \leq PSI < 3.0$	Fair	Deficient	Non-deficient
$1.0 \leq PSI < 2.5$	Poor	Deficient	Deficient
$0.0 \leq PSI < 1.0$	Very Poor	Deficient	Deficient

SURVEY SUMMARY OF STATE OF PRACTICE OF RUT DEPTH DATA COLLECTION AND USE

A survey was performed to learn about the state of practice of rut depth data collection or measurements and use by state Departments of Transportation (DOTs). Based on the scope of this project, the survey did not intend including all the state DOTs. The survey contained 13 main questions and was distributed to pavement management engineers of a sample of state DOTs in the U.S.A. during fall of 2008 and spring of 2009. Most of the survey questions and responses were given by e-mail but some contacts and interviews were made by telephone (notes were kept for the records). The survey questions are provided in Appendix C. The survey responses from 22 states, including New Mexico, and the contact information of the responders are provided in Appendix D. Some relevant observations and information extracted from the survey results are presented next.

For the state DOTs surveyed in fall 2008 and spring 2009, the following observations and statistics were drawn:

- All the state DOTs in the survey performed some type of measurements or visual estimates of rut depth. About 14% of the agencies collected both automated and manual rutting data; one agency (5%) collected manual rut depth data only; and one agency (5%) estimated rut depth through windshield surveys. The remaining 76% of the agencies collected automated rut depth data only (Figure 8).
- About 55% of the surveyed agencies used their own state DOT personnel in the rutting data collection, and 27% contracted out this work completely (Figure 9). About 18% of the agencies used both DOT personnel and contractors to collect rutting data, especially when they collected rutting information manually and automatically.
- Less than half of the agencies (40%) collected rutting data annually and 23% collected rutting data biennially (every two years) in their entire state-maintained highway network (Figure 10). About 32% of the agencies collected rutting data annually in selected routes, generally National Highway System (NHS) routes, and biennially in the remaining highways, generally non-NHS routes. One agency (5%) collected rutting data in its highway network in an 18 month cycle (Figure 10).
- Among the agencies that collected automated rutting data, the type of profiler or sensors, the number of sensors and the frequency of the data storing and reporting or averaging varied significantly.
- Two agencies did not collect roughness data as part of their pavement management system. One of the agencies had planned to start collecting automated roughness data in 2009. One agency (5%) estimated roughness and rutting visually in windshield surveys.
- Agencies used rutting data or ratings in many different ways and levels in their pavement management system.
- No consistency was found regarding the type or definition of the pavement condition indexes used at the network level by the surveyed agencies. The indexes varied from agency to agency, and most of the indexes were developed for/by the agencies to meet their own standards or requirements. However, most agencies used pavement distresses, rutting and roughness information as input data to calculate or deduct their pavement condition indexes or distress rate. One agency reported not using an index for assessment of pavement condition.

COMPARISON OF RUT DEPTH AUTOMATED DATA AND MANUAL RATINGS WITH DETAILED PROFILE MEASUREMENTS

As part of this research, a series of detailed transverse profiles were carefully measured manually in selected test sections of flexible pavement. Rut depth values and ratings were determined from the transverse profiles. This information was used to assess the accuracy of the automated rut depth data collected by NMDOT and to compare it with the rutting and shoving ratings obtained in manual surveys. The manual profile measurements and distress ratings were done in May of 2009. Distress ratings (including rutting) from previous years were also available for these test sections. During the field measurements, the traffic in the test sites was limited to a single lane so that crews could work safely on the other lane. Traffic control was provided by the Maintenance Patrol of District 1, based in Las Cruces, New Mexico (NM).

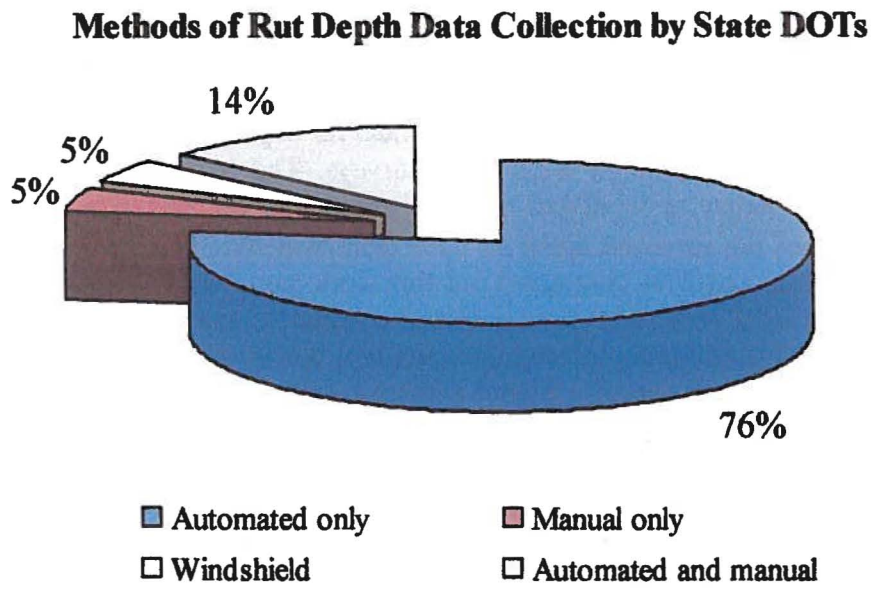


FIGURE 8 Methods of Rut Depth Data Collection by Surveyed State DOTs

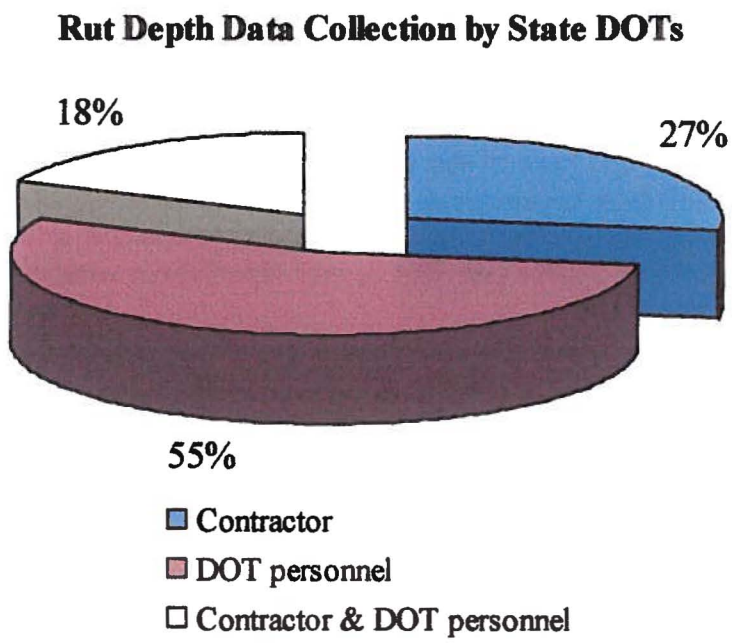


FIGURE 9 Type of Personnel that Performed Pavement Condition Data Collection for the Surveyed State DOTs

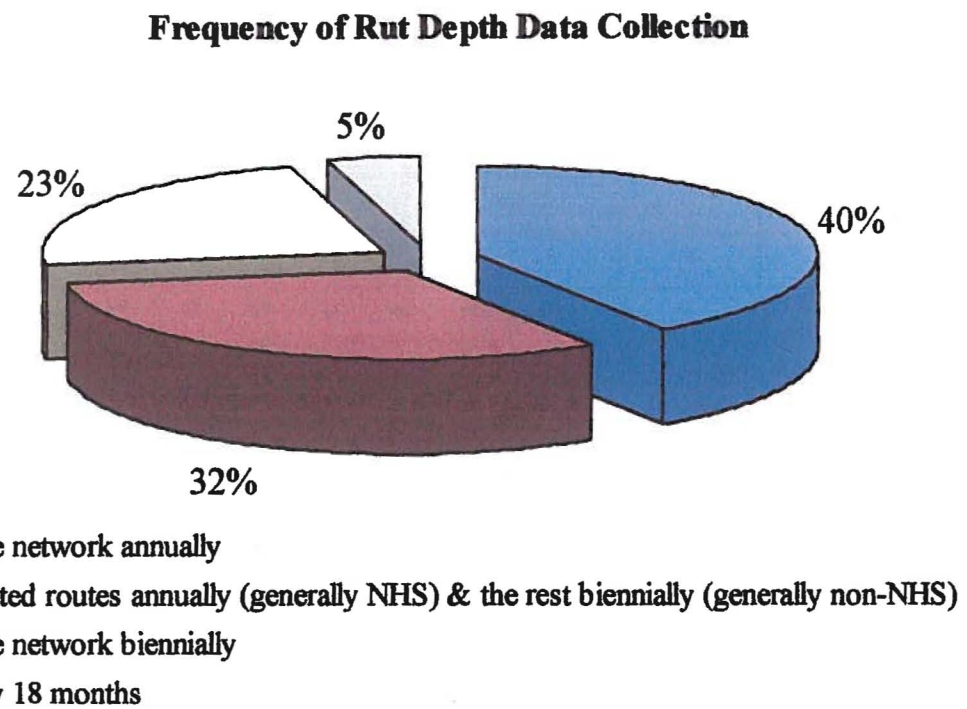


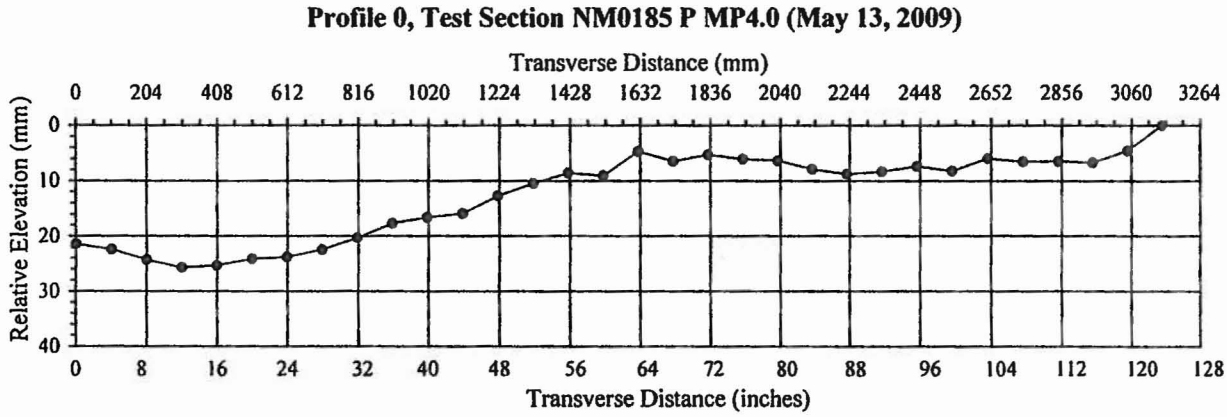
FIGURE 10 Frequency of Rut Depth Data Collection at the Network Level by Surveyed State DOTs

TEST SECTIONS AND TRANSVERSE PROFILES

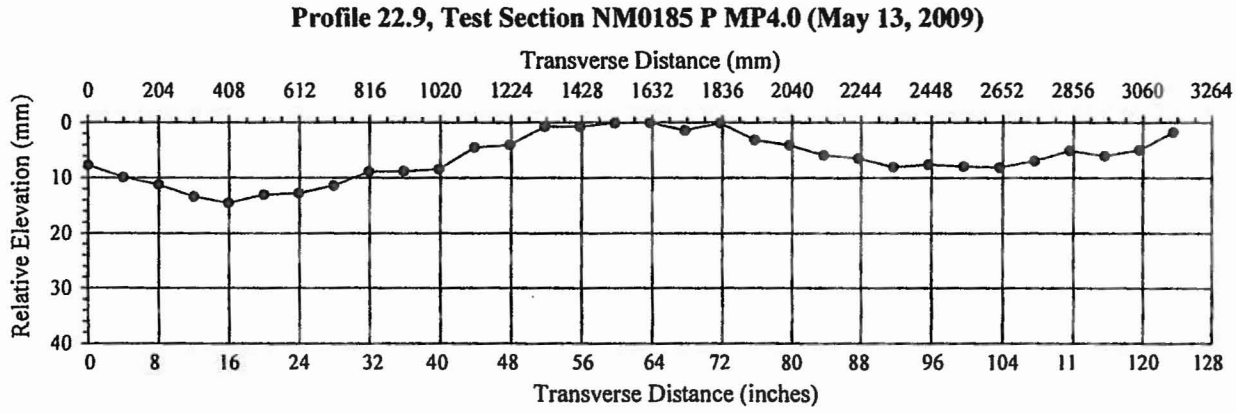
The test sections were located in highway NM 185. This is a two-lane state-maintained highway in the northwest area of Las Cruces, NM. The test sections for this research were 161 m (0.1 mile) long and had the width of the driving lane. In a given test section, the transverse profiles were spaced 7.62 m (25 ft) in the direction of the traffic flow, so each test section included 22 transverse profiles. The first profile was located at the beginning of the test section. The beginning of the test sections were located in the milepost points 4.0, 5.1, 6.0 and 7.1 in the positive direction (Northwest bound) of highway NM 185 (called locally North Valley Dr.). Figures 11 and 12 show typical transverse profiles measured in this research. All the transverse profiles are provided in Appendix D.

The transverse profiles were between 3.05 m and 3.66 m (120 in. and 144 in.) long and started at the center of the edge stripe and ended approximately in the center line stripe. The transverse profiles were labeled with a number corresponding to their distance in meters from the beginning of the test section. For example, profile 0, profile 7.6 and profile 15.2 corresponded to profiles located at 0 m, 7.6 m and 15.2 m from the beginning of the test section.

The transverse profiles were determined based on closely spaced vertical measurements from the bottom of a leveled straightedge to the pavement surface. The straightedge was positioned horizontally across the section and perpendicularly to the traffic direction. Two identical straightedges were used during the field measurements. The straightedges were 3.66 m



(a)



(b)

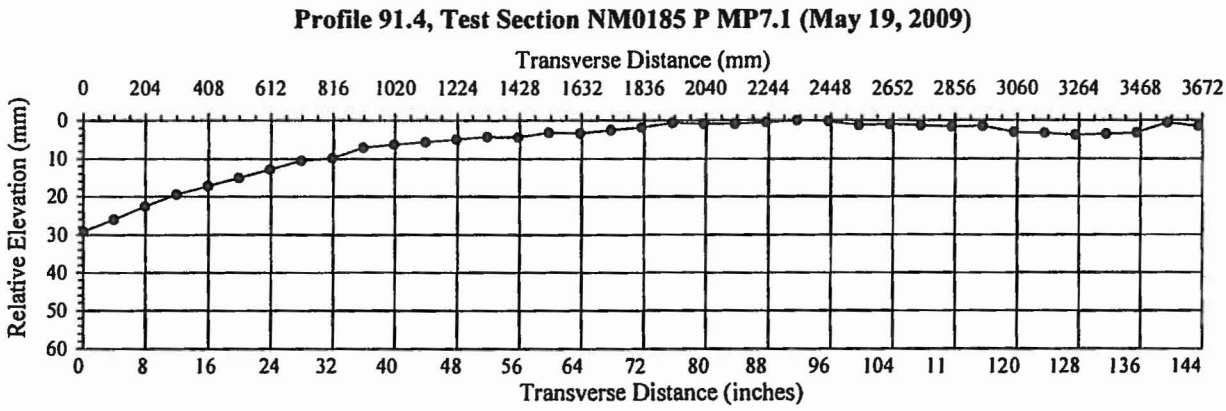
FIGURE 11 Examples of Transverse Profiles at Milepost (MP) 4: (a) Profile 0 and (b) Profile 22.9

(12 ft) long aluminum screeds, with a cross section of approximately 38.1 mm × 76.2 mm (1.5 in. × 3.0 in.). These straightedges were rigid enough to avoid significant bending and prevent distortion of the horizontal reference plane. The measurements were done manually using digital calipers with accuracy of 0.02 mm (0.001 in.). Calipers with depth probes of 152.4 mm (6 in.) and 304.8 mm (12 in.) in length were available on site to allow measurements of different shapes of pavement profile and rutting levels.

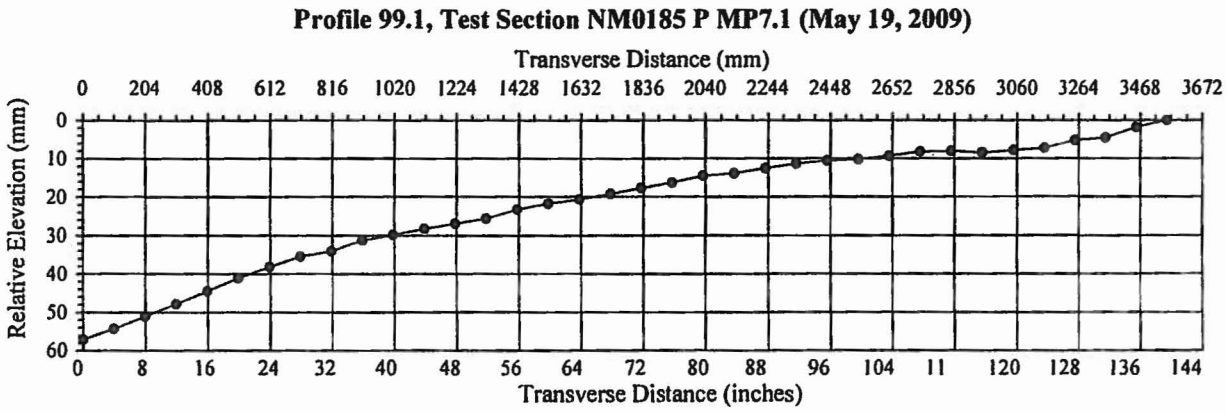
Two people worked simultaneously in a profile; one positioned the caliper and took the measurements while the other recorded the measurements and other relevant data. Two crews worked concurrently in a test section (Figure 13). The measurements were done at 101.6 mm (4 in.) intervals, starting from the edge end of the profile and moving toward the center line. The protocol to perform these measurements is described as follows:

1. Starting at the beginning of the test section, the locations of the transverse profiles were marked on the pavement edge (with chalk) and labeled with the profile number.
2. The straightedge (aluminum screed) was placed across the driving lane in the location of a transverse profile, perpendicular to the direction of the traffic. The longer side of the straightedge profile was laid parallel to the pavement surface (Figure 14).

3. The straightedge was leveled by placing spacers and shims under one or both ends (Figure 15). Wooden blocks of various thicknesses were used to elevate the straightedge to a horizontal position. The straightedge was leveled in both directions of the horizontal plane. Straightedge-type bubble levels and torpedo-type levels were used to ensure that the 12 ft long aluminum straightedge remained in a horizontal position during the measurements. No pivoting of the straightedge was allowed.
4. Using chalk and a ruler, small marks were made on the pavement surface at 101.6 mm (4 in.) intervals following the length of the straightedge (Figure 16). These were the measurement points along the transverse profile. The first mark was located in the center of the edge stripe.
5. At each measurement point, the vertical distance or depth was measured with a digital caliper, from the top of the straightedge to the pavement surface (Figure 17). When a measurement point coincided with an open crack or large pit on the pavement surface that was not representative of rutting in this profile, the caliper's depth probe was move slightly to the right or left to make contact with the pavement surface. The zero of the caliper was regularly checked during measurements. The measurements were recorded in paper data forms (Figure 18).



(a)



(b)

Figure 12 Examples of Transverse Profiles at Milepost (MP) 7.1: (a) Profile 91.4 and (b) Profile 99.1

FIGURE 13 Crews Measuring Depth with Respect to an Aluminum Straightedge Along Transverse Profiles

FIGURE 14 Placing of the Straightedge to Perform Measurements Along a Transverse Profile

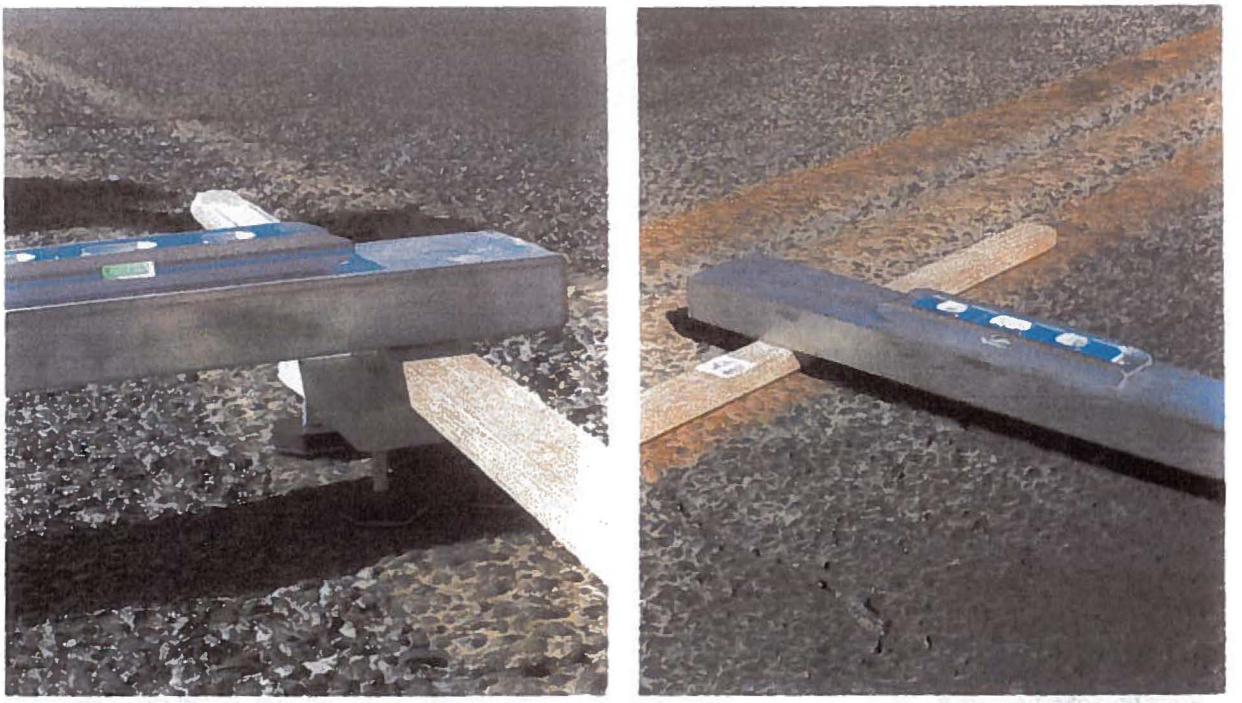


FIGURE 15 Spacers and Shims Used to Level Horizontally the Straightedge

(a) **(b)**

FIGURE 16 (a) Marking the Measurement Points (at 4 in. Intervals) on the Pavement and (b) Marks After the Aluminum Straightedge Was Removed

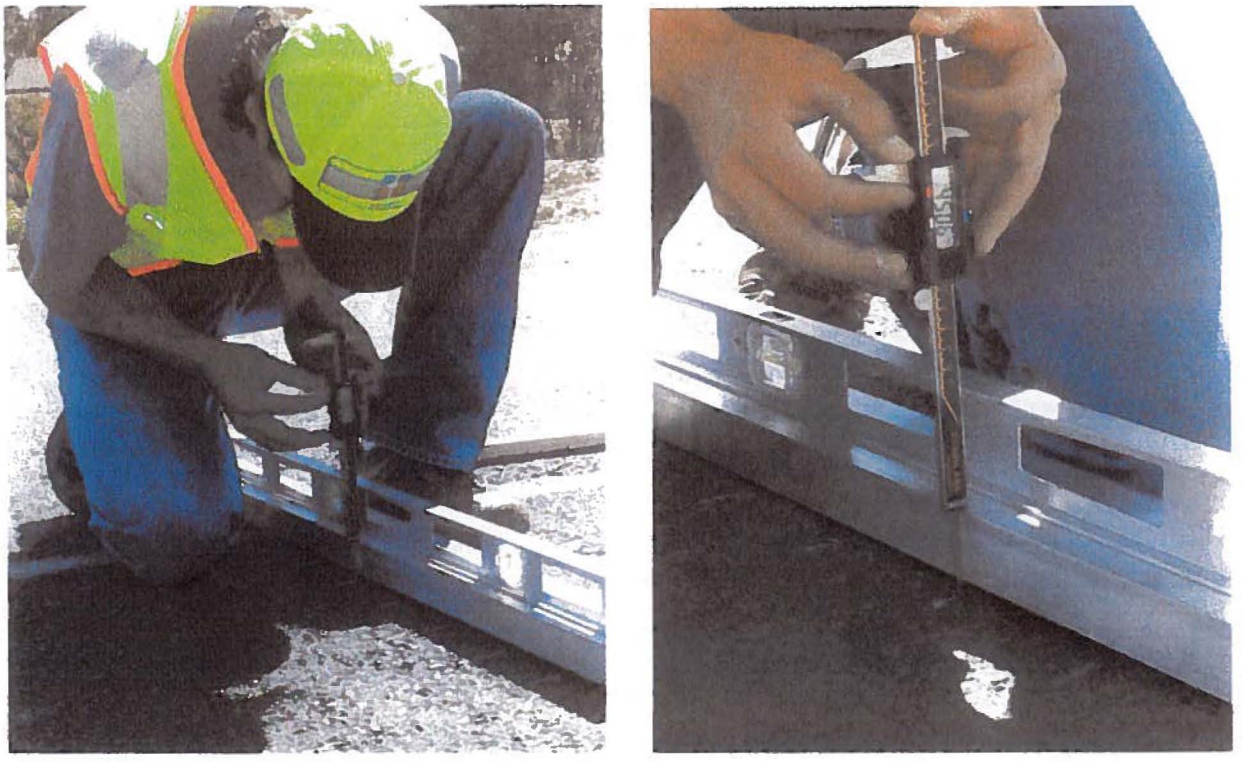


FIGURE 17 Depth Measurements with Digital Caliper Along a Transverse Profile

FIGURE 18 Depth Measurements Along a Transverse Profile and Data Recording

RUT DEPTH FROM TRANSVERSE PROFILES

The vertical depths at the measurement points along a transverse profile were adjusted by subtracting the vertical distance from the upper (top) side of the straightedge and the highest point in the profile (or pavement surface). In this way, the relative elevations were referenced with respect to the imaginary horizontal plane passing through the highest point of each transverse profile (This reference plane was different in each profile). The data were plotted using spreadsheet software. Outliers were revised and corrected. The data points were joined with straight line segments. All the profiles are shown in Figures 19 through 22; individual profiles are enclosed in Appendix D.

In each transverse profile graph, the rutting (if any) and location of the wheelpaths were visually identified. Two straight lines were drawn, one for each wheelpath depression or rut. The straight lines were individually placed (digitally) on the graph so that each straight line made contact with the profile line on both sides of each wheelpath or rut without crossing it (Figures 23 and 24).

The greatest vertical distance from each straight line to the profile line below was computed. For a given transverse profile, the rut depth was defined as the maximum of these two vertical distances. Tables 5 through 8 contain the rut depths obtained according to this procedure. These values were confirmed with the ones calculated by a computer code written for this purpose using the same criteria.

In some cases, the straight lines drawn on the transverse profiles, as described in this section, were longer than 1.2 m (4 ft), which is the length of a typical rut bar according to NMDOT protocol for manual pavement distress ratings and rut depth surveys. Therefore, in some instances, this straight line procedure to determine rut depth from the transverse profiles yielded greater rut depths than ratings of manual surveys. This difference should be taken into consideration when comparing the data. An example of the difference is shown in Figure 25 for profile 152.4 of MP 5.1. In this figure, the rut depth from the straight line (red line) was 13.74 mm (0.56 in.) and the rut depth simulating a 4 ft rut bar (blue line) was 11.96 mm (0.49 in.). If these values were compared using NMDOT's distress rating criteria (14) for rutting and shoving, the straight line (red line in Figure 25) would correspond to a severity 2 (Medium severity: rut depth between 0.5 and 1.0 in.) and the 4 ft rut bar (blue line in Figure 25) would correspond to a severity 1 (Low severity: rut depth between 0.25 and 0.5 in.).

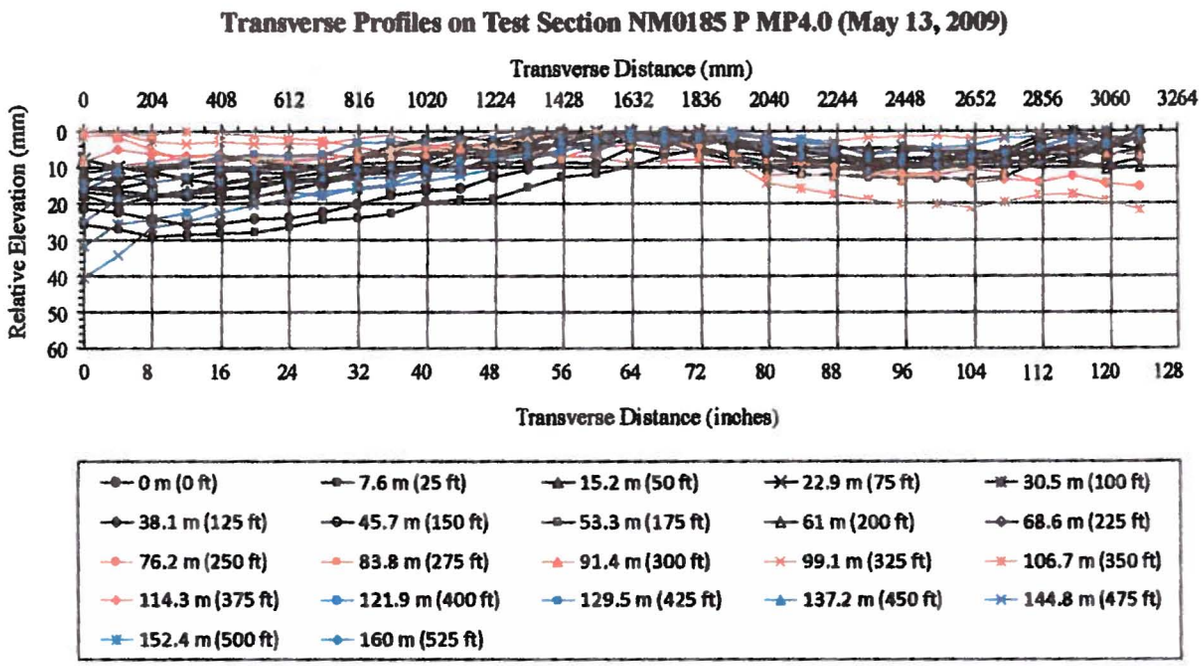


FIGURE 19 Transverse Profiles on Test Section NM0185 MP 4.0

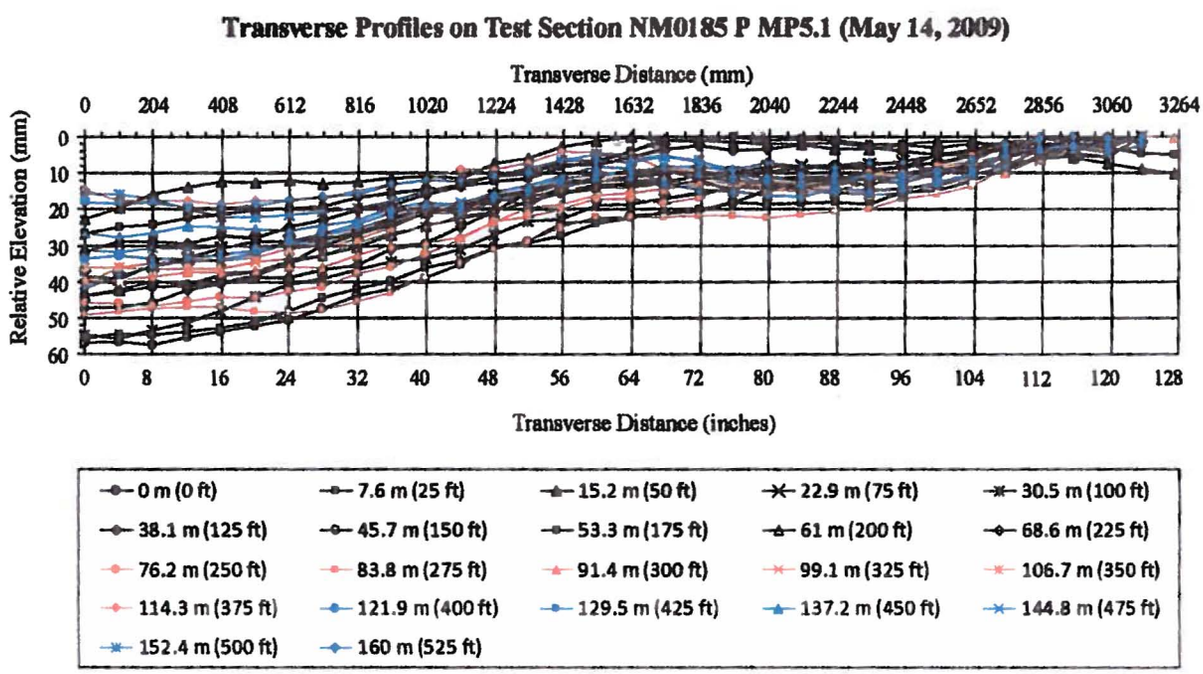


FIGURE 20 Transverse Profiles on Test Section NM0185 MP 5.1

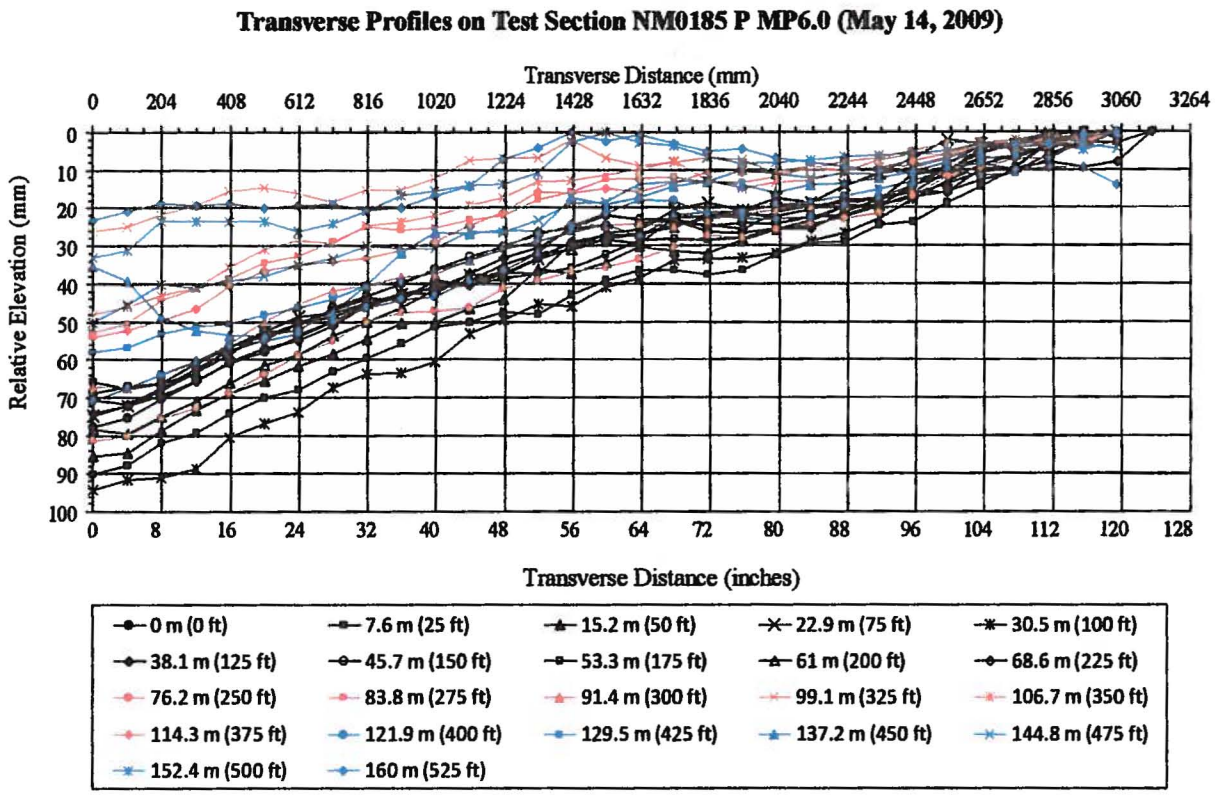


FIGURE 21 Transverse Profiles on Test Section NM0185 MP 6.0

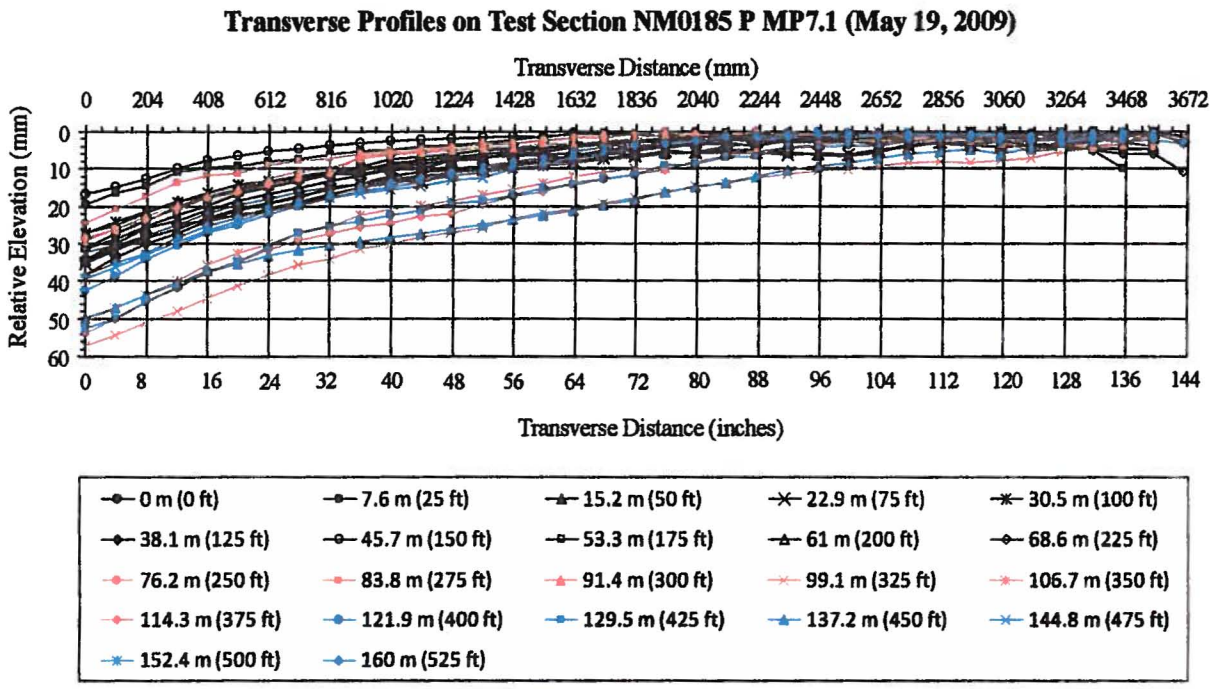
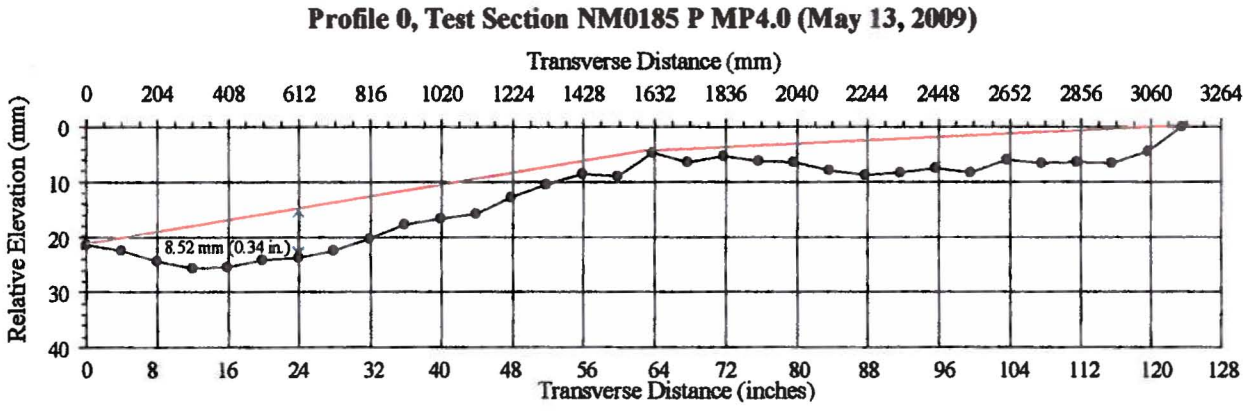
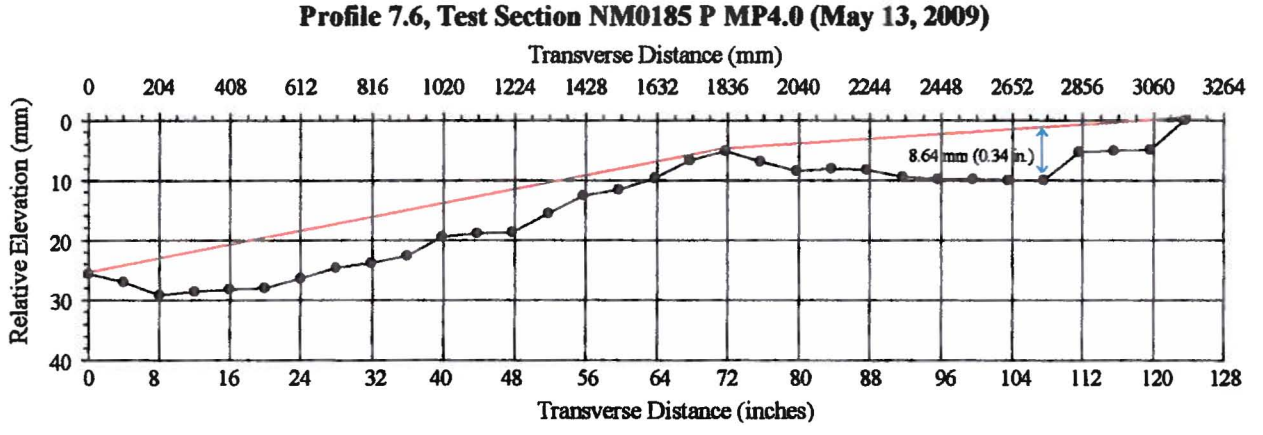


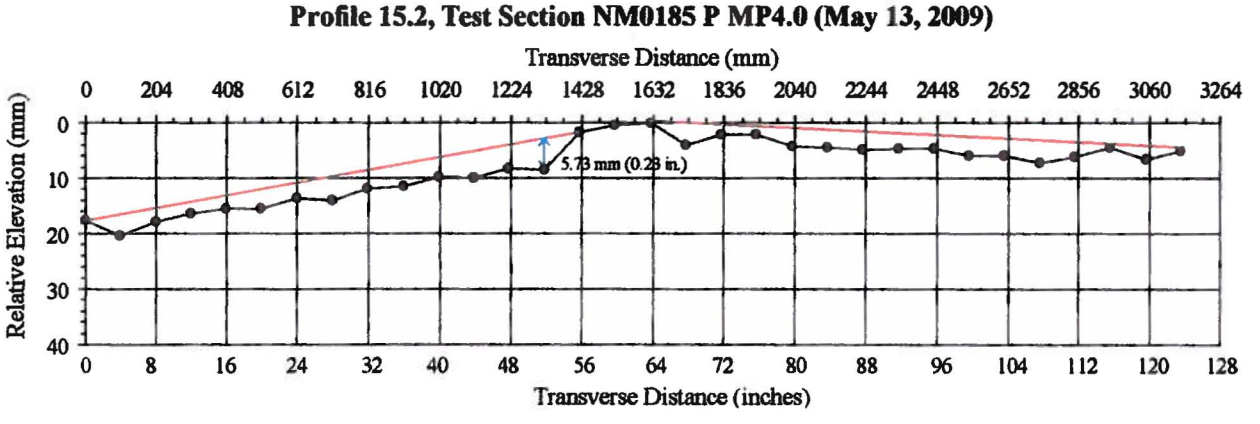
FIGURE 22 Transverse Profiles on Test Section NM0185 MP 7.1



(a)



(b)



(c)

FIGURE 23 Illustration of the Method to Determine Rut Depth from Transverse Profiles at Milepost (MP) 4.0: (a) Profile 0, (b) Profile 7.6 and (c) Profile 15.2

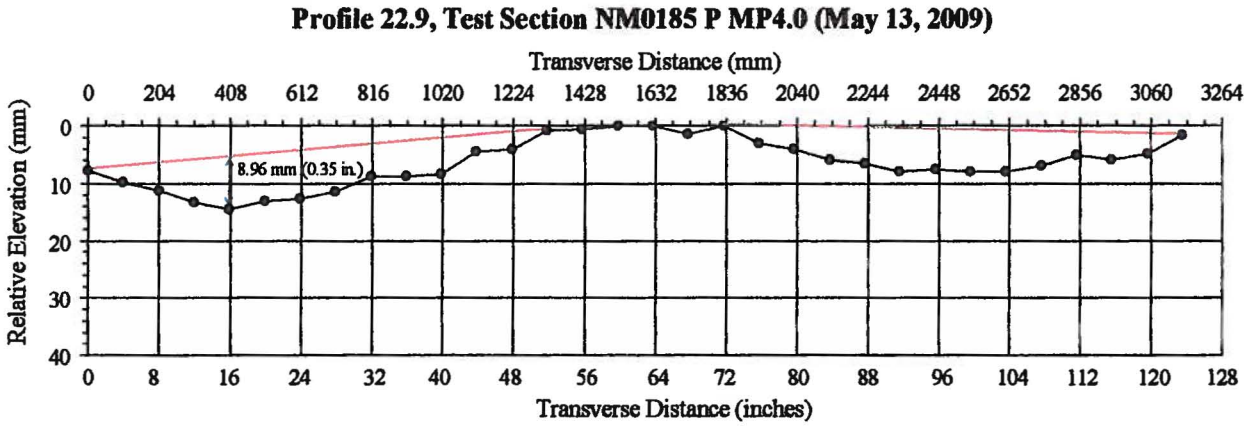


FIGURE 24 Illustration of the Method to Determine Rut Depth from Transverse Profile 22.9 at Milepost (MP) 4.0

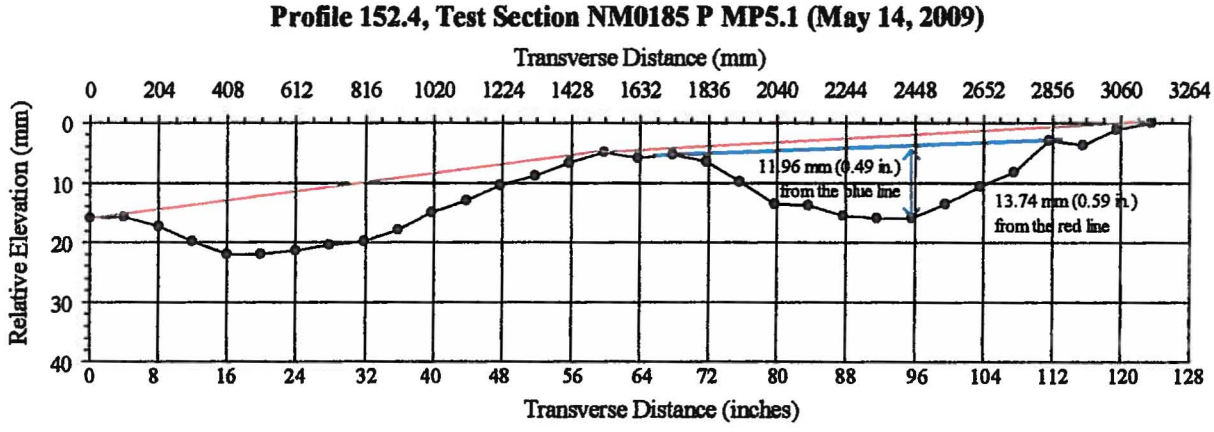


FIGURE 25 Comparison of the Rut Depth Using a Straight Line (Red Line) and a 4 ft Rut Bar (Blue Line) in a Transverse Profile

TABLE 5 Rut Depths Determined Graphically from the Transverse Profile in Highway NM0185 MP 4 and Equivalent Severity Ratings for Rutting and Shoving.

Profile label		Rut Depth		Equivalent Severity Rating
(m)	(ft)	(mm)	(in.)	
0	0	8.64	0.34	1
7.6	25	8.52	0.34	1
15.2	50	5.73	0.23	0
22.9	75	8.96	0.35	1
30.5	100	10.08	0.40	1
38.1	125	10.22	0.40	1
45.7	150	9.56	0.38	1
53.3	175	7.19	0.28	1
61	200	7.95	0.31	1
68.6	225	4.69	0.18	0
76.2	250	5.73	0.23	0
83.8	275	4.35	0.17	0
91.4	300	15.74	0.62	2
99.1	325	3.68	0.14	0
106.7	350	7.06	0.28	1
114.3	375	5.28	0.21	0
121.9	400	7.81	0.31	1
129.5	425	10.84	0.43	1
137.2	450	7.15	0.29	1
144.8	475	5.95	0.24	0
152.4	500	5.45	0.22	0
160	525	8.92	0.36	1

TABLE 6 Rut Depths Determined Graphically from the Transverse Profile in Highway NM0185 MP 5.1 and Equivalent Severity Ratings for Rutting and Shoving.

Profile label		Rut Depth		Equivalent Severity Rating
(m)	(ft)	(mm)	(in.)	
0	0	5.85	0.23	0
7.6	25	4.53	0.18	0
15.2	50	6.16	0.24	0
22.9	75	3.65	0.14	0
30.5	100	4.36	0.17	0
38.1	125	5.79	0.23	0
45.7	150	7.91	0.31	1
53.3	175	6.76	0.27	1
61	200	4.92	0.19	0
68.6	225	6.23	0.25	1
76.2	250	9.03	0.36	1
83.8	275	11.25	0.44	1
91.4	300	7.46	0.29	1
99.1	325	8.81	0.35	1
106.7	350	5.38	0.21	0
114.3	375	12.21	0.48	1
121.9	400	7.94	0.31	1
129.5	425	7.43	0.29	1
137.2	450	11.44	0.47	1
144.8	475	7.08	0.29	1
152.4	500	13.74	0.56	2
160	525	8.63	0.35	1

TABLE 7 Rut Depths Determined Graphically from the Transverse Profile in Highway NM0185 MP 6 and Equivalent Severity Ratings for Rutting and Shoving.

Profile label		Rut Depth		Equivalent Severity Rating
(m)	(ft)	(mm)	(in.)	
0	0	6.95	0.27	1
7.6	25	9.95	0.39	1
15.2	50	7.12	0.28	1
22.9	75	7.40	0.29	1
30.5	100	7.04	0.28	1
38.1	125	10.61	0.42	1
45.7	150	11.27	0.44	1
53.3	175	6.05	0.24	0
61	200	9.31	0.37	1
68.6	225	7.30	0.29	1
76.2	250	5.50	0.22	0
83.8	275	4.24	0.17	0
91.4	300	8.11	0.32	1
99.1	325	9.55	0.38	1
106.7	350	8.32	0.33	1
114.3	375	5.33	0.21	0
121.9	400	11.19	0.44	1
129.5	425	6.05	0.24	0
137.2	450	24.70	1.01	3
144.8	475	5.71	0.23	0
152.4	500	10.06	0.41	1
160	525	11.96	0.49	1

TABLE 8 Rut Depths Determined Graphically from the Transverse Profile in Highway NM0185 MP 7.1 and Equivalent Severity Ratings for Rutting and Shoving.

Profile label		Rut Depth		Equivalent Severity Rating
(m)	(ft)	(mm)	(in.)	
0	0	1.27	0.5	0
7.6	25	0.57	0.02	0
15.2	50	2.64	0.10	0
22.9	75	2.60	0.10	0
30.5	100	2.47	0.10	0
38.1	125	1.20	0.05	0
45.7	150	1.26	0.05	0
53.3	175	1.12	0.04	0
61	200	1.03	0.04	0
68.6	225	0.13	0.01	0
76.2	250	2.90	0.11	0
83.8	275	1.22	0.05	0
91.4	300	2.88	0.11	0
99.1	325	3.40	0.13	0
106.7	350	1.32	0.05	0
114.3	375	1.22	0.05	0
121.9	400	1.65	0.07	0
129.5	425	0.00	0.00	0
137.2	450	1.98	0.08	0
144.8	475	1.55	0.06	0
152.4	500	1.51	0.06	0
160	525	1.92	0.08	0

DISTRESS RATINGS IN TEST SECTIONS

Experienced distress raters independently performed manual surveys in the test sections, immediately before the profile measurements. The severity and extent ratings for eight distress types, including rutting and shoving, were done according to NMDOT's *Distress Evaluation Charts for Flexible Pavements* (Appendix A) and NMDOT's distress survey protocols (14). The distress ratings for the test sections are given in Tables 9 through 12. Additionally, distress ratings for test sections at milepost points 4.0 and 6.0 were available from the 2009 NMDOT Annual Pavement Distress Evaluation Program and are shown as Crew 3 in Tables 9 and 11. Tables 9 through 12 also provide equivalent severity ratings for the rut depth determined for each transverse profile applying the NMDOT's distress rating criteria for manual surveys for rutting and shoving (14). These criteria are:

- Rating = 0: Rut depth less than 0.25 in.
- Rating = 1 (Low severity): Rut depth between 0.25 in. and 0.5 in.
- Rating = 2 (Medium severity): Rut depth between 0.5 in. and 1.0 in.
- Rating = 3 (High severity): Rut depth greater than 1.0 in.

TABLE 9 Distress Ratings for Test Section in Highway NM0185 MP 4 (May 2009).

Distress Type	Rater A		Rater B		Rater C		Crew 3	
	Severity	Extent	Severity	Severity	Extent	Extent	Severity	Extent
Raveling and Weathering	1	3	1	3	1	3	1	3
Bleeding	1	3	1	1	1	3	1	3
Rutting and Shoving	2	1	2	1	2	1	2	1
Longitudinal Cracking	2	1	2	2	2	1	2	1
Transverse Cracking	2	1	2	2	2	2	2	1
Alligator Cracking	3	1	3	1	3	2	3	1
Edge Cracks	2	1	2	1	2	1	1	3
Patch Condition	2	1	2	1	0	0	2	1

TABLE 10 Distress Ratings for Test Section in Highway NM0185 MP 5.1 (May 2009).

Distress Type	Rater B		Rater D	
	Severity	Extent	Severity	Extent
Raveling and Weathering	1	3	1	3
Bleeding	1	3	1	3
Rutting and Shoving	1	3	1	2
Longitudinal Cracking	3	1	2	1
Transverse Cracking	1	2	1	2
Alligator Cracking	1	1	1	1
Edge Cracks	3	1	3	1
Patch Condition	0	0	0	0

TABLE 11 Distress Ratings for Test Section in Highway NM0185 MP 6 (May 2009).

Distress Type	Rater C		Rater D		Crew 3	
	Severity	Extent	Severity	Extent	Severity	Extent
Raveling and Weathering	1	3	1	3	1	3
Bleeding	2	3	2	3	1	3
Rutting and Shoving	3	1	3	1	1	1
Longitudinal Cracking	2	2	2	2	3	1
Transverse Cracking	2	3	2	3	2	1
Alligator Cracking	3	1	3	1	1	3
Edge Cracks	1	3	1	2	1	3
Patch condition	0	0	0	0	0	0

TABLE 12 Distress Ratings for Test Section in Highway NM0185 MP 7.1 (May 2009).

Distress Type	Rater C		Rater D	
	Severity	Extent	Severity	Extent
Raveling and Weathering	1	3	1	3
Bleeding	1	1	0	0
Rutting and Shoving	0	0	0	0
Longitudinal Cracking	2	1	2	1
Transverse Cracking	1	1	1	1
Alligator Cracking	0	0	0	0
Edge Cracks	1	3	1	3
Patch Condition	0	0	0	0

COMPARISON OF AUTOMATED RUT DEPTH, DISTRESS RATINGS AND TRANSVERSE PROFILES

The three types of rut depth data compared were the automated rut depth, the rutting ratings from manual surveys and the rut depth determined from transverse profiles in the test sections. These three data sets had different characteristics. The automated rut depth was first determined as an average for the two wheelpaths and recorded at 152.4 mm (6 in) intervals with a 3-laser profiler (also called 3-point profilometer). In the post-processing stage, the automated data were averaged and reported at 161 m (0.1 mile) intervals. The automated rut depth data were available for the entire length of the mile. The severity and extent ratings were 0, 1, 2 or 3, and the manual survey protocol did not require recording or reporting the measured rut depth from the rut bar checks. The test sections in manual surveys were 161 m (0.1 mile) long and were assumed to be representative samples of the entire mile. The rut depth from the transverse profiles was defined as the largest vertical difference between the pavement surface and two straight lines joining the outer-most points that most likely defined the ruts or depressions along the wheelpaths. These straight lines could be longer than 1.2 m (4 ft).

Additionally, overall equivalent severity and extent ratings were estimated from the transverse profiles, for a given test section, applying NMDOT's distress rating criteria for manual surveys (14). For example, a severity rating was assigned to each transverse profile according to the value of rut depth determined using straight lines. The percentage of transverse profiles with the highest severity rating in the test section was calculated. The extent was assessed by comparing this percentage with the extent rating criteria for rutting and shoving (14).

A summary of the rut depth data for the test sections is provided in Tables 13 through 16. The severity and extent ratings from manual surveys were consistent among the various raters and with the overall equivalent ratings from the transverse profiles. In general, the ratings were in agreement. For test sections MP 5.1 and MP 6, the differences among ratings from manual surveys were within acceptable margins and could be attributed to the inherent subjectivity of the manual survey procedure. No deterministic measurements were carried out during the manual surveys.

TABLE 13 Comparison of Rut Depth Data and Rutting and Shoving Ratings for Test Section NM0185 MP 4.

Test Section	Rater A (May 2009)		Rater B (May 2009)		Rater C (May 2009)		Crew 3 (May 2009)		Overall Equivalent Rating from Transverse Profiles		Averaged Automated Rut Depth		
											2007	2008	2009
	Sev.	Ext.	Sev.	Ext.	Sev.	Ext.	Sev.	Ext.	Sev.	Ext.	(in.)	(in.)	(in.)
MP 4	2	1	2	1	2	1	2	1	2	1	-0.09	-0.15	0.69

TABLE 14 Comparison of Rut Depth Data and Rutting and Shoving Ratings for Test Section NM0185 MP 5.1.

Test Section	Rater B (May 2009)		Rater D (May 2009)		Overall Equivalent Rating from Transverse Profiles		Averaged Automated Rut Depth		
							2007	2008	2009
	Sev.	Ext.	Sev.	Ext.	Sev.	Ext.	(in.)	(in.)	(in.)
MP 5.1	1	3	1	2	2	1	-0.07	-0.21	1.0

TABLE 15 Comparison of Rut Depth Data and Rutting and Shoving Ratings for Test Section NM0185 MP 6.

Test Section	Rater C (May 2009)		Rater D (May 2009)		Crew 3 (May 2009)		Overall Equivalent Rating from Transverse Profiles		Averaged Automated Rut Depth		
									2007	2008	2009
	Sev.	Ext.	Sev.	Ext.	Sev.	Ext.	Sev.	Ext.	(in.)	(in.)	(in.)
MP 6	3	1	3	1	1	1	3	1	-0.18	-0.18	0.63

TABLE 16 Comparison of Rut Depth Data and Rutting and Shoving Ratings for Test Section NM0185 MP 7.1.

Test Section	Rater C (May 2009)		Rater D (May 2009)		Overall Equivalent Rating from Transverse Profiles		Averaged Automated Rut Depth		
							2007	2008	2009
	Sev.	Ext.	Sev.	Ext.	Sev.	Ext.	(in.)	(in.)	(in.)
MP 7.1	0	0	0	0	0	0	-0.05	-0.06	0.82

For test section MP 5.1, the overall equivalent severity was 2 (from the transverse profiles), whereas the raters reported severity of 1 using a 1.2 m (4 ft) rut bar (Table 14). If 1.2 m (4 ft) long lines (simulating 4 ft rut bars) were used to determine the rut depth from the transverse profiles in this test section, the overall equivalent severity and extent ratings would have also been 1 and 3 respectively. The percentage of profiles with severity of 1 would have been 63%, which is just over the 60% limit value between extent level 2 and extent level 3. This is illustrated in Figure 25. The proximity of the percent area affected by severity 1 to the 60% limit value may also help explain why Rater B reported an extent of 3 and Rater D reported an extent of 2 for rutting and shoving in the same test section (Table 14).

In test section MP 6, Crew 3 rated rutting and shoving with severity of 1 and extent of 1. The same crew rated alligator cracking with severity and extent of 1 and 3 respectively. The other two raters assessed rutting and shoving and alligator cracking with severity and extent of 3 and 1 respectively (Table 15). A later detailed observation of the test section indicated that the ratings of Raters C and D were correct. A small pavement area near the end of the test section exhibited alligator cracking of severity level 3 at the time of the surveys, and the transverse profiles located in this area also showed rut depths greater than 1 in. From the experience of the authors, rutting and depressions along the wheelpaths can be associated with alligator cracking (or fatigue cracking) of severity level 2 or 3. It is likely that Crew 3 failed to observe the area with severity 3 alligator cracking very near the end of the test section and, therefore, did not do rut bar checks there.

In test section MP 7.1, raters reported ratings 0 for severity and extent of rutting and shoving, which coincide with the transverse profiles (Figure 22). This section did not show any rutting of 0.25 in. or greater. Two typical transverse profiles of test section MP 7.1 are shown in Figure 12 and all the transverse profiles are provided in Appendix D.

The averaged automated rut depths for 2007 and 2008 in the test sections were negative values (Tables 13 through 16). Rut depth collected with the NMDOT-owned profilometers (T6600 Inertial Profilometers) was positive; therefore, negative values in the data were considered as no rutting (Tito T. Medina, personal communication, 2009). The averaged automated rut data collected in August of 2009 for these test sections were positive but significantly greater than what the manual survey ratings indicated and the rut depth from the transverse profiles. The difference was very obvious, especially for test section MP 7.1, which showed no or insignificant rutting throughout the section. The reason for this lack of correlation of the automated rut depth data is unknown. It is strongly recommended that quality control calibration with other profilers and with data from other methods be performed in a regular basis for this equipment to ensure that the collected automated rut depth data are accurate and reliable.

REPLACING RUTTING RATINGS FROM MANUAL SURVEYS WITH AUTOMATED RUT DEPTH DATA

The main goal of this research was to determine the modifications that are needed in the NMDOT's Pavement Serviceability Index (PSI) formulation and/or weight factors to replace rutting and shoving ratings from manual surveys with the automatic rut depth data obtained with NMDOT-owned 3-point profilometers. The modifications to the PSI formulation and/or factors should introduce the minimum difference (minimum error) compared with the PSI values obtained with the current methodology and data from manual surveys. The following sections

describe the data available for this study and their characteristics, the methodology applied and the analysis results and recommendations.

CHARACTERISTICS OF NMDOT'S PAVEMENT CONDITION DATA

Automated Rut Depth and Roughness Data

The NMDOT has collected automated rut depth and roughness data since 1991 (14). In 2001, NMDOT started using Dynatest T6600 High Speed Profilometers for rutting and roughness data collection. This equipment uses three infrared laser displacement sensors (3-point system) and two accelerometers. The following is a summary of information and observations about the NMDOT automated rut depth and roughness data (Tito T. Medina, personal communications, 2009, 2010):

- Automated rutting and roughness data were not collected in 2006 due to software upgrade and lack of personnel available for the annual pavement condition surveys.
- The quality of the automated rutting data collected in 2007 was questionable and should not be used. In the 2007 data collection cycle, the automated rut depth values in interstates and loops were very large and unrealistic.
- Positive values of rut depth imply rutting, and negative values imply no rutting (and will be considered zero rut depth in this research).
- Since 2002, the rut depth data were recorded at 6 in. intervals by the software provided by the vendor of the profilometers. In a post processing stage, these raw data files were summarized by averaging the rut depth at 161 m (0.1 mile) intervals. The averaging intervals coincided approximately with milepost markers.
- The rut depth data weare given in inches. The roughness data were given in inches/mile and represent the International Roughness Index (IRI).
- The rut depth and roughness (IRI) data files, for data averaged at 161 m (0.1 mile) intervals, have extensions .RUT and .DAT, respectively, and can be accessed as text files. The IRI data files contain the IRI values for the two wheelpaths.
- At the time of publication of this report, there was neither consistency nor correlation, in terms of length and location of the sections, among the pavement sections of the NMDOT's Pavement Management System (used to report PSI and RQI) and the test sections of the distress surveys and the intervals for reporting automated rut depth and IRI data.
- A set of spreadsheet files that contain annual RQI, IRI and PSI data for the New Mexico pavement sections, from 2003 through 2009, is available. (At the time of publication of this report, the sections in the NMDOT's Pavement Management System have variable length and location, meaning that the sections do not have all the same length, do not necessarily start or end at mile markers and could be shorter, equal or longer than one mile.) In these files, the RQI values were rounded to one decimal place (i.e., one digit after the decimal point). The IRI values shown are approximated because they were back calculated from the RQI values rounded to one decimal place using the equation:

$$IRI = \frac{\ln\left(\frac{RQI}{5}\right)}{-0.004104} \tag{6}$$

The RQI values were originally calculated using the IRI data files (.DAT extension) and Equation 5.

- For a given year, NMDOT calculates PSI values according to Equations 1 through 4 using distress ratings (including rutting and shoving) from the year's manual survey, and IRI data collected during the previous year (or previous pavement condition data collection cycle). Roughness data were not collected in 2006; thus the PSI values for 2007 were likely calculated using the IRI data collected in 2005.
- Spreadsheet files that contain annual average IRI values for each of the NMDOT pavement sections from 1985 through 2007 are also available.

Rutting and Shoving Ratings from Manual Surveys

The NMDOT has collected distress ratings from manual surveys since the 1980s. In 2001, NMDOT revised its distress ratings criteria and in 2002 started rating eight types of distress in flexible pavements. These are called raveling and weathering, bleeding, rutting and shoving, longitudinal cracking, transverse cracking, alligator cracking, edge cracking, and patching. (Similarly, in 2001 NMDOT also reduced the distresses evaluated in rigid pavements from 17 to 8.) The following is a summary of information about the NMDOT distress rating data:

- Distress ratings for flexible pavements are available for 1996 through 2009, except for 2001. No distress survey was carried out in 2001. These data are in spreadsheet files, at intervals of approximately 1.6 km (1 mile).
- Distress ratings for individual rating crews are available from 2006 through 2009. These data are in text files at 1 mile intervals and were collected by New Mexico State University (NMSU) and University of New Mexico (UNM) under contract.
- The distress ratings were collected in 161 m (0.1 mile) test sections, generally starting or ending at a milepost marker, along the full width of the right-most lane (driving lane).
- Distress ratings of severity and extent are given in values of 0, 1, 2 or 3.

Comparison of Rut Depth Data and Rutting Ratings

The goal of this project was to recommend a procedure to replace rutting and shoving ratings from manual surveys with automated rut depth data for the calculation of NMDOT's PSI values. Substituting one type of data for the other presented challenges because of the different characteristics of the data sets. The automated rut depth data can take any value (positive, negative or zero), within a reasonable range for this parameter depending on the pavement condition. The automated rut depth data can be described by a continuous function. For the analyses, zero was set as the lower bound for the automatic rut depth data. Any negative value of rut depth was made equal to zero.

On the other hand, each of the DR_i components in Equation 4 can have only nine discrete values, including zero, and represent discrete functions. For rutting and shoving, DR_i (or DR_{Rut})

is the product of a severity rating (1, 2 or 3), an extent rating factor (0.5, 0.8 or 1.0) and the weight factor (14). When severity and extent ratings are zero, then $DR_i = 0$. Therefore, DR_i for rutting and shoving can only take the following discrete values: 0, 7, 11.2, 14, 21, 22.4, 28, 33.6, and 42.

For illustration purposes, the automated rut depth data and the corresponding DR_i values for rutting shoving from manual surveys are compared in Figure 26 for 2003 through 2009 data. It is obvious that the relationships between these two data sets cannot be represented by a continuous function. Therefore, the comparisons between automated rut depth data and rutting ratings from manual surveys should be done in terms of PSI values.

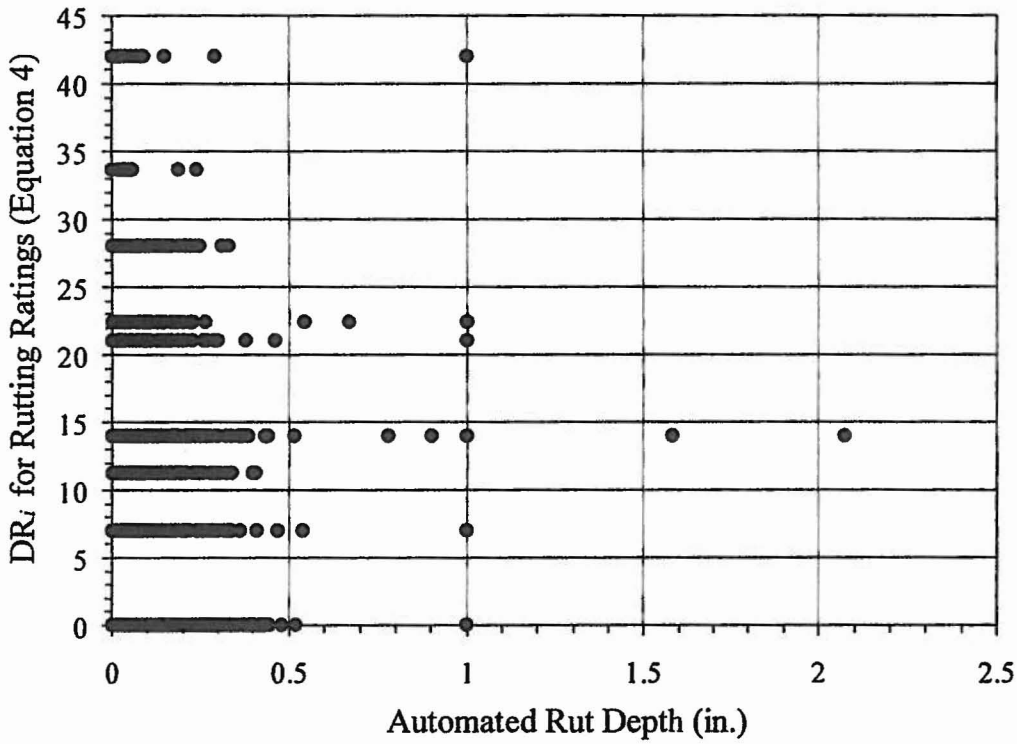


FIGURE 26 Comparison of Automated Rut Depth Data and the Corresponding DR_i Values for Rutting and Shoving from Manual Surveys

STATISTICAL METHODOLOGY

The statistical analyses were carried out in terms of PSI values. Available NMDOT's historic data of PSI, IRI, automated rut depth and distress ratings from manual surveys were used. Several approaches were considered, but the following three were found to be the most promising strategies from the point of view of practicality and feasibility of implementation:

- Modify the interim value X (Equation 3) used to calculate PSI.
- Modify the extent factors and/or the weight factor for rutting in the total distress rate (DR) (Equation 4).
- Convert automated rut depth data into equivalent severity and extent ratings for rutting, and maintain the current formulation unchanged.

In any case, the statistical analyses sought to minimize the difference (or error) between the PSI values reported by NMDOT (calculated using distress and rutting ratings from manual surveys, IRI and Equations 1 through 4) and the PSI calculated with the new approach (using automated rut depth data instead of ratings from manual surveys). The method of least squares was applied for the data fitting, so that the sum of squared residuals was minimized. In this problem, for a given pavement section, the sum of squared residuals (SSE) was defined as the squared difference between the PSI value calculated using rutting ratings from manual surveys (observed value, $PSI_{Man.Rut}$) and the PSI value calculated using the automated rut depth data (value provided by the model, $PSI_{Auto.Rut}$):

$$\text{Minimize}\ \ SSE = \sum_{i=1}^{N} (PSI_{Man.Rut} - PSI_{Auto.Rut})^2 \tag{7}$$

where N is the number of PSI values in the data set (number of observed values). The coefficient of determination R^2 was defined as

$$R^2 = 1 - \frac{SSE}{SST} \tag{8}$$

in which SST is the total sum of squares (proportional to the sample variance):

$$SST = \sum_{i=1}^{N} (PSI_{Man.Rut} - \overline{PSI_{Man.Rut}})^2 \tag{9}$$

where $\overline{PSI_{Man.Rut}}$ is the mean of the PSI data set (calculated with input data from manual surveys) and is given by

$$\overline{PSI_{Man.Rut}} = \frac{1}{N} \sum_{i=1}^{N} (PSI_{Auto.Rut}) \tag{10}$$

The coefficient of determination provides information about goodness of fit. It is a statistical measure of how well a regression line or model approximates the real data points. The pooled sample variance (S_p^2) and mean values of the data sets were also calculated. The pooled sample variance is the average of the two sample variances (for $PSI_{Man.Rut}$ and $PSI_{Auto.Rut}$) weighted by the degrees of freedom (19). The group comparison t-test was also used (19). The t-test is a statistical hypothesis test to assess whether the means of two groups are statistically different from each other.

The regression analyses were done in terms of PSI values. During the initial inspection and preprocessing of the available data, it was found that the PSI values reported in the NMDOT data files could not be reproduced consistently for all the pavement sections. It is likely that several factors affected the precision that could be achieved in back calculating these PSI values. First, in the files of the annually reported PSI, IRI and RQI data, were not the original IRI values; these IRI values were back calculated from RQI with Equation 6, and the RQI was rounded to

one decimal place. Additionally, the criteria to calculate weighted averages of IRI for the pavement sections implemented in the NMDOT's computer code could not be fully deciphered by the authors. The difficulty is that the sections in the NMDOT's Pavement Management System are not consistent, in terms of length and location, with IRI data (given at 161 m [0.1 mile] intervals) and distress ratings (given only for the first 0.1 mile section of every mile, starting or ending at each mile marker).

Therefore, for each NMDOT's pavement section, the IRI value was back calculated from the known $PSI_{Man.Rut}$ and distress ratings, using Equations 1 through 4. Then $PSI_{Auto.Rut}$ could be calculated with the revised formulation or factors, the back calculated IRI and the automated rut depth data.

ANALYSIS AND RESULTS

Three different approaches were evaluated in this research, and they are described in this section. The first analysis is the most recommended approach because of its practicality and ease of implementation. Two other alternative approaches are also presented. This section refers to Appendix F (Implementation Plan for Replacing Rutting Ratings from Manual Surveys with Automated Rut Depth Data), which describes the resources and/or steps required for the recommended and alternative approaches to be implemented by NMDOT.

Recommended Approach (Approach A)

The Recommended Approach (Approach A) preserved the current PSI formulation, the equation of the interim X value (Equations 1 through 3), and the values of the extent rating factors and weight factor W_{Rut} (= 14). In this approach, the modification was made to the automated rut depth data. "Equivalent" severity and extent ratings were estimated from the automated rut depth data for the entire length of each section. This means that the automated rut depth data were "converted" into equivalent ratings of rutting to be used in the current PSI formulation.

Before equivalent ratings could be determined, the relationship between the two types of data (automated rut depth and rutting ratings) was evaluated. It was found that there was no relationship between the two data sets, which means that there was not a continuous function that could represent well the relationship between the two data sets. For illustration, Table 17 shows the two types of data for selected sections. Even the greatest (or maximum) automated rut depths were often considerably smaller than what the ratings from manual surveys indicated. It was also observed that the NMDOT's automated rut depth data had a tendency to underestimate significantly the actual rut depth. During the data preprocessing, negative values of automated rut depth were made equal to zero before calculating $PSI_{Auto.Rut}$ values used in the regression analyses.

Therefore, several modifications to NMDOT's severity ratings were considered and evaluated for estimating the equivalent severity ratings (i.e., to convert automated rut depth data into rutting ratings comparable to those from the manual surveys). The modified severity rating criteria were evaluated based on the percentage of sections that would produce the same severity and extent ratings for rutting as the manual surveys, SSE, pooled sample variance (S_p^2), t-test and other statistical indicators. Applying a heuristic approach, several modifications to the severity rating criteria were considered and evaluated. Table 18 shows the rating criteria with high performance for the data analyzed when the $PSI_{Auto.Rut}$ values were computed using IRI,

automated rut depth and distress ratings all collected during the same year when the PSI values were reported. This will be called herein Approach A-Case 1.

The equivalent severity level for rutting was found for each 161 m (0.1 mile) interval by comparing the automated rut depth with the modified criteria given in Table 18. The greatest severity found in a given mile was taken as the equivalent severity rating for rutting. The percentage of 161 m (0.1 mile) intervals with the highest severity rating in the entire mile was

TABLE 17 Example of Rutting Ratings and Automated Rut Depth Collected in 2008 in Interstate Routes in 0.1 Mile Long Sections.

Route	Direction	Beginning	End	Rutting and Shoving Ratings		Automated Rut Depth (Average)	Maximum Automated Rut Depth [b]
				Severity	Extent	(in.)	(in.)
I00040	M	62	62.1	3	3	-0.45	-0.16
I00040	M	66	66.1	3	1	-0.35	-0.05
I00040	M	88	88.1	3	1	-0.39	-0.28
I00025	M	216	216.1	3	1	0.10	0.22
I00025	M	202	202.1	3	1	0.13	0.31
I00025	M	199	199.1	3	1	0.21	0.36
I00010	P	0	0.1	3	2	0.27	0.70
I00010	P	80	80.1	3	2	0.18	0.31
I00010	P	83	83.1	3	1	0.22	0.36
I00040	P	174	174.1	3	1	0.30	0.79
I00040	P	152	152.1	3	3	-0.11	0.02
I00040	P	184	184.1	3	1	0.07	0.20
I00010	M	0	0.1	1	1	0.10	0.10
I00010	M	8	8.1	1	3	-0.06	-0.06
I00010	M	10	10.1	1	2	0.12	0.12
I00025	P	180	180.1	1	2	-0.17	-0.17
I00025	P	186	186.1	1	1	-0.12	-0.12
I00040	M	88	88.1	2	1	-0.41	-0.41
I00040	M	91	91.1	1	2	-0.36	-0.36

[a] M: Minus direction, P: Positive direction.
[b] Maximum (or greatest) rut depth recorded in the 161 m (0.1 mile) interval.

TABLE 18 Approach A-Case 1: Modified Rutting Rating Criteria.

Rating	Criteria	
	Severity (Modified-Approach A Case 1)	Extent (NMDOT's criteria)
0	Rut depth less than 0.18 in.	Severity rating is 0
1	Rut depth between 0.18 in. and 0.25 in.	From 1% to 30% of the test section
2	Rut depth between 0.25 in. and 0.32 in.	From 31% to 60% of the test section
3	Rut depth greater than 0.32 in.	61% of the test section or more

calculated. The equivalent extent rating was assessed by comparing this percentage with the NMDOT's extent rating criteria given in Table 18. By doing this, the automated rut depth data were converted into a set represented by a discrete function (no longer a continuous function).

Figure 27 compares the results applying the criteria in Table 18 for data of 2003 through 2009 (Approach A-Case 1). In this and subsequent figures, the best-fit straight line is in red and its equation is shown. A total of 79,321 sections were used in the analysis. The statistical indicators were SSE = 1,227, S_p^2 = 0.830, t = 1.210 and R^2 = 0.981. The mean values of $PSI_{Man.Rut}$ and $PSI_{Auto.Rut}$ were 3.491 and 3.486 respectively. When the criteria in Table 18 were applied, the results showed that the model has a slight tendency to underestimate the PSI value. For the data analyzed, 35.2% of the sections had $PSI_{Man.Rut} > PSI_{Auto.Rut}$, 22% of the sections had $PSI_{Man.Rut} < PSI_{Auto.Rut}$, and 43.2% had $PSI_{Man.Rut} = PSI_{Auto.Rut}$.

For the data set analyzed, 5,258 sections (6.63%) would be rated, based on their PSI value, in a pavement condition level that was either higher or lower than the one in which they would have been ranked if the current PSI formula and rutting ratings from manual surveys would have been used. Of these, 2,605 sections (49.5%) fell in a higher (better) condition level, whereas 2,653 sections (50.5%) fell in a lower (worse) condition level. The rest of the sections (76,668 or 93.37%) were rated in the same condition level (i.e., they fell in the same pavement condition level based on PSI) regardless of the type of rut depth data used. As a reference, the NMDOT's pavement condition ranking criteria for interstates and non-interstates are given in Table 4.

It is the current practice of NMDOT to use the automated pavement condition data (roughness data or IRI) of the prior data collection cycle to calculate PSI values with the distress ratings of the current year. This is mainly due to the scheduling of automated pavement condition collection. With this in mind and for consistency with NMDOT practices, the automated rut depth data of the corresponding previous year were used to determine the equivalent ratings to calculate $PSI_{Auto.Rut}$. For example, the 2009 $PSI_{Auto.Rut}$ values were calculated using IRI data and automated rut depth data collected in 2008 and distress ratings from surveys done in 2009.

Applying a heuristic approach again, the ranges in the severity rating criteria were modified to obtain the best performance of the model in terms of statistical indicators. Table 19 shows the criteria with high performance for the data analyzed when the $PSI_{Auto.Rut}$ values were calculated using IRI and automated rut depth data from the previous collection cycle and distress ratings collected during the same year when PSI values were reported. This will be referred as Approach A-Case 2.

TABLE 19 Approach A-Case 2: Modified Rutting Rating Criteria Using IRI and Automated Rut Depth Data from Previous Year.

Rating	Criteria	
	Severity (Modified-Approach A Case 2)	Extent (NMDOT's criteria)
0	Rut depth less than 0.22 in.	Severity rating is 0
1	Rut depth between 0.22 in. and 0.30 in.	From 1% to 30% of the test section
2	Rut depth between 0.30 in. and 0.38 in.	From 31% to 60% of the test section
3	Rut depth greater than 0.38 in.	61% of the test section or more

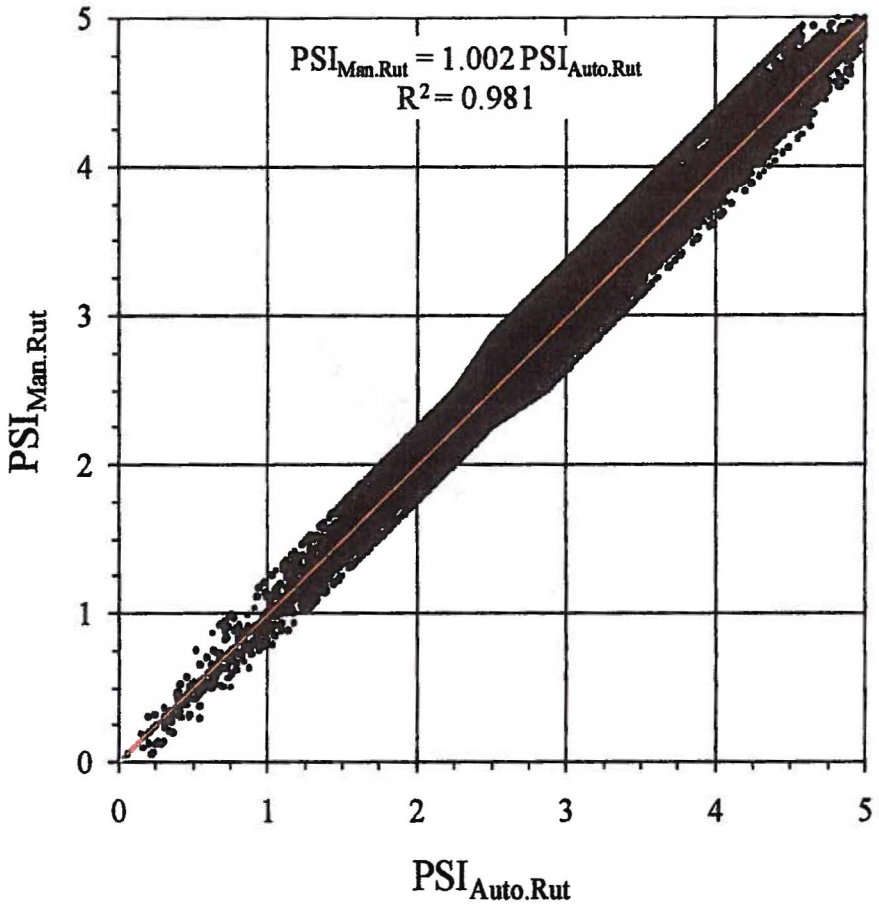


FIGURE 27 Comparison of $PSI_{Man.Rut}$ Calculated with the Current Formulation and $PSI_{Auto.Rut}$ Calculated Using Equivalent Rutting Ratings for Approach A-Case 1 (Table 18)

The equivalent severity level for rutting was found for each 161 m (0.1 mile) interval by comparing the automated rut depth with the modified criteria given in Table 19. The greatest severity found in a given mile was taken as the equivalent severity rating for rutting. The percentage of 161 m (0.1 mile) intervals with the highest severity rating in the entire mile was calculated. The equivalent extent rating was assessed by comparing this percentage with the NMDOT's extent rating criteria given in Table 19.

Figure 28 compares the results applying the criteria in Table 19 for data from 2003 through 2009. A total of 79,294 sections were used in the analyses. The statistical indicators were SSE = 533, S_p^2 = 0.845, t = 7.545 and R^2 = 0.990. The mean values of $PSI_{Man.Rut}$ and $PSI_{Auto.Rut}$ were 3.430 and 3.466 respectively. In this case, the t value was significantly large (t > 1.67), so further analysis was needed to improve this test statistic. When the criteria in Table 19 are applied (Approach A-Case 2), the results showed a moderate tendency to underestimate the PSI value. For the data analyzed, 42.8% of the sections had $PSI_{Man.Rut} > PSI_{Auto.Rut}$, 8.8% of the sections had $PSI_{Man.Rut} < PSI_{Auto.Rut}$, and 48.7% had $PSI_{Man.Rut} = PSI_{Auto.Rut}$.

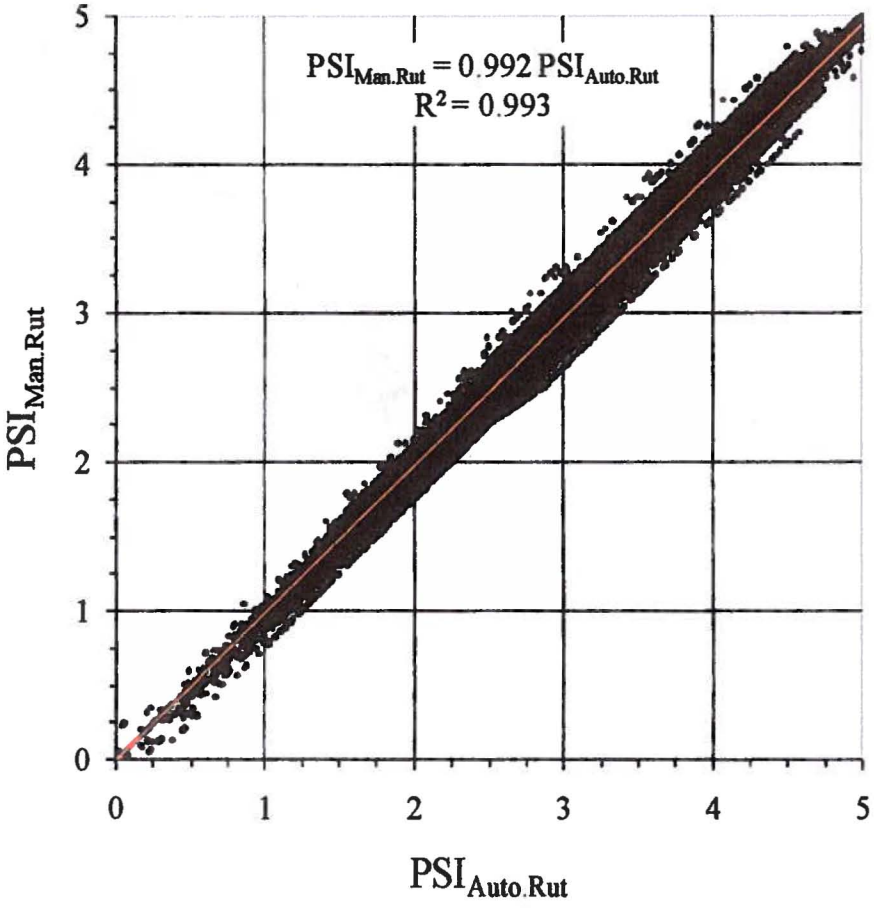


FIGURE 28 Comparison of $PSI_{Man.Rut}$ Calculated with the Current Formulation and $PSI_{Auto.Rut}$ Calculated Using Equivalent Ratings for Approach A-Case 2 (Table 19)

For the data set analyzed, 4,398 sections (6.20%) would be rated, based on their PSI value, in a pavement condition level that was either higher or lower than the one in which they would have been ranked if the current PSI formula and rutting ratings from manual surveys would have been used. Of these, 587 sections (13.3%) fell in a higher (better) condition level, whereas 3,811 sections (86.7%) fell in a lower (worse) condition level. The rest of the sections (74,896 or 93.80%) were rated in the same condition level (i.e., they fell in the same pavement condition level based on PSI) regardless of the type of rut depth data used.

The NMDOT pavement condition data collection underwent important changes in 2005 and 2006. In this period, NMDOT changed the software to collect and process roughness and rut depth data automatically. Roughness and automated rut depth data were collected only in a small percentage of routes in 2006 due to lack of personnel available for this task (Tito T. Medina, personal communication, 2010). The format of these files and the interval of data reported also changed around that period. Additionally, starting in summer of 2006, NMDOT contracted with two universities, New Mexico State University (NMSU) and the University of New Mexico (UNM), to collect annually distress ratings (including rutting) in manual surveys.

To study the possible effect of these circumstances, additional statistical analyses were performed on available data from 2006 through 2009. It was found that the ranges of the severity rating criteria could be further refined to obtain the best performance of the model. Table 20 shows the criteria with high performance for the data analyzed when the $PSI_{Auto.Rut}$ values were calculated using IRI and automated rut depth data from the previous collection cycle and distress ratings collected during the same year when PSI values were reported. This will be referred as Recommended Approach (Approach A-Case 3).

Figure 29 compares the results applying the criteria in Table 20 for data from 2006 through 2009. A total of 18,114 sections were used in the analyses. The statistical indicators were SSE = 86, S_p^2 = 0.664, t = 1.917 and R^2 = 0.993. The mean values of $PSI_{Man.Rut}$ and $PSI_{Auto.Rut}$ were 3.594 and 3.610 respectively. The t value was satisfactory and significantly lower than the one for 2003-2009 data. When the criteria in Table 20 were applied, the results continued to show a slight tendency to underestimate the PSI value. For the data analyzed, 30.8% of the sections had $PSI_{Man.Rut} > PSI_{Auto.Rut}$, 10.1% of the sections had $PSI_{Man.Rut} < PSI_{Auto.Rut}$, and 59.2% had $PSI_{Man.Rut} = PSI_{Auto.Rut}$.

For the data set analyzed, 813 sections (4.49%) would be rated, based on their PSI value, in a pavement condition level that was either higher or lower than the one in which they would have been ranked if the current PSI formula and rutting ratings from manual surveys would have been used. Of these, 209 sections (25.7%) fell in a higher (better) condition level, whereas 604 sections (74.3%) fell in a lower (worse) condition level. The rest of the sections (17,301 or 95.51%) were rated in the same condition level (i.e., they fell in the same pavement condition level based on PSI) regardless of the type of rut depth data used. Appendix F explains further how this procedure could be applied.

TABLE 20 Recommended Approach (Approach A-Case 3): Rutting Rating Criteria Using IRI and Automated Rut Depth Data from Previous Year.

Rating	Criteria	
	Severity (Modified-Approach A Case 3)	Extent (NMDOT's criteria)
0	Rut depth less than 0.20 in.	Severity rating is 0
1	Rut depth between 0.20 in. and 0.28 in.	From 1% to 30% of the test section
2	Rut depth between 0.28 in. and 0.36 in.	From 31% to 60% of the test section
3	Rut depth greater than 0.36 in.	61% of the test section or more

Alternative Approach B

Alternative Approach B consisted of applying a minor modification to the current NMDOT's Pavement Serviceability Index (PSI) formulation for flexible pavements, particularly to the equation of the interim value X (Equation 3). The component of the total Distress Rate (DR) corresponding to the distress of rutting and shoving (DR_i) was moved outside the distress rating (DR) term in Equation 3 for flexible pavements. Regression analyses were performed on the PSI data to find an appropriate mathematical form for DR_i of rutting (also called DR_{Rut}), so that the sum of squared residuals (SSE) (Equation 7) was minimized.

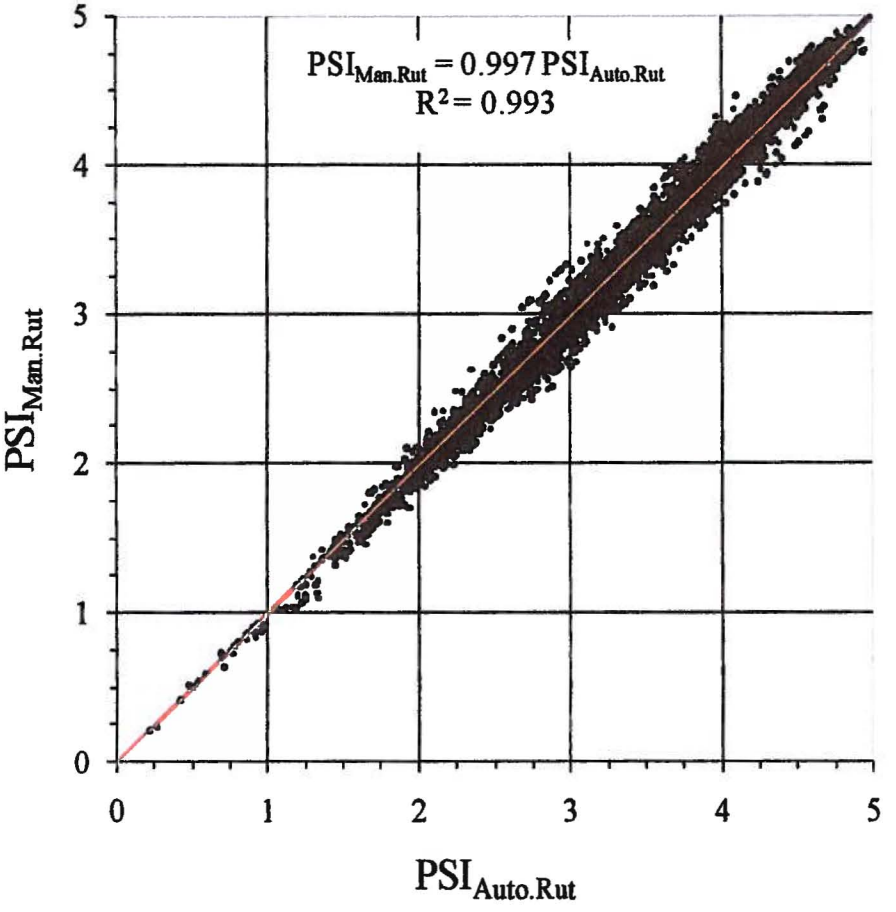


FIGURE 29 Comparison of $PSI_{Man.Rut}$ Calculated with the Current Formulation and $PSI_{Auto.Rut}$ Calculated Using Equivalent Ratings for the Recommended Approach (Approach A-Case 3, Table 20) for Data from 2003 through 2009

Alternative Approach B proposed that the interim value X in the PSI calculation be replaced with the following expression:

$$X = 100 - \left[\frac{0.6\,(\mathrm{IRI} - 25) + (0.4\,\mathrm{DR})}{2.9} + k_1 \exp^{k_2\,(\mathrm{Auto.Rut})} \right] \tag{11}$$

where IRI was the International Roughness Index (inches/mile) for the section, Auto.Rut was the automated rut depth (inch) for the section, obtained with the NMDOT's 3-point profilometer (Dynatest T6600 High Speed Profilometer), k_1 and k_2 were new fitting coefficients for the rut depth term, and DR was the total distress rate for the section calculated as

$$\mathrm{DR} = \sum_{i=1}^{n} \left[(\text{Severity Rating}_i)(\text{Extent Rating Factor}_i)(\text{Weight Factor}_i) \right] = \sum_{i=1}^{n} (\mathrm{DR}_i) \tag{12}$$

in which i denoted one of the remaining seven distress types of flexible pavements (n = 7), not including rutting, and DR_i was the component of the total distress rate (DR) value corresponding to the distress type i (for i = 1, 2, ... 7) for a given pavement section. Note that in the original PSI formulation, rutting and shoving ratings were included as one of the DR_i terms in Equation 4, for a total of n = 8 distresses. The fitting coefficients k_1 and k_2 resulted from the regression and do not have a physical meaning. Appendix F explains further how this approach could be applied.

During the data preprocessing, negative values of automated rut depth were made equal to zero before calculating $PSI_{Auto.Rut}$ values used in the regression analysis. From the regression analyses, the values of the coefficients k_1 and k_2 in Equation 11 that minimized the statistical error were found to be: k_1 = 0.73311 and k_2 = –2.80284, with the sum of squared residuals SSE = 119.7, S_p^2 = 0.699, t = 0.2929 and R^2 = 0.994. The mean values of $PSI_{Man.Rut}$ and $PSI_{Auto.Rut}$ were 3.486 and 3.488 respectively. A total of 27,453 sections were used in the statistical analysis. For consistency with the current practice of NMDOT, the automated rut depth data of the previous year was used to calculate $PSI_{Auto.Rut}$; for example, the $PSI_{Auto.Rut}$ for 2009 was calculated using automated rut depth data collected in 2008 with the distress ratings collected in manual surveys in 2009.

Figure 30 compares $PSI_{Man.Rut}$ and $PSI_{Auto.Rut}$ for all the available data. The PSI model of Alternative Approach B showed a tendency to underestimate the PSI value. For the data analyzed, 61.6% of the sections had $PSI_{Man.Rut} > PSI_{Auto.Rut}$ and 38.4% of the sections had $PSI_{Man.Rut} \leq PSI_{Auto.Rut}$.

As explained earlier, the error introduced by using the automated rut depth in Equation 11 could cause that some sections be rated, based on the PSI value, in a pavement condition level that is either higher or lower than the one in which they would be if the current PSI formula and rutting ratings from manual surveys would have been used. For the data set analyzed, 1,594 sections were in this situation, which represented 5.8% of the data. Of these, 919 sections (58%) fell in a higher (better) condition level, whereas 675 sections (42%) fell in a lower (worse) condition level. The rest of the sections (25,859 or 94.2%) were rated in the same condition level (i.e., they fell in the same pavement condition level based on PSI) regardless of the equation or type of rut depth data used.

Evaluation of Approach C

A third approach (Approach C) was evaluated. It preserved the current PSI formulation and interim value X (Equations 1 through 3). Applying the method of least squares, a new weight factor (W_{Rut}) for the rutting component of DR was determined so that the sum of the squared residuals (SSE) was minimized. (The current weight factor for rutting and shoving ratings from manual surveys is W_{Rut} = 14.) Additionally, equivalent severity and extent ratings were determined from the automated rut depth data of the entire mile. The equivalent severity and extent ratings for rutting were determined using the same criteria applied in NMDOT's manual surveys for rutting ratings (Table 21).

In this analysis, the rutting component (DR_{Rut}) of the Distress Rate (DR) (Equation 4) was modified:

$$DR_{Rut} = [(\text{Equivalent Severity Rating})(\text{Extent Rating Factor}_i)(W_{Rut})] + k_3 \qquad (13)$$

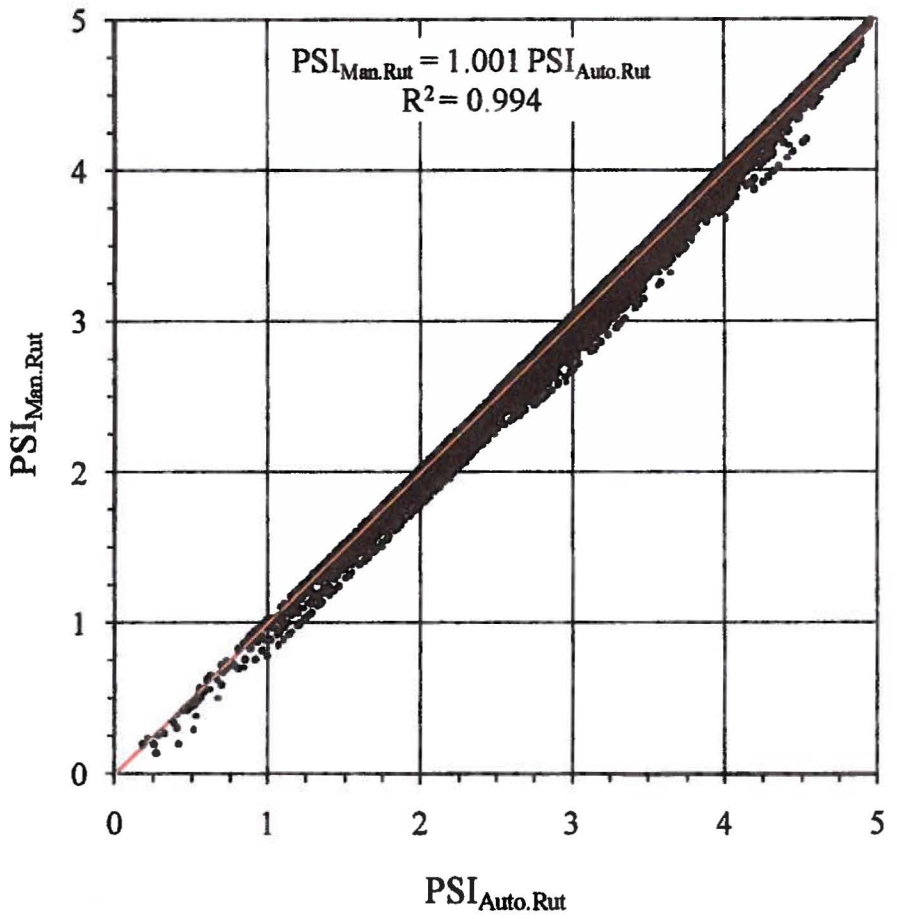


FIGURE 30 Comparison of $PSI_{Man.Rut}$ Calculated with the Current Formulation (Equation 3) and $PSI_{Auto.Rut}$ Calculated According to Alternative Approach B (Equation 11)

TABLE 21 NMDOT's Criteria for Rutting and Shoving Ratings in Manual Surveys.

Rating	Criteria	
	Severity	Extent
0	Rut depth less than 0.25 in.	Severity rating is 0
1	Rut depth between 0.25 in. and 0.5 in.	From 1% to 30% of the test section
2	Rut depth between 0.5 in. and 1.0 in.	From 31% to 60% of the test section
3	Rut depth greater than 1.0 in.	61% of the test section or more

where k_3 was a fitting coefficient from the regression analysis, and the extent rating factor was determined according to Table 2. The other components DR_i in Equation 4 (for $n = 8$) remained unchanged.

A severity level for rutting was found for each 161 m (0.1 mile) interval by comparing the automated rut depth with the criteria in Table 21. The greatest severity found in the entire mile was taken as the equivalent severity rating for rutting. The percentage of 0.1 mile intervals with the highest severity rating in the mile was calculated. The equivalent extent rating was assessed by comparing this percentage with the extent rating criteria in Table 21.

During the data preprocessing, negative values of automated rut depth were made equal to zero before calculating $PSI_{Auto.Rut}$ values used in the regression analysis. It was found that $k_3 = 5.5668$ and the weight factor $W_{Rut} = 1.07338$, with the sum of squared residuals SSE = 394 and $R^2 = 0.994$. A total of 83,726 sections were used in the statistical analyses. For consistency with the current practice of NMDOT, the automated rut depth data of the previous year was used to determine the equivalent ratings to calculate $PSI_{Auto.Rut}$. For the data set analyzed, 4,921sections (5.87%) would be rated, based on the PSI value, in a pavement condition level that was either higher or lower than the one in which they would have been if the current PSI formula and rutting ratings from manual surveys would have been used. The rest of the sections were rated in the same condition level (i.e., they fell in the same pavement condition level based on PSI) regardless of the type of rut depth data used.

When evaluating this procedure, the use of a fitting coefficient $k_3 = 5.5668$ (Equation 13) with a very small weight factor ($W_{Rut} = 1.07338$) for DR_{Rut} was found not to be appropriate from the practical and engineering points of view, even though the analysis would be statistically valid and correct. The engineering significance of k_3 and W_{Rut} with a value very close to 1 (much smaller than any other weight factor in Table 3) is questionable because it makes PSI insensitive to the values of the automated rut depth. This approach was evaluated and it is not recommended for implementation.

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

1) The results of the transverse profiles confirmed that the rutting and shoving ratings from manual surveys are in very good agreement with the actual rut depth and the distribution of the rutting throughout the test sections. The automated rut depth data for the test sections were not consistent with the transverse profiles.

2) The automated rut depth data used in this study showed a clear tendency to underestimate the actual rut depth. The data recorded for a significant number of test sections throughout the years were negative values. The reason for such a large percentage of negative data (which has been interpreted as "no rutting") should be investigated further and avoided in the future.

3) The Recommended Approach does not require modifications of the current PSI formulation and can be implemented by NMDOT relatively easily. It converts the automated rut depth into equivalent ratings of severity and extent of rutting. Additionally, with this approach, NMDOT will be able to use either rutting ratings from manual surveys or automated rut depth data without the need for further modifications. If automated rut depth data are not collected in a given year, NMDOT may decide to reincorporate rutting and shoving ratings into the manual surveys as part of the Annual Pavement Distress Evaluation Program for that year. This flexibility is important.

4) Implementation of Alternative Approach B is also feasible, but it requires modifications of the PSI formulation in the NMDOT's Transportation Information Management System (TIMS). A third approach was considered but it is not recommended.

RECOMMENDATIONS

1) It is strongly recommended that quality control checks and equipment calibration of the NMDOT-owned 3-point profilometers be performed systematically in an annual basis. For this purpose, rut-bar checks and other quality control checks could be scheduled as part of the NMDOT's annual pavement distress data collection program in selected test sections.

2) As new data become available or if different profilometer equipment is used, it is highly recommended that the performance of the proposed approaches and rating criteria be reevaluated. Additionally, it is important to assess if (and how much) the implemented changes would affect the overall condition rankings of the highway network (based on PSI) in the medium term (for example, two cycles following the implementation).

3) It is also important to evaluate how the proposed modifications would be affected by other possible recommendations and modifications that may results from other ongoing and future research in the NMDOT.

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APPENDICES

APPENDIX A

NMDOT's Distress Evaluation Chart for Flexible Pavements

NMDOT's Distress Evaluation Chart for Flexible Pavements

DISTRESS	SEVERITY	EXTENT
Raveling & Weathering: The wearing away of the pavement surface, due to dislodged aggregate particles and loss of asphalt binder. Normally the extent will be throughout the test section.	Low: (1) Aggregate or binder has started to wear away on pavement surface. Some dislodged aggregate can be found on the shoulder. Med: (2) Aggregate or binder has worn away. Surface texture is rough and pitted. High: (3) Aggregate and/or binder has worn away, and surface texture is severely rough and pitted.	Low: (1) 1% to 30% of test section. Med: (2) 31% to 60% of test section. High: (3) 61% of test section, or more.
Bleeding: A film of bituminous material on the pavement surface.	Low: (1) Film is evident, but aggregate can still be seen. Spotty. Med: (2) Film is clearly seen, covers most of the aggregate, and is a little sticky. High: (3) Film is predominant, very sticky, and material is thick enough to shove.	Low: (1) 1% to 30% of test section. Med: (2) 31% to 60% of test section. High: (3) 61% of test section, or more.
Rutting and Shoving: Longitudinal surface depressions in wheel path. (Check with a 4-foot rut bar.)	Low: (1) ¼-inch to ½-inch in depth. Med: (2) ½-inch to 1-inch in depth. High: (3) More than 1-inch in depth.	Low: (1) 1% to 30% of test section. Med: (2) 31% to 60% of test section. High: (3) 61% of test section, or more.
Cracks: **Longitudinal Cracks:** Wheel Track Mid-Lane Center Line **Transverse Cracks:** Full Width	Low: (1) Sealed or non-sealed with a mean width of less than ¼-inch. May have very minor spalls. Med: (2) A. Sealed or non-sealed, and moderately spalled. Any width. B. Sealed, but sealant separated, allowing water to penetrate. C. Non-sealed cracks that are not spalled, but are over ¼-inch wide. D. Low severity alligator cracks exist near crack, or at the corners of intersecting cracks. E. Causes a significant bump to a vehicle. High: (3) A. Severely spalled. (Any width.) B. Medium to high severity alligator cracks exists near the crack, or at the corners of intersecting cracks. C. Causes a severe bump to a vehicle.	Low: (1) 1% to 30% of test section. Med: (2) 31% to 60% of test section. High: (3) 61% of test section, or more.
Alligator Cracks: Pattern of interconnected cracks resembling chicken wire or alligator skin.	Low: (1) Hairline, disconnected cracks. 1/8-inch wide, or less. no spalls. Med: (2) Fully developed cracks greater than 1/8-inch wide. Lightly spalled. High: (3) Severely spalled. Cells rock. May pump.	Low: (1) 1% to 30% of test section. Med: (2) 31% to 60% of test section. High: (3) 61% of test section, or more.
Edge Cracks: Cracks which occur on the edge of the pavement.	Low: (1) ¼-inch wide, or less. No spalls. Med: (2) Greater than ¼-inch wide. Some spalls. High: (3) Severely spalled.	Low: (1) 1% to 30% of test section. Med: (2) 31% to 60% of test section. High: (3) 61% of test section, or more.
Patching: An area where the original pavement has been removed and replaced with similar or different material. Types of Patching: Hot Mix Patch. Skin Patch. Other types (Please note on "note section" of the evaluation card.)	Low: (1) Patch is present, and is in good condition. Med: (2) Somewhat deteriorated. Low to medium of any type of distress on patch. High: (3) Patch is deteriorated to point of soon or immediately needing replacement.	Low: (1) 1% to 30% of test section. Med: (2) 31% to 60% of test section. High: (3) 61% of test section, or more.

APPENDIX B

Weight Factors and Extent Factors Used by NMDOT for the Calculation of the Distress Rate (DR) and Pavement Serviceability Index (PSI) for All Distress Types in Flexible Pavements

TABLE B1 Factors for Extent Ratings and Weight Factors for Flexible Pavements.

Distress Type	Weight Factor	Extent Level	Extent Rating	Extent Factor
Raveling and Weathering		Low	1	0.3
	2	Medium	2	0.6
		High	3	1.0
Bleeding		Low	1	0.3
	3	Medium	2	0.6
		High	3	1.0
Rutting and Shoving		Low	1	0.5
	14	Medium	2	0.8
		High	3	1.0
Longitudinal Cracking		Low	1	0.7
	20	Medium	2	0.9
		High	3	1.0
Transverse Cracking		Low	1	0.7
	12	Medium	2	0.9
		High	3	1.0
Alligator Cracking		Low	1	0.7
	25	Medium	2	0.9
		High	3	1.0
Edge Cracking		Low	1	0.5
	3	Medium	2	0.8
		High	3	1.0
Patching		Low	1	0.3
	2	Medium	2	0.6
		High	3	1.0

APPENDIX C

Rutting Data Collection and Use Survey Questions

Question 1: Does your State's DOT collect rut depth data?
If yes, please continue to the following questions.

Question 2: Are the rutting data collected by your State DOT's personnel or by a contractor?

Question 3: Are rut depth data collected in your State's entire highway network or only in some sections? (Approximate number of miles)

Question 4: Are rut depth data collected annually by your State DOT? What is the frequency of data collection?

Question 5: How is the rut depth measured by your State DOT? (Manually or automatically?) In either case, what is the data collection method used?

Question 6: If rut data are collected automatically, what is the model of the equipment used? How many sensors does it have? What is the frequency of averaging of the rut depth data?

Question 7: Are roughness data collected simultaneously with rut depth?

Question 8: How long have your state DOT been collecting rutting measurements automatically?

Question 9: Are there problems or issues with the rut depth measurements (regarding equipment, data processing, accuracy) that your State DOT had to resolve or still need to resolve?

Question 10: How does your State DOT use the rut depth data? Are the rut depth data used to calculate a pavement serviceability index (PSI) or a pavement condition index (PCI)?

Question 11: What is the equation of PSI or PCI used by your State DOT to assess the conditions of the pavement at the network level?

Question 12: What are the inputs to the PSI or PCI equation? (distresses, roughness, rutting)

Question 13: Is there any other relevant information that your want to share?
Please provide your name, position, District/Section or Bureau, state, phone, fax, e-mail, and address.

APPENDIX D

Rutting and Distress Data Collection Survey Responses

Important note: Minor editorial changes were made to some responses to increase clarity and consistency of presentation.

Question 1: Does your State's DOT collect rut depth data?
Question 2: Are the rutting data collected by your State DOT's personnel or by a contractor?
Question 3: Are rut depth data collected in your State's entire highway network or only in some sections? (Approximate number of miles?)

Agency	**Q1: Rut depth data collected?**	**Q2: Rut depth data collected by DOT or contractor?**	**Q3: Rut depth data collected in entire state's network or selected sections?** [a, b]
Alaska DOT	Yes	Contractor	Highway network (4,000 miles)
Alabama DOT	Yes	Contractor (but ALDOT has the capacity to do it)	Highway network (19,610 miles)
California DOT	Yes	Caltrans personnel (In the future it will be contracted out)	Highway network (50,000 lane miles) until 2007. In 2008, NHS highways only.
Delaware DOT	Yes	Contractor	Highway network (5,600 center line miles)
Florida DOT	Yes	FDOT personnel	Highway network (42,000 miles)
Georgia DOT	Yes	GDOT personnel	Highway network
Idaho DOT	Yes	ITD personnel	Highway network (5,000 miles)
Indiana DOT	Yes	Contractor	Highway network
Kansas DOT	Yes	KDOT personnel	Highway network (10,000 miles)
Louisiana DOT	Yes	Contractor	Highway network (18,000 miles)
Minnesota DOT	Yes	Mn/DOT personnel	Highway network (31,000 miles)
Missouri DOT	Yes	MoDOT personnel	Highway network
Nebraska DOR	Yes	NDOR personnel	Highway network (9,000 miles)
Nevada DOT	Yes	NDOT personnel	Highway network (5,323 center line miles, 10,646 miles)
New Hampshire DOT	Yes	NHDOT personnel	Highway network (48,000 miles)
New Mexico DOT	Yes	NMDOT personnel (automated data) and contractor (manual surveys)	Highway network (26,688 lane miles)

[a] Some states specified if lane miles
[b] NHS: National Highway System

Questions 1, 2 and 3 - Continued

Agency	Q1: Rut depth data collected?	Q2: Rut depth data collected by DOT or contractor?	Q3: Rut depth data collected in entire state's network or selected sections? [a, b]
New York State DOT	Yes	NYSDOT staff/equipment and contractor	Highway network (17,000 center line miles, 41,000 lane miles)
Oregon DOT	Yes	ODOT personnel & contractor	Highway network (5,000 miles)
Pennsylvania DOT	Yes	Contractor	Highway network (27,000 miles/year)
Tennessee DOT	Yes	TDOT personnel & contractor	Highway network (67,000 miles)
Texas DOT	Yes	TxDOT personnel	Highway network (170,000 lane miles)
Wisconsin DOT	Yes	WisDOT personnel	Highway network (13,000 center line miles)

[a] Some states specified if lane miles
[b] NHS: National Highway System

Question 4: Are rut depth data collected annually by your State DOT? What is the frequency of data collection?
Question 5: How is the rut depth measured by your State DOT? (Manually or automatically?) In either case, what is the data collection method used?

Agency	**Q4: Frequency of rut depth data collection?** [a, b]	**Q5: Rut depth data collected manually or automatically?**
Alaska DOT	Most routes annually and the other routes biennially	Automatically
Alabama DOT	NHS routes annually and non-NHS routes biennially	Automatically
California DOT	Approximately every 18 months	Automatically & manually
Delaware DOT	Annually (but may change to biennially in near future)	1) Estimated visually (Windshield survey, given by severity and extent)
		2) Automatically starting in 2009
Florida DOT	Annually	Automatically
Georgia DOT	Annually	Manually. Estimated visually in units of 1/8 in. If rutting is excessive (over 3/8 in.), it is measured with a straightedge.
Idaho DOT	Annually	Automatically
Indiana DOT	Annually	Automatically
Kansas DOT	Annually	Automatically
Louisiana DOT	Biennially	Automatically
Minnesota DOT	Annually	Automatically
Missouri DOT	Some routes annually and other routes biennially, but considering collecting data annually for all routes.	Automatically
Nebraska DOR	Annually	Automatically
Nevada DOT	NHS routes annually and non-NHS routes biennially	Automatically. Also, in each manual rating segment, raters report if rut depth is greater or equal to 0.5 in.
New Hampshire DOT	Biennially	Automatically
New Mexico DOT	Manual surveys: annually. Automated data: annually in NHS routes and biennially in non-NHS routes	Automatically & manually (manual surveys)
New York State DOT	Interstate highways and NHS routes annually and other routes biennially	Automatically

[a] Biennially means here that a route is evaluated every other year
[b] NHS: National Highway System

Questions 4 and 5 - Continued

Agency	Q4: Frequency of rut depth data collection? [a, b]	Q5: Rut depth data collected manually or automatically?
Oregon DOT	Biennially	Automatically
Pennsylvania DOT	NHS routes annually and non-NHS routes biennially	Automatically
Tennessee DOT	Mostly annually except in Region 2 (biennially)	Automatically
Texas DOT	Annually	Automatically
Wisconsin DOT	Biennially	Automatically

[a] Biennially means here that a route is evaluated every other year
[b] NHS: National Highway System

Question 6: If rut data are collected automatically, what is the model of the equipment used? How many sensors does it have? What is the frequency of averaging of the rut depth data?
Note: Intervals for recording, averaging and reporting rut depth data shown below are for individual agencies and do not represent specs for vendors or typical values for other agencies.

Agency	**Model/Brand of profilometer** [a]	**Number of sensors**	**Frequency of rut data averaging**
Alaska DOT	Dynatest system	7 Lasers (front-bumper mounted)	Averaged in 10 ft intervals in urban areas and 0.01 mile intervals in rural areas
Alabama DOT	International Cybernetics Corp. (ICC) Profiler (ALDOT owned); and PathRunner Scanning laser system (Pathway Services)	3 Lasers in ICC Profiler	With PathRunner, max. and mean every 52.8 ft; with ICC, reported in 0.1 mile intervals.
California DOT	Pathview	5 Sensors	*(No response)*
Delaware DOT	Will use ICC Road Profiler with current version of WinPRO starting 2009	3 Sensors	Recorded at 3 in. intervals; typically reported at 1 ft intervals
Florida DOT	Dual Selcom SLS 5200 300-RO	*(No response)*	6 in.
Georgia DOT	N/A	N/A	Manual/visual measurements in a selected 100 ft long sample within each mile.
Idaho DOT	Profilometer by Pathway Services	5-Point laser system	0.1 mile intervals
Indiana DOT	PathRunner PSI-3LG (Pathway Services Inc.). InDOT also uses an LMI Selcom SLS-5000 (16 kHz sensors)	5 Sensors in the PathRunner	Captured every 0.75 in. and sampled every 2-3 in.
Kansas DOT	ICC MDR (Mobile Data Recorder) 4090 van	3 Lasers and 2 accelerometers	Recorded at 1 ft intervals; averaged at 0.1 mile intervals
Louisiana DOT	ARAN Laser Transverse Profiler (Laser XVP) (Roadware)	Refer to: http://roadware.com/_lib/pdf/datasheet.laser_xvp.pdf	Reported at 0.01 miles intervals (every 0.1 miles from 1995 to 2004)

N/A: Does not apply
[a] Survey was done during Fall 2008 and Spring 2009

Question 6 – Continued

Agency	Model/Brand of profilometer [a]	Number of sensors	Frequency of rut data averaging
Minnesota DOT	PathRunner INO Profiler mounted in a van (Pathway Services)	2 Lasers (rut) in the rear, 3 lasers in the front and digital camera	5 ft intervals
Missouri DOT	Roadware's SmartBar System	31 Sensors for rut data	Averaged in 0.01 mile intervals
Nebraska DOR	PathRunner INO Profiler mounted in a van (Pathway Services)	2 INO lasers on the rear and 3 lasers in the front bumper	Stored in 1.5 in. intervals, reported in 0.1 mile intervals
Nevada DOT	ICC high speed profiler	5 Lasers	*(No response)*
New Hampshire DOT	K. J. Law Profilometer	5 Lasers	0.1 mile intervals
New Mexico DOT	Two Dynatest T6600 Inertial High Speed Profilometers (K.J. Law Engineers Inc.)	3 Infrared displacement lasers and 2 accelerometers	Recorded every 6 in., averaged every 0.1 mile
New York State DOT	Roadware ARAN 4900 (5 sensors) and Mandli Communications Inc. Profiler (3 sensors)	For rutting: Roadware with 5-point lasers; Mandli with 3-point lasers	Measured every 26.4 ft; reported in 0.1 mile intervals
Oregon DOT	PathRunner INO Profilometer (contractor, Pathway); and ICC van (ODOT owned)	INO scanning laser; 5 Lasers in ICC Profilometer	Recorded every 6 in. with ICC van
Pennsylvania DOT	*(No response)*	*(No response)*	Every 2.94 ft to nearest 0.125 in. Data are averaged at 6.5 ft intervals
Tennessee DOT	ICC MDR profilometer	5 Laser sensors	6 in.
Texas DOT	TxDOT-fabricated profilers, hardware and software	5-Point fixed acoustic sensors (rut) and 2 lasers (profile)	Measured every 48 in. and averaged in 0.1 mile intervals
Wisconsin DOT	Pathway Services Inc. Profiler and Mandli Communications Inc. Profiler	*(No response)*	Stored at 1 ft intervals with Pathway's profiler and at 5 ft intervals with Mandli's profiler. Summarized to 1 mile intervals.

N/A: Does not apply

[a] Survey was done during Fall 2008 and Spring 2009

Question 7: Are roughness data collected simultaneously with rut depth?
Question 8: How long have your state DOT been collecting rutting measurements automatically?

Agency	Q7: Roughness data collected with rutting data?	Q8: How long have collected automated rut depth data? [a]
Alaska DOT	Yes	Since 1997
Alabama DOT	Yes	Since early 1990's
California DOT	Yes (visually recorded)	About 2 years
Delaware DOT	No, but will collect roughness data in near future	Next collection cycle will be the first experience using a profiler
Florida DOT	Yes	*(No response)*
Georgia DOT	(No) Information on cracking, raveling, edge distresses, bleeding, pushing and patches/ potholes is also collected, which are an indication of roughness.	N/A
Idaho DOT	Yes	Since 1994
Indiana DOT	Yes	Since 1998
Kansas DOT	Yes	Since 1996
Louisiana DOT	Yes	Since 1995
Minnesota DOT	Yes	Since 2005
Missouri DOT	Yes	Since 1988
Nebraska DOR	Yes	Since 1995
Nevada DOT	Yes	Since 1992
New Hampshire DOT	Yes	Since 1998
New Mexico DOT	Yes	Since 1991
New York State DOT	Yes	Since 2003 (with Roadware ARAN)
Oregon DOT	Yes	Since 2003 with ICC Profilometer; since 2008 with PathRunner INO Profilometer
Pennsylvania DOT	Yes	Since 1997
Tennessee DOT	Yes	Since 1998
Texas DOT	Yes	Since 1995
Wisconsin DOT	Yes	Since 1995

N/A: Does not apply
[a] Survey was done during Fall 2008 and Spring 2009

Question 9: Are there problems or issues with the rut depth measurements (regarding equipment, data processing, accuracy) that your State DOT had to resolve or still need to resolve?

Agency	Responses (Open-ended responses)
Alaska DOT	Some of the District engineers still only believe in hand (manual) measurements.
Alabama DOT	The accuracy of the 3-point rut data is highly influenced by the vehicle's location in the lane. The scanning laser data has to be processed to a higher degree by the vendor, but the vehicle's position in the lane isn't as big a factor to the rut measurement accuracy. The ALDOT 3-laser system will give negative rut depths, which can be difficult to process out. If we get negative values, we set those to zero.
California DOT	Some problems with rut measurements being out of range. Data processing has mostly solved this problem by eliminating out of range data.
Delaware DOT	N/A
Florida DOT	No problems. Collecting data is very time consuming.
Georgia DOT	N/A
Idaho DOT	The results depend on the driver of the van, who should drive in a straight path. Increasing accuracy and repeatability requires higher costs.
Indiana DOT	We are not aware of any issues with the automated data collections, ie. Rut and IRI.
Kansas DOT	Rutting is not much of a problem on our state highways these days, so data collection or processing is not a problem. We are aware of changes coming to the Highway Performance Monitoring System requirements that may force us to make changes from our 3 point system to a 5 or more point system.
Louisiana DOT	Our problems are changes in technology. For instance in 1995 and 1998, collected rutting using ultrasonic foot print; in 2000 and 2002, collected rutting using 3 point laser; in 2005, 2007 and currently, collected rutting using scanning laser. The problem is that the answers from a scanning laser are more precise than the other methods, but are not comparable to the ultrasonic and/or 3 point laser. Thus, rutting determination curves have to be developed from 2005 to present data.
Minnesota DOT	No problems. Goggles should be used to see the laser beam. Rutting needs to be verified.
Missouri DOT	In order to accurately measure ruts automatically the equipment must scan the entire lane. This is not an ideal situation for the roadway users, the operators and the equipment.
Nebraska DOR	There are no major problems with collecting or processing rutting data. Regular maintenance and calibration of equipment take care of normal problems. Once in a great while the INO system stops collecting data, then it will go back on line and start collecting data again.

N/A: does not apply

Question 9 – Continued

Agency	Responses (Open-ended responses)
Nevada DOT	None
New Hampshire DOT	This 5-laser system can not be used for secondary roads because of how the pavements are constructed in this type of roads.
New Mexico DOT	NMDOT is considering replacing its current 3-point profilometers with a scanning laser profilometer. Funding is an issue.
New York State DOT	The Mandli van began production testing in 2008. We still have to compare the rut measures from the 5-point ARAN to the 3-point Mandli van. We expect to see some difference, but we don't know how much.
Oregon DOT	5-Laser rut is not accurate in both wheelpaths when the rut spacing does not match the distance between the wheeltrack lasers. The INO should help with this. We are still learning about INO limitations.
Pennsylvania DOT	We cannot QA the vendor rutting data other than a manual verification on limited sites at beginning of each survey year.
Tennessee DOT	Pretty satisfied.
Texas DOT	Yes. Acoustic sensors cannot provide ¼-inch rut depth with enough reliability at highway speeds. Although they are cheap and easy to maintain, they are subject to significant problems with wind and humidity. Also, the fixed-width configuration is not wide enough to get full 12-foot lane width. We are working on a 3-dimensional camera to get 11.5-foot lane width measurements with basically a continuous transverse profile measured every 1-2 inches (instead of our current 8.5-foot width measured every 48 inches). Results are very promising, even at 70 miles per hour, but we have not deployed the new camera on our 16-profiler fleet yet (more accuracy and precision testing are required, and we still have to write a program to interpret the transverse profile to calculate rut depth).
Wisconsin DOT	There are no significant problems associated with WI DOT rut data.

Question 10: How does your State DOT use the rut depth data? Are the rut depth data used to calculate a pavement serviceability index (PSI) or a pavement condition index (PCI)?

Agency	Responses (Open-ended responses)
Alaska DOT	Rutting data is used to develop pavement rehabilitation recommendations
Alabama DOT	The rut data is used, along with other distress measurements to report a pavement condition rating.
California DOT	The automatic data is not currently being used. The manually collected data is used in priority matrix for maintenance strategies.
Delaware DOT	Currently the rut data is used along with other distresses collected to calculate an overall pavement condition. This is used to formulate a list of candidates for rehabilitation. If a segment has ruts <1 in., it has a medium severity score. High severity is greater than 1 in. Extent of rutting is low if the segment affected is 1-9% of the area that is being surveyed, medium if it is 10-25% of the area, and high if it is greater than 25% of the area.
Florida DOT	The data collected is used to calculate an International Roughness Index (IRI)
Georgia DOT	Rutting is part of the deduct values for a section of roadway, along with cracking, raveling, edge distresses, bleeding, pushing and patches/ potholes, that provides our overall PACES (Pavement Condition Evaluation System) rating for a section of road.
Idaho DOT	Roughness data is used for IRI.
Indiana DOT	It was used to calculate PSI. It is now used as a stand alone measurement
Kansas DOT	Rutting is considered a secondary distress in our distress state.
Louisiana DOT	Data are used to calculate a pavement condition index and a performance index.
Minnesota DOT	Use information to calculate a pavement quality index (PQI) and other condition indexes
Missouri DOT	Rut depth is a component of the Present Serviceability Rating (PSR) score.
Nebraska DOR	The rutting or faulting measurement is used to provide a single value termed the Nebraska Serviceability Index (NSI)
Nevada DOT	The rutting data is one component used to calculate PSI.
New Hampshire DOT	Data are used to calculate a Rut Rate Index (RRI)
New Mexico DOT	Data are used to calculate a performance index, the New Mexico Pavement Serviceability Index (PSI). The PSI is used to characterize the conditions of New Mexico's highways.
New York State DOT	Rut depth is one of the factors used to calculate the PCI (Pavement Condition Index).
Oregon DOT	Rut depth is used in the PCI calculation.

Question 10 – Continued

Agency	Responses (Open-ended responses)
Pennsylvania DOT	Rutting Index (RUT) is used to calculate Overall Pavement Index (OPI)
Tennessee DOT	Measurements are used to calculate a condition index (PSR)
Texas DOT	Rut depth is summarized into categories. For example, shallow rut (0.25-0.49 in.), deep rut (0.50-0.99 in.), severe rut (1.00-1.99 in.) and failure rut (2 in. or more). Each category contains the percentage of wheelpath length of rutting.
Wisconsin DOT	The (rut depth) information is used in support of PCI

Question 11: What is the equation of PSI or PCI used by your State DOT to assess the conditions of the pavement at the network level?
Question 12: What are the inputs to the PSI or PCI equation? (distresses, roughness, rutting)

Agency	Responses (Open-ended responses)
Alaska DOT	Currently, Dynatest's Pavement Economic Rating System (PERS) programs for network analysis. PERS programs have transfer functions for IRI, Rutting and structural layer modulus degradation along with future time and traffic inputs.
Alabama DOT	Currently developing a new equation. [a]
California DOT	California doesn't use PSI or PCI
Delaware DOT	Distress scores are given to asphalt patching, surface defects, fatigue cracking, block cracking, transversal cracks, edge cracks and rough crowns. Then the average score is calculated. The standard deviation is also calculated. The Overall Pavement Condition: OPC = (Average value) – (Standard Deviation) x 1.25 Input data: Composite: fatigue cracking, reflective cracking, surface defects and block cracking Surface Treatment: fatigue, bleeding, surface defects, edge cracking, and roughness/crown. Flexible: fatigue, transverse, block cracking, patch deterioration, and surface defects.
Florida DOT	Ride Rating (0 to 100 scale): RR_{100} = RN x 20, where RN = Ride Number (0 to 5 scale). Input: distresses, roughness and rutting
Georgia DOT	We do have a research report that can be sent that defines the development of the equations used in the COPACES (computerized PACES) application. Rutting is part of the deduct values for a section of roadway, along with cracking, raveling, edge distresses, bleeding, pushing and patches/potholes.
Idaho DOT	IRI and a Surface Index (SI). Inputs: Distress, roughness and rutting.
Indiana DOT	No longer used to calculate PSI.

[a] Survey was done during Fall 2008 and Spring 2009

Questions 11 and 12 – Continued

Agency	Responses (Open-ended responses)
Kansas DOT	We use a distress state instead of PSI or PCI because it provides a condition that maintains the component information. The Distress State index concatenates three digits. The first digit is roughness level. Basically, if the roughness is less than 105 in/mile it is RL1; greater than 164 in/mile is RL3. The next digit represents transverse cracking for black surfaces and joint distress for PC surfaces. These are a bit more difficult to describe, but individual crack and joint distress ratings are combined based on their severity and extent to determine the level. Finally, rutting and faulting levels make up the last digit. The rutting levels are set as less than 0.5" for RutLev1; >1" for RutLev3. Therefore, the distress state will end up being 111 to 333. The nice thing about this indicator is that it retains info about pavement roughness, transverse cracking, rutting, or any combination of the three within the same index.
Louisiana DOT	Rut index is calculated by interpolating between two known points in a chart or graph (Chart and graph were provided). Inputs for composite and asphalt pavements: Random, Alligator, Patching, Roughness and Rut.
Minnesota DOT	$PQI = \sqrt{(RQI)\ (SR)}$ where RQI = Ride Quality Index; SR = Surface Rating (Additional information on PQI calculation was provided) Input: pavement roughness, distresses and overall pavement quality.
Missouri DOT	For asphalt pavements, Present Serviceability Rating: PSR = Ride (20) + Cracking (10) + Rutting (5) + Patching/Raveling (5) The total maximum score of PSR is 40.
Nebraska DOR	Nebraska Serviceability Index (NSI). This provides a single value which can be used to monitor pavement performance with time. The NSI rating is calculated using a combination of the visual distresses and the rutting or faulting. (Additional information on NSI was provided)
Nevada DOT	$PSI = 5e^{(-0.0041\ IRI)} - 1.38(RD)^2 - 0.03(C+P)$ where IRI =International Roughness Index; RD= Average rut depth; C = cracking percent; P = patching percent
New Hampshire DOT	Own performance index: Rut Rate Index (RRI) and a composite index. RRI varies between 0.6 and 4.8 and correlates to rut depth. Input for composite index: distresses, roughness and rutting

Questions 11 and 12 – Continued

Agency	Responses (Open-ended responses)
New Mexico DOT	PSI = Pavement Serviceability Index) PSI = 0.041666 X, if $X \leq 60$, or PSI = [0.0625(X – 60)] + 2.4999, if $X > 60$, where $X = 100 - \left[\frac{0.6(IRI - 25) + (0.4DR)}{2.9}\right]$, IRI = International Roughness Index; DR = Distress Rate, which is a function of the ratings of eight distress types including rutting. The PSI of a roadway section ranges from 0.0 to 5.0. Interstate and non-interstate highway sections are considered to be in good condition when their respective PSI values are equal to or greater than 3.0 and 2.5, respectively. Input: distresses, roughness (IRI) and rutting
New York State DOT	The PCI (Pavement Condition Index) is calculated by starting with a perfect score of 100 and subtracting deduction points for each distress based on the distress type and severity. For Asphalt/Overlay Pavements: Surface Score: 35 pts.; IRI: 35 pts.; Rutting: 15 pts.; Alligator Crack: 15 pts.; or Widening Drop: 15 pts. (Additional information on PCI calculation was provided)
Oregon DOT	Pavement Condition Index (PCI). Refer to: http://www.oregon.gov/ODOT/HWY/CONSTRUCTION/docs/pavement/2008_pavement_condition_report.pdf
Pennsylvania DOT	An overall pavement index (OPI) is used on a limited basis. Inputs: distresses, roughness and rutting (Additional information on OPI calculation was provided)
Tennessee DOT	Condition index (PSR). Input: distresses, roughness and rutting
Texas DOT	Texas DOT does use PSI, but it is calculated from the average of left and right IRI (International Roughness Index). Condition Score includes distress, rut, and ride, with adjustment factors for ADT and Speed Limit.
Wisconsin DOT	The equations used for the rut aspect of PCI can be obtained in ASTM D6433. Input: Surface distress and rut depth per ASTM D6433.

Question 13: Is there any other relevant information that your want to share?

Agency	Responses (Open-ended responses)
Alaska DOT	I was the Pavement Management Engineer for 12 years until 2007 when I took my current position. Pavement management is mostly done by consultants now.
Alabama DOT	*(No response)*
California DOT	Not at this time
Delaware DOT	We are currently in the process of hiring a consultant who will perform this work semi-automated. We will be collecting IRI and rutting measurements for all segments.
Florida DOT	*(No response)*
Georgia DOT	*(No response)*
Idaho DOT	Further improvements in the equipment may be needed. Possibly increase the number of sensors
Indiana DOT	*(No response)*
Kansas DOT	Slope or horizontal ground can get better result.
Louisiana DOT	*(No response)*
Minnesota DOT	*(No response)*
Missouri DOT	*(No response)*
Nebraska DOR	*(No response)*
Nevada DOT	In 1992, as we switched to an automatic data collection system, we did a comparison of the manual rut measurements taken with a rut gauge to the data obtained with a 5-sensor ultrasonic road profiler. We found on average a 3% difference. In 2001, we switched from an ultrasonic system to a 3-laser sensor system and in 2007 we switched to a 5-laser system.
New Hampshire DOT	*(No response)*
New Mexico DOT	*(No response)*

Question 13 – Continued

Agency	Responses (Open-ended responses)
New York State DOT	We are aware of the LTTP rut measurement study published a few years ago. That study essentially concluded that 3 point rut measures were worthless and 5 point was not much better. The problem is that if the laser is not in the deepest part of the rut, then the rut depth is under-measured. We have done some study of rut measures from our 5 point system compared to hand measurements and found quite good correlation when we used the maximum rut measured per 0.10 mile. The compensating factor is that the vehicle naturally wanders back and forth across the lane as the data is collected. As long as the laser passes through the deepest part of the rut at least once in the 0.10 mile, then a representative measure is obtained. We feel that the rut data we obtain with the 5-point system is good enough for network level analysis, especially given the relative simplicity and lower cost of the system. We are a little more skeptical of the quality of data from the Mandli 3-point system, but we haven't had the opportunity to take a detailed look.
Oregon DOT	*(No response)*
Pennsylvania DOT	*(No response)*
Tennessee DOT	Need much more research on these data.
Texas DOT	How you define the rut determines the values obtained for rut depth. We use a broken-stringline method: left edge of lane to center of the lane defines the left rut; right edge of lane to center of lane defines the right rut. This is not the same as a constant elevation method which would give the depth of water ponds in a rut. On many of our roads, rutting is more like surface distortion than it is actual U-shaped rut troughs.
Wisconsin DOT	*(No response)*

Name and contact information of responders

Agency	Name and Title or Position	Address and/or Phone, Fax and Email
Alaska DOT	R. Scott Gartin, State Quality Assurance Engineer, Statewide Materials Section	Alaska Department of Transportation & Public Facilities, Ph: 907-269-6244, Fax: 907-269-6231, scott.gartin@alaska.gov
Alabama DOT	Scott W. George, Pavement Management Engineer Materials And Tests Bureau	3700 Fairground Road, Montgomery, AL 36110, Ph: 334-206-2220, Fax: 334-264-6263, georges@dot.state.al.us
California DOT	Bob Moore, Pavement Management Engineer, Chief Pavement Management Information Branch	1120 N St. Sacramento , CA 98814, Ph: 916-651-2011, Fax: 916-653-5859, Bob_moore@dot.ca.gov
Delaware DOT	Kim Johnson, Pavement Management	800 Bay Road, Dover, DE 19903, Ph: 302-760-2067, Fax: 302-739-5270, Kimberly.johnson@state.de.us
Florida DOT	Joshua Whitaker, Pavement Management Engineer	Ph: 352-955-2918, Joshua.whitaker@dot.fl.us
Georgia DOT	Georgene M. Geary, State Materials and Research Engineer	15 Kennedy Dr., Forest Park, GA 30297, Ph: 404-363-7512, Fax: 404-362-4925, ggear@dot.ga.gov
Idaho DOT	Charles Gillin, Pavement, Management Engineer, Division of Planning	3311 W. State St., P.O. Box 7129, Boise, ID 83707-1129, Ph: 208-334-8232, Fax: 208-334-4432, Charles.gillin@itd.idaho.gov
Indiana DOT	Jewell Stone, Pavement Management Engineer	INDOT Central Office Planning, Pavement Section, Ph: 317-234-5726, JSTONE@indot.IN.gov
Kansas DOT	Rick Miller, Asst. Geotechnical Engineer	Ph: 785-291-3842, rick@ksdot.org
Louisiana DOTD	Christopher Fillastre, Pavement Management Engineer	Louisiana Department of Transportation and Development, Section 21, Management Systems and Data Collection, 1201 Capitol Access Road, P.O. Box 94245, Baton Rouge, LA 70804-9245, Ph: 225-242-4577, Fax: 225-242-4595, christopheFillastre@dotd.la.gov
Minnesota DOT	Dave Janisch, Pavement Management Engineer	Office of Materials and Road Research 1400 Gervais Ave., Maplewood, MN 55109 Ph: 651-366-5567, Fax: 651-366-5461, Dave.janisch@dot.state.mn.us
Missouri DOT	John Donahue, Construction and Materials Liaison Engineer	1617 Missouri Blvd., Jefferson City, MO 65109, Ph: 573-526-4334, Fax: 573-526-4324, John.donahue@modot.mo.gov

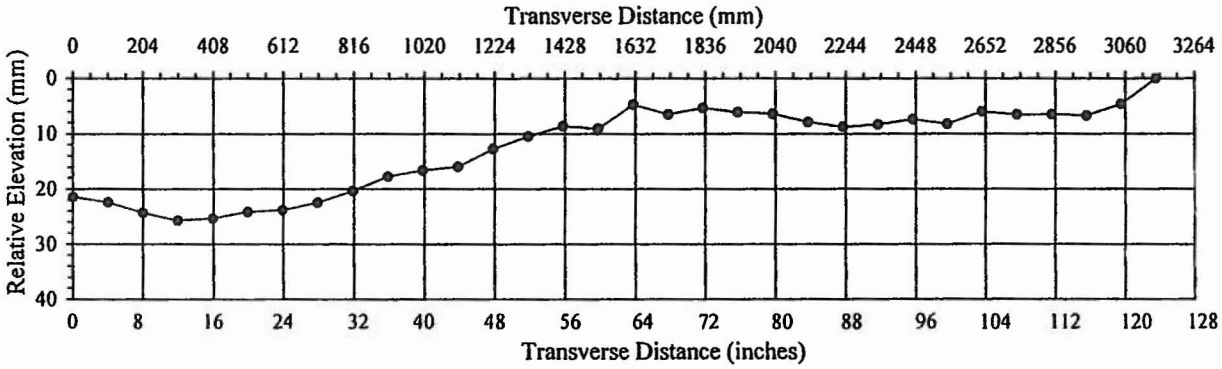
Name and contact information of responders – Continued

Agency	Name and Title or Position	Address and/or Phone, Fax and Email
Nebraska DOR	Gary Brhel, Pavement Management Supervisor	Nebraska Department of Roads, Ph: 401-479-3620, Gary.brhel@nebraska.gov
Nevada DOT	Patricia Lu Polish, Senior Materials Supervisor	1263 South Stewart St., Carson City, Nevada 89712, Ph: 775-888-7173, Fax: 775-888-7501, pPolish@dot.state.nv.us
New Hampshire DOT	Eric S. Thibodeau, Chief Pavement Management Office	Bureau of Materials & Research PO Box 483, 5 Hazen Drive Concord, NH 03302-0483, Ph: 603-271-3151, Fax: 603-271-8700, EThibodeau@dot.state.nh.us
New Mexico DOT	Robert S. Young, Pavement Preservation Engineer	State Maintenance Bureau, SB-2, PO Box 1149, 1120 Cerrillos Road, Santa Fe, NM 87504-1149, Ph: 505-827-0051, Fax: 505-827-3202, Robert.Young@state.nm.us
New York State DOT	Rick Bennett, Pavement Manager, Office of Technical Services	Ph: 518-485-8976, rbennett@dot.state.ny.us
Oregon DOT	John S. Coplantz, Pavement Management Engineer	Ph: 503-986-3119, john.s.coplantz@odot.state.or.us
Pennsylvania DOT	Janice L. Arellano, Chief, Roadway Inventory and Testing Section, Bureau of Maintenance and Operations	907 Elmerton Ave, Harrisburg, PA 17110, Ph: 717-787-7294, Fax: 717-787-6013, jarellano@state.pa.us
Tennessee DOT	James Maxwell, Pavement Design Engineer	1200 James K. Polk Building Nashville, TN 37243-0340 Ph: 615-741-0839, Fax: 615-253-5218 james.maxwell@state.tn.us
Texas DOT	Bryan E. Stampley, Senior Pavement Engineer, Construction Division, Materials & Pavements Section	125 East 11th St., Austin, TX 78701, Ph: 512-465-3676, Fax: 512-465-3059, Bstample@dot.state.tx.us
Wisconsin DOT	Bill Duckert, Pavement Management Engineer	3502 Kinsman Blvd, Madison, WI 53704, Ph: 608-246-5440, Fax: 608-245-8959, william.duckert@dot.wi.gov

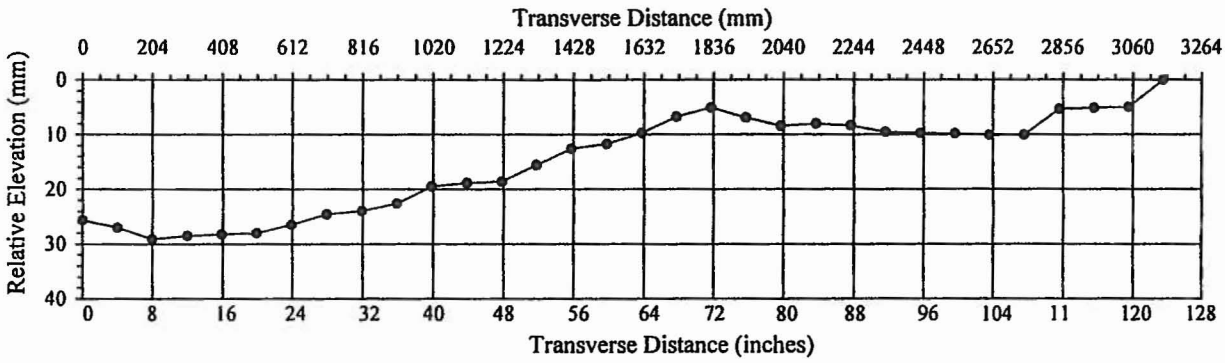
APPENDIX E

Transverse Profiles for Highway NM0185, Milepost (MP) Points 4.0, 5.1, 6.0 and 7.1

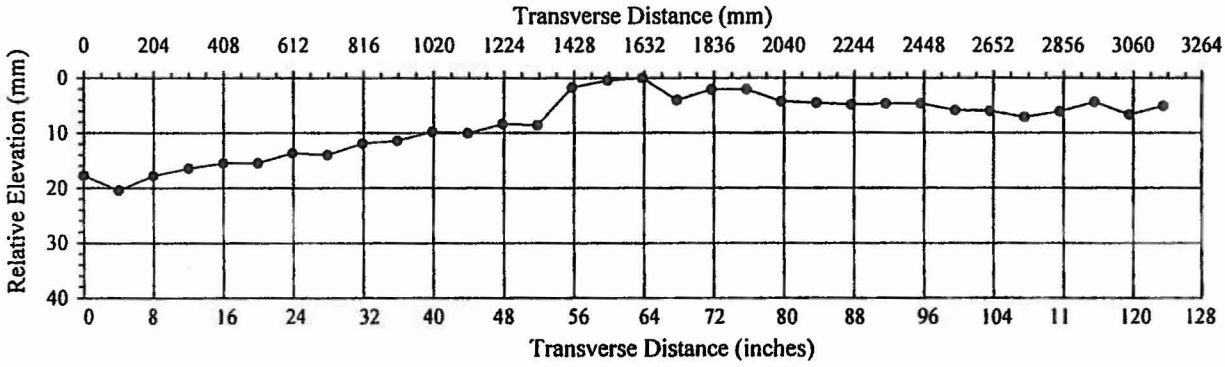
Profile 0, Test Section NM0185 P MP4.0 (May 13, 2009)



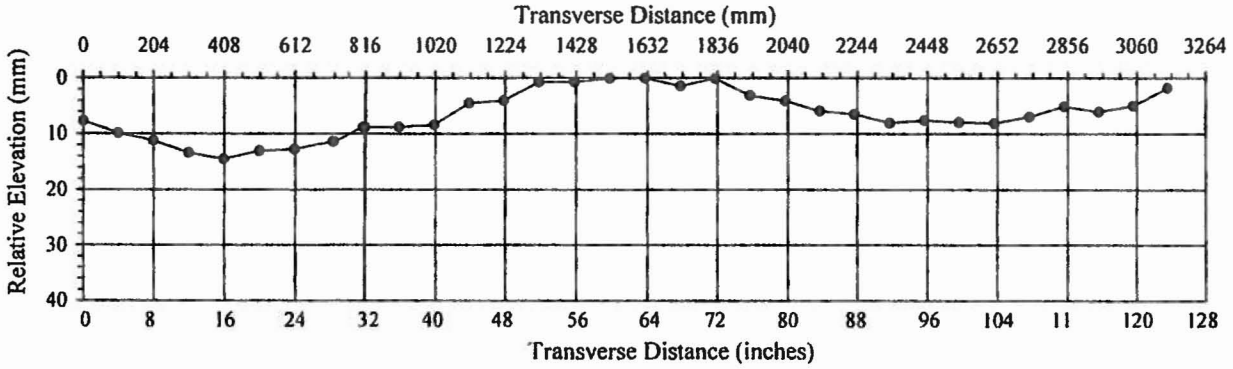
Profile 7.6, Test Section NM0185 P MP4.0 (May 13, 2009)



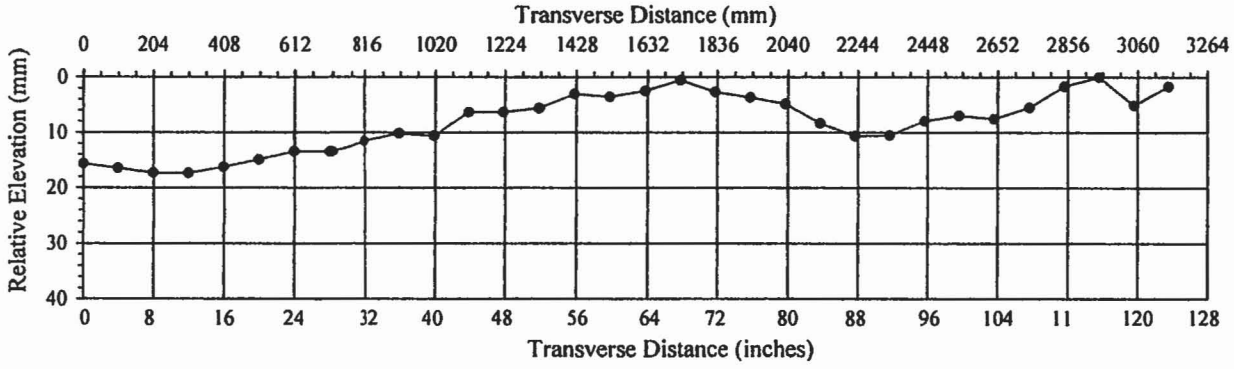
Profile 15.2, Test Section NM0185 P MP4.0 (May 13, 2009)



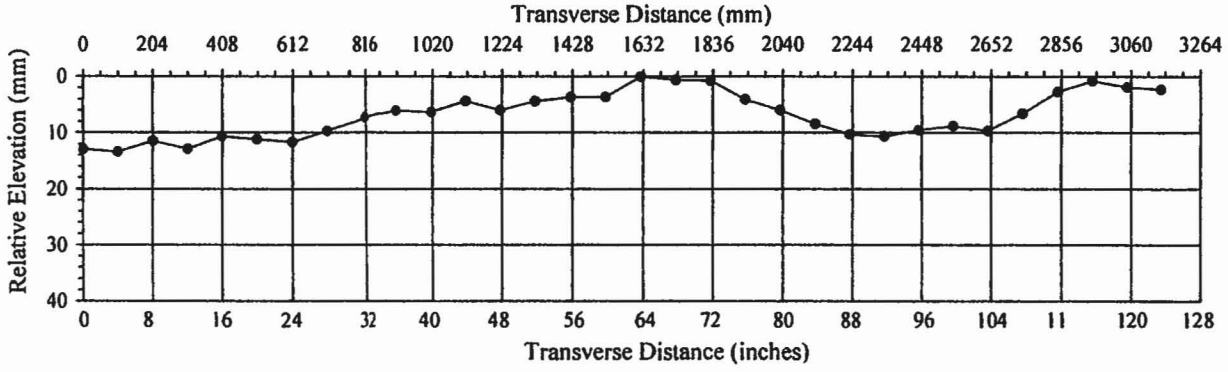
Profile 22.9, Test Section NM0185 P MP4.0 (May 13, 2009)



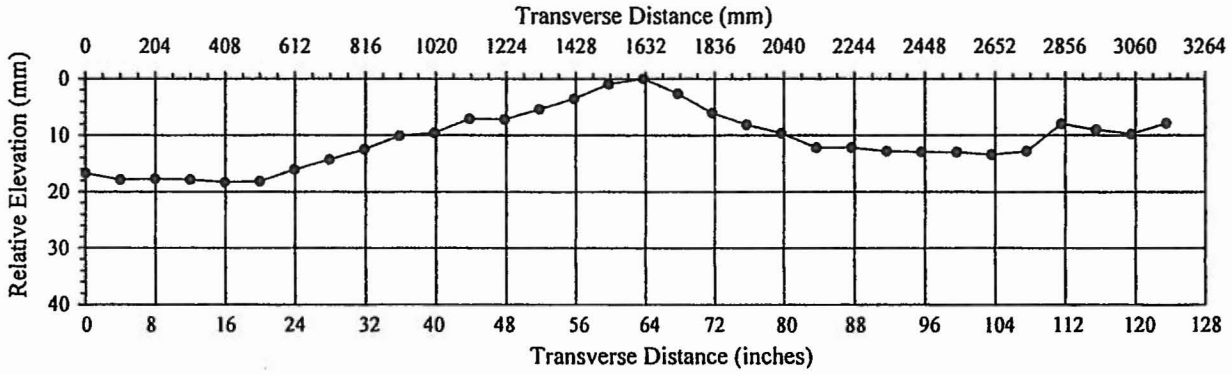
Profile 30.5, Test Section NM0185 P MP4.0 (May 13, 2009)



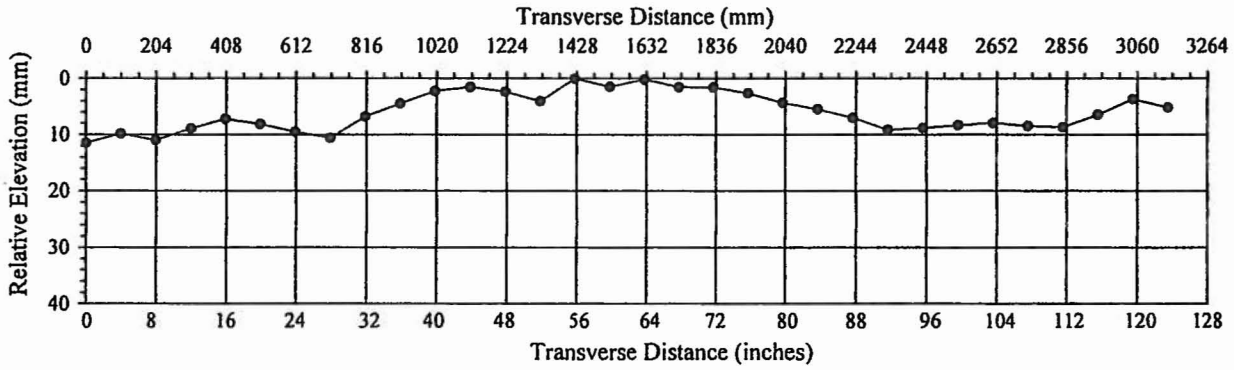
Profile 38.1, Test Section NM0185 P MP4.0 (May 13, 2009)



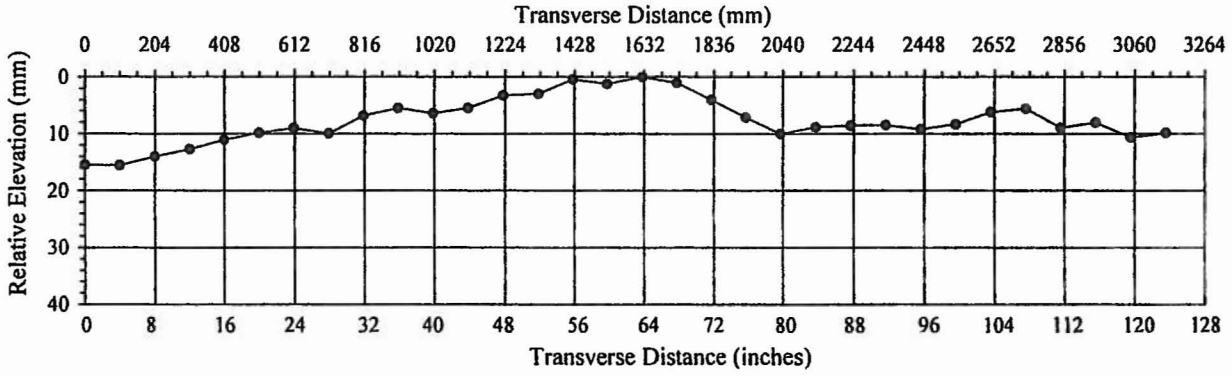
Profile 45.7, Test Section NM0185 P MP4.0 (May 13, 2009)



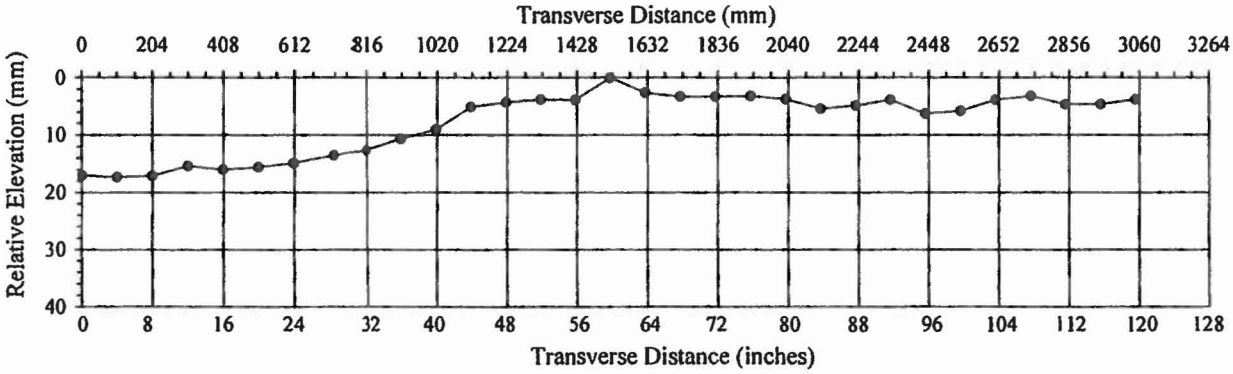
Profile 53.3, Test Section NM0185 P MP4.0 (May 13, 2009)



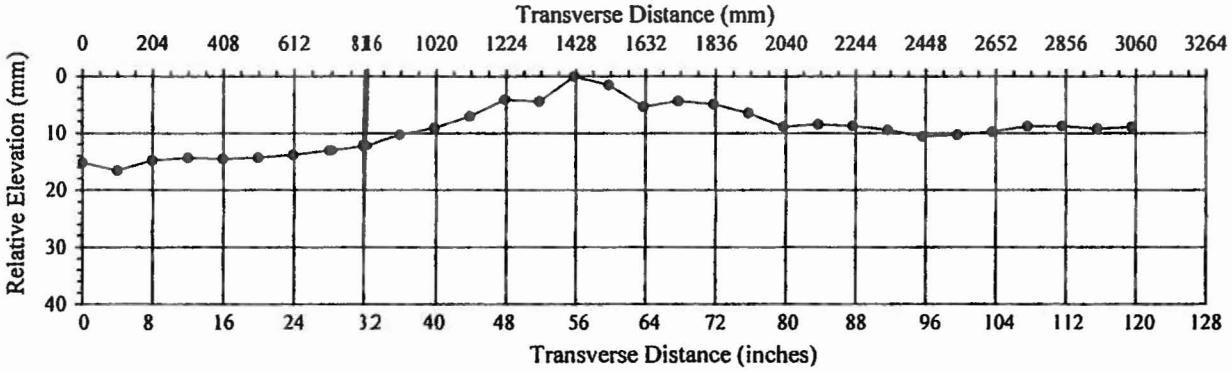
Profile 61, Test Section NM0185 P MP4.0 (May 13, 2009)



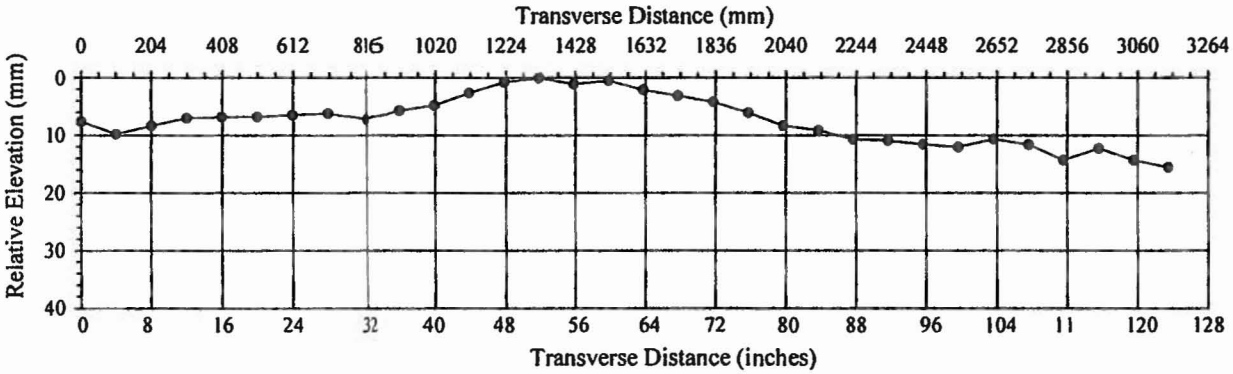
Profile 68.6, Test Section NM0185 P MP4.0 (May 13, 2009)



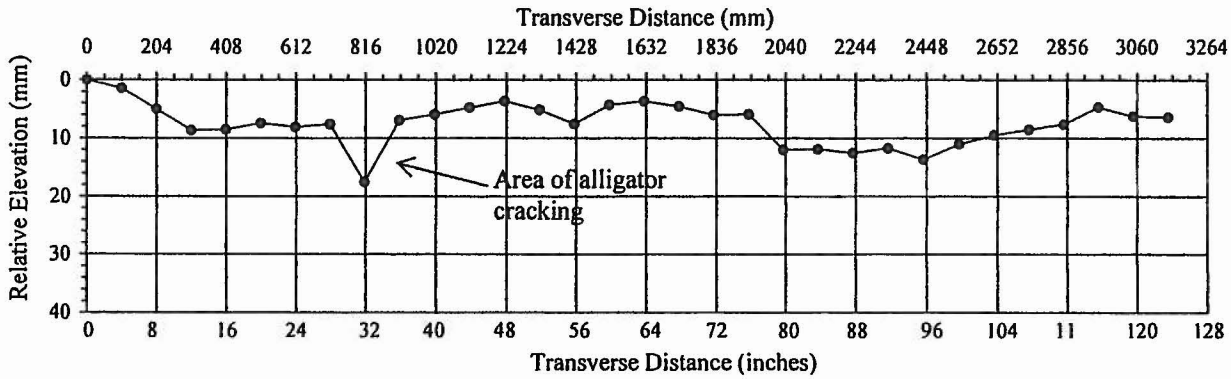
Profile 76.2, Test Section NM0185 P MP4.0 (May 13, 2009)



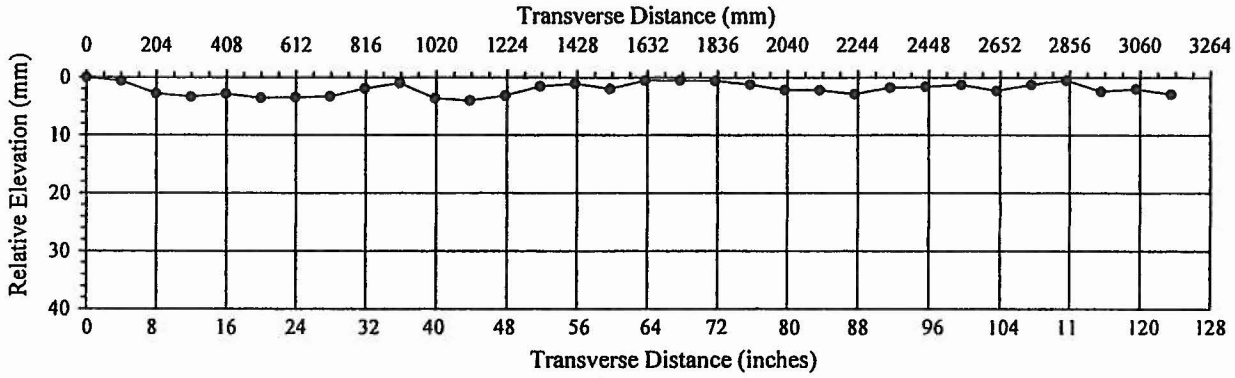
Profile 83.8, Test Section NM0185 P MP4.0 (May 13, 2009)



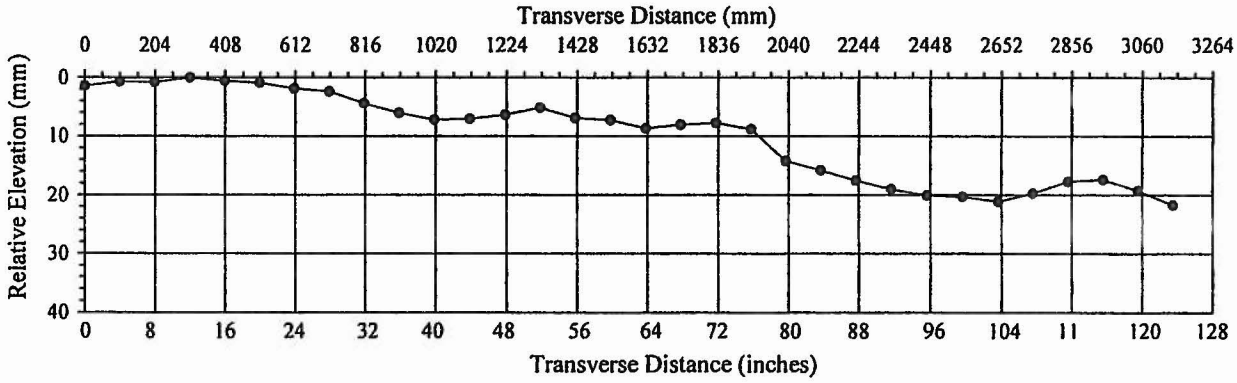
Profile 91.4, Test Section NM0185 P MP4.0 (May 13, 2009)



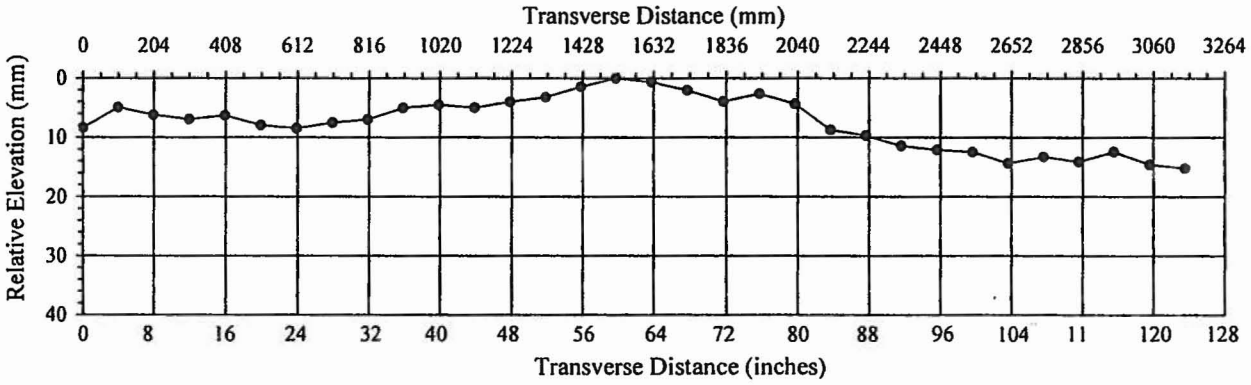
Profile 99.1, Test Section NM0185 P MP4.0 (May 13, 2009)



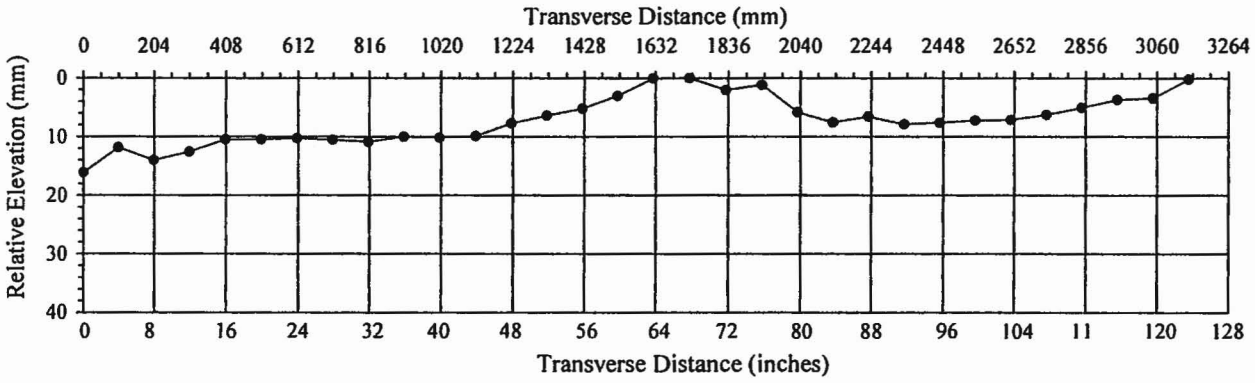
Profile 106.7, Test Section NM0185 P MP4.0 (May 13, 2009)



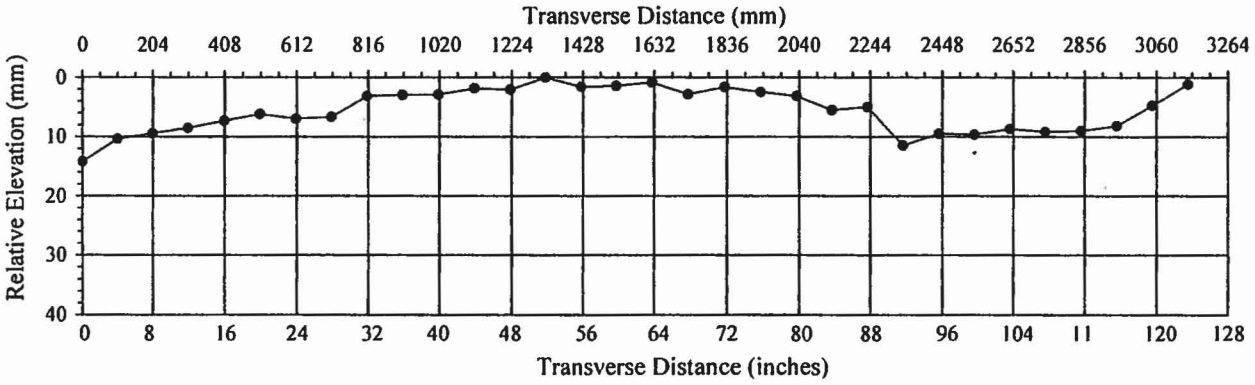
Profile 114.3, Test Section NM0185 P MP4.0 (May 13, 2009)



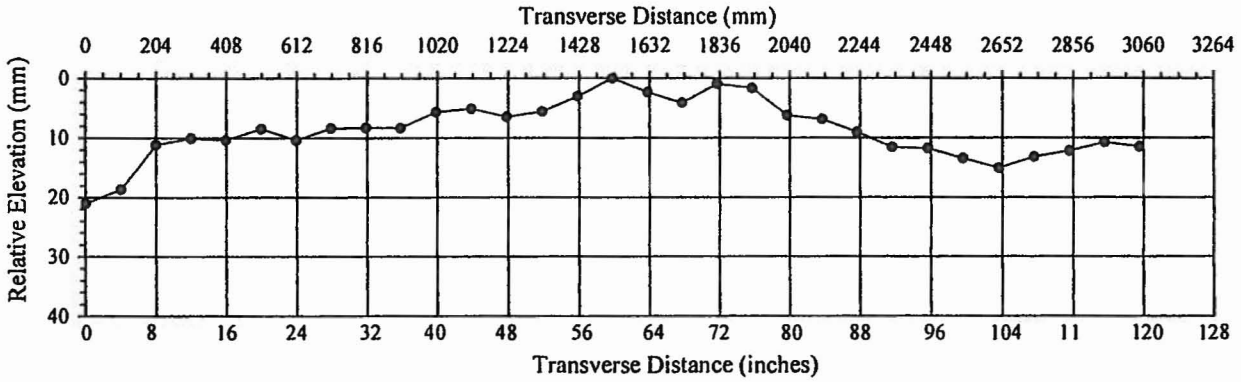
Profile 121.9, Test Section NM0185 P MP4.0 (May 13, 2009)



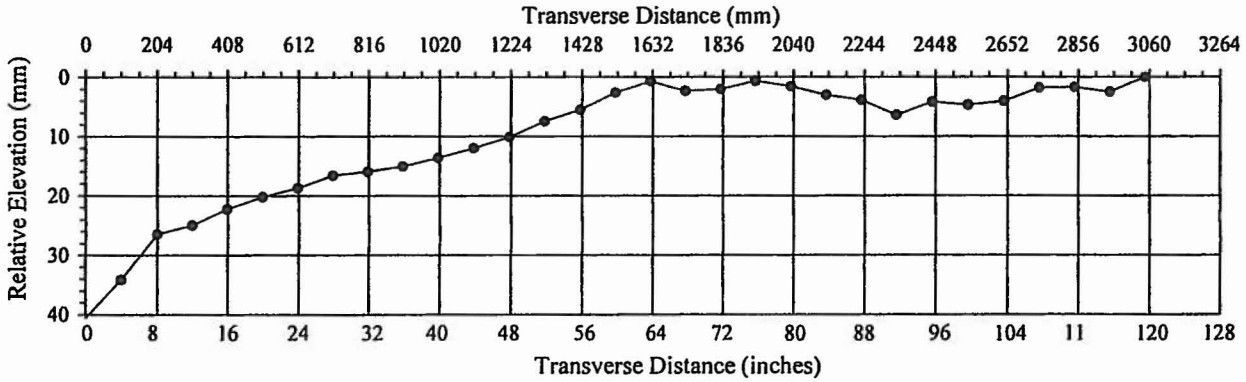
Profile 129.5, Test Section NM0185 P MP4.0 (May 13, 2009)



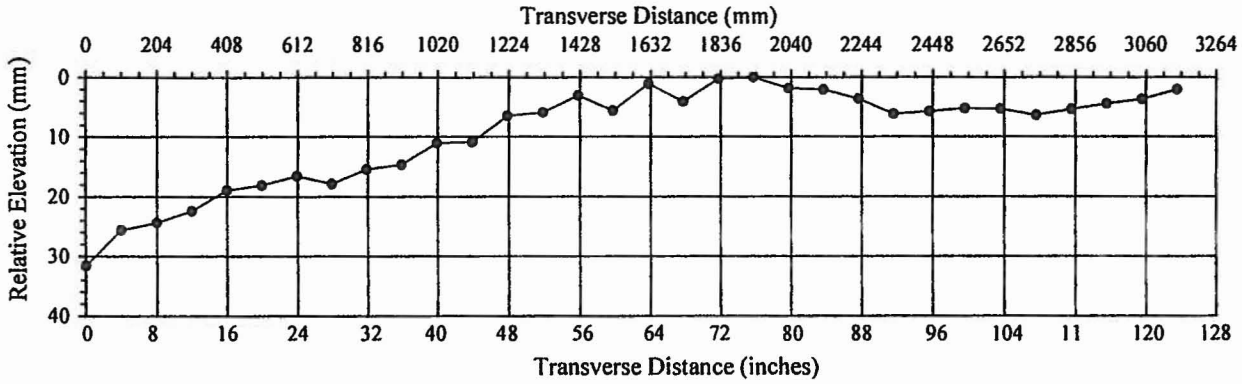
Profile 137.2, Test Section NM0185 P MP4.0 (May 13, 2009)



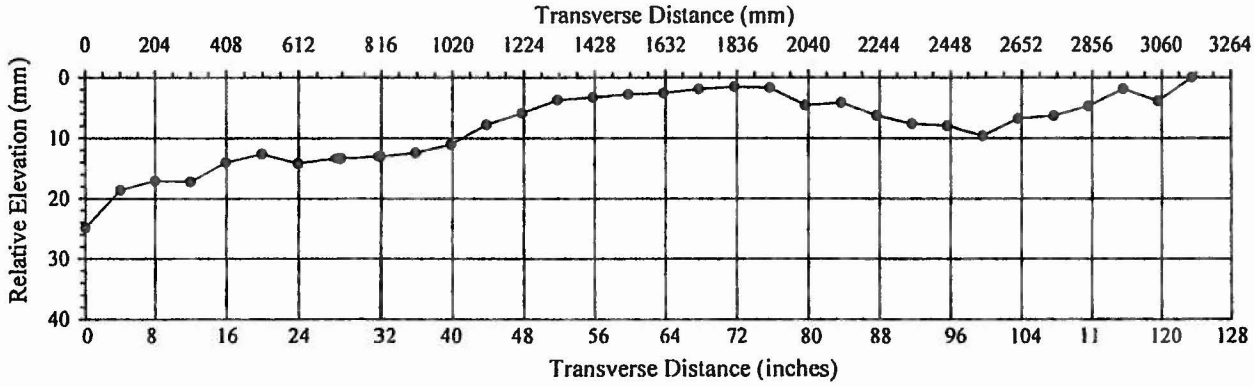
Profile 144.8, Test Section NM0185 P MP4.0 (May 13, 2009)



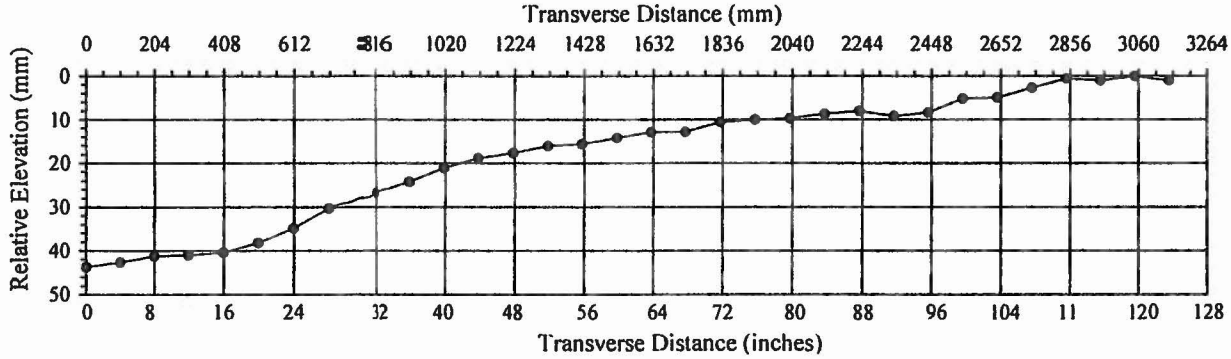
Profile 152.4, Test Section NM0185 P MP4.0 (May 13, 2009)



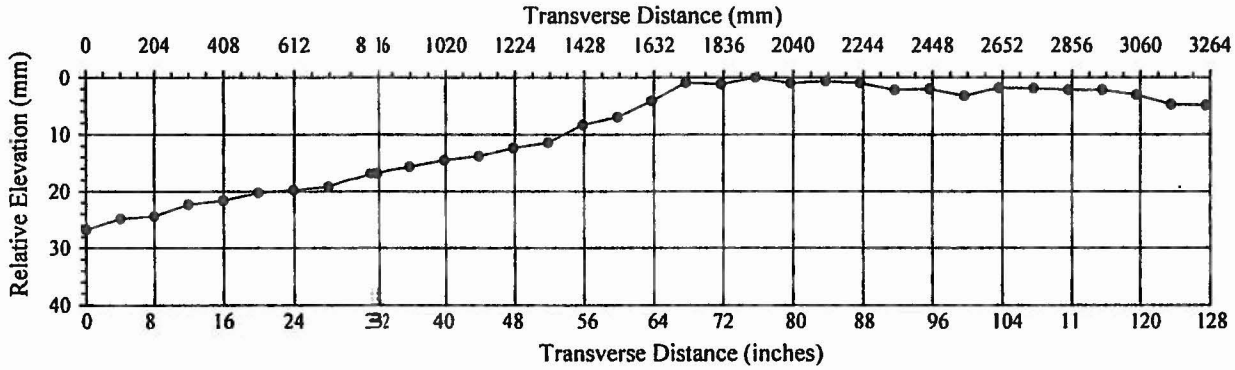
Profile 160, Test Section NM0185 P MP4.0 (May 13, 2009)



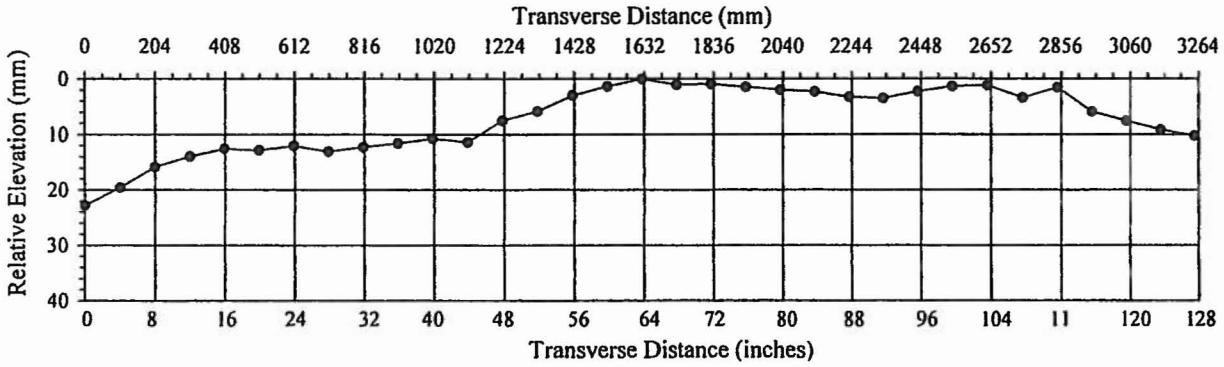
Profile 0, Test Section NM0185 P MP5.1 (May 14, 2009)



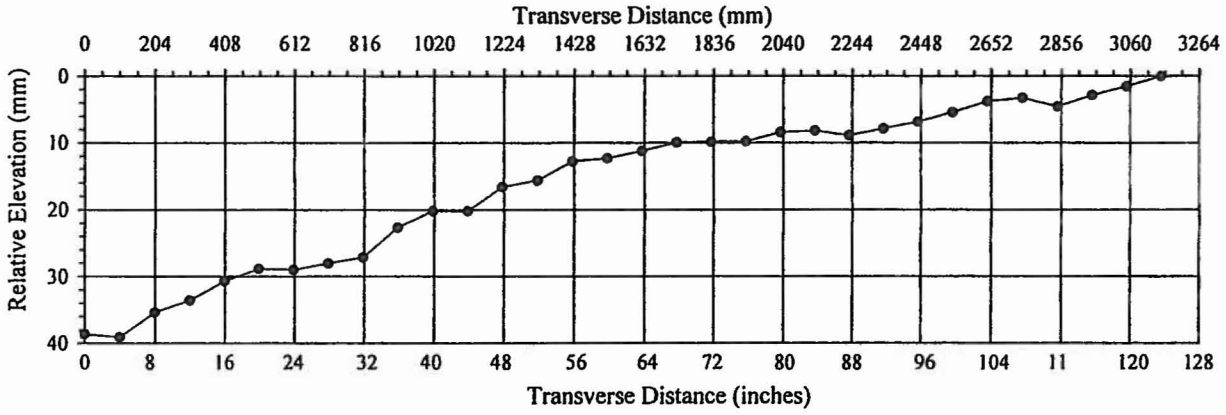
Profile 7.6, Test Section NM0185 P MP5.1 (May 14, 2009)



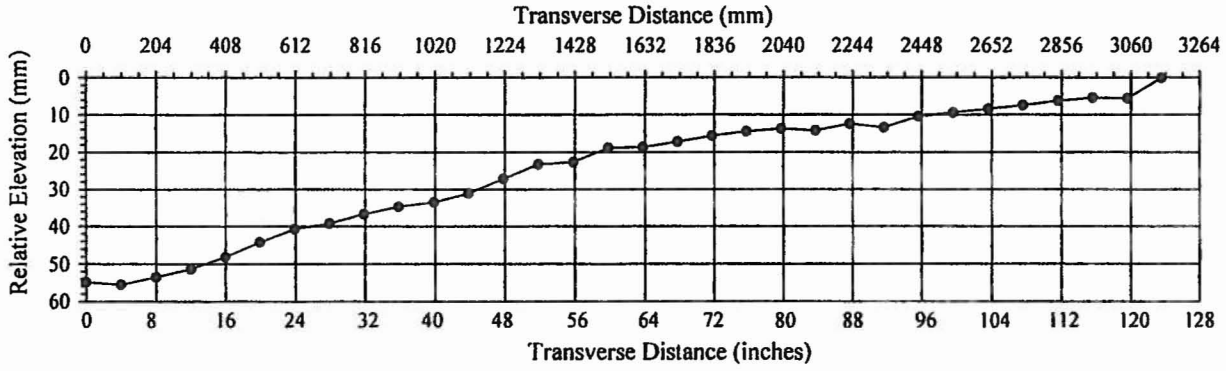
Profile 15.2, Test Section NM0185 P MP5.1 (May 14, 2009)



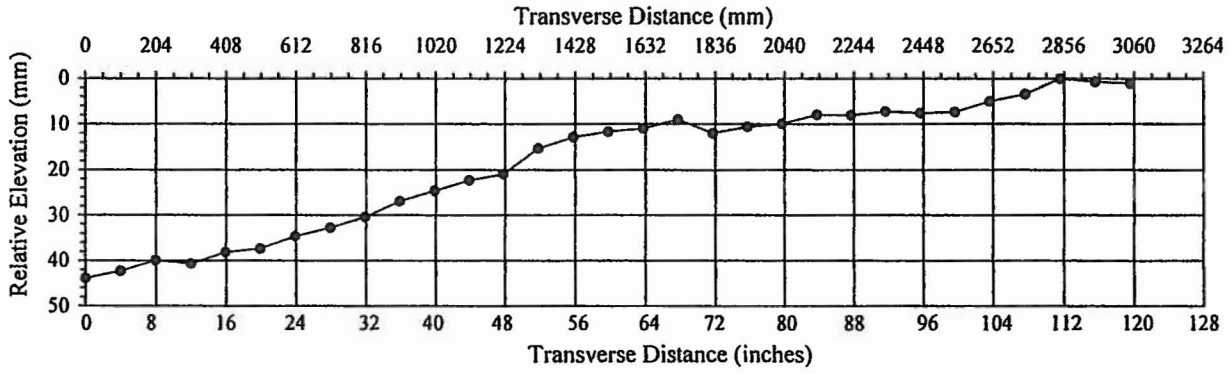
Profile 22.9, Test Section NM0185 P MP5.1 (May 14, 2009)



Profile 30.5, Test Section NM0185 P MP5.1 (May 14, 2009)



Profile 61, Test Section NM0185 P MP5.1 (May 14, 2009)



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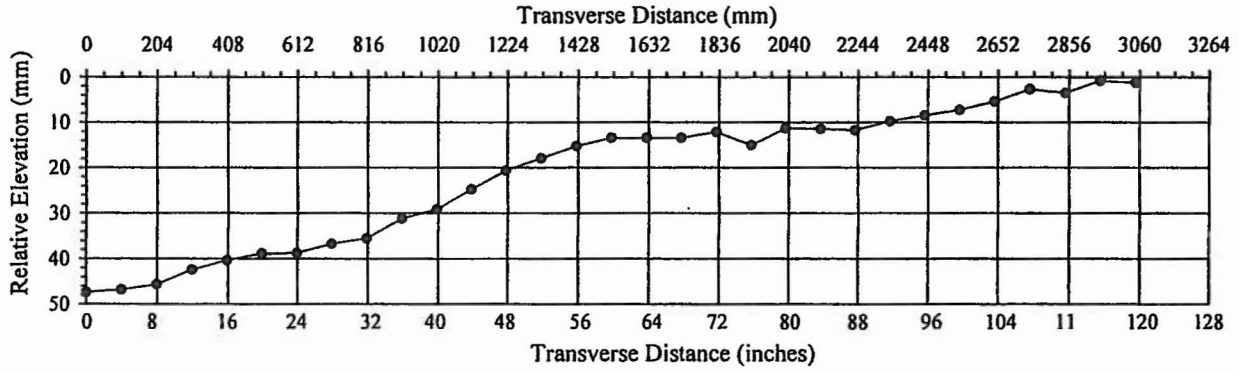

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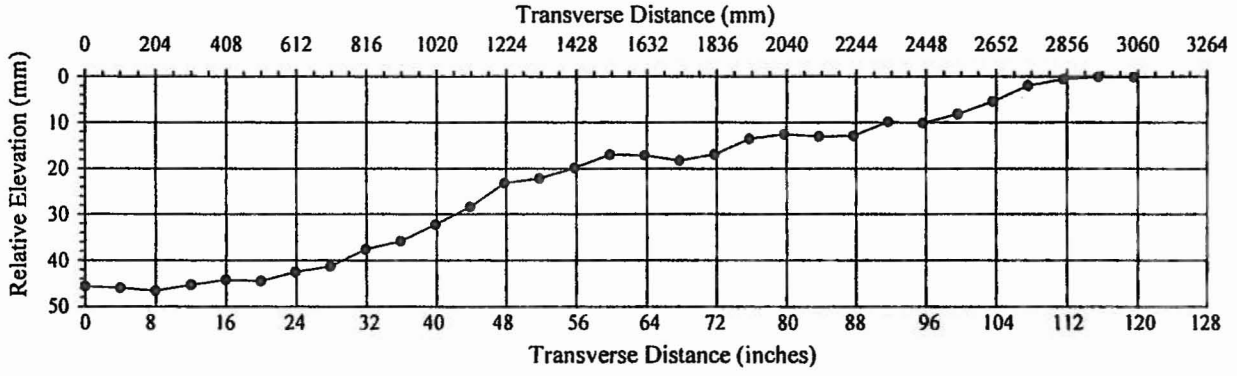
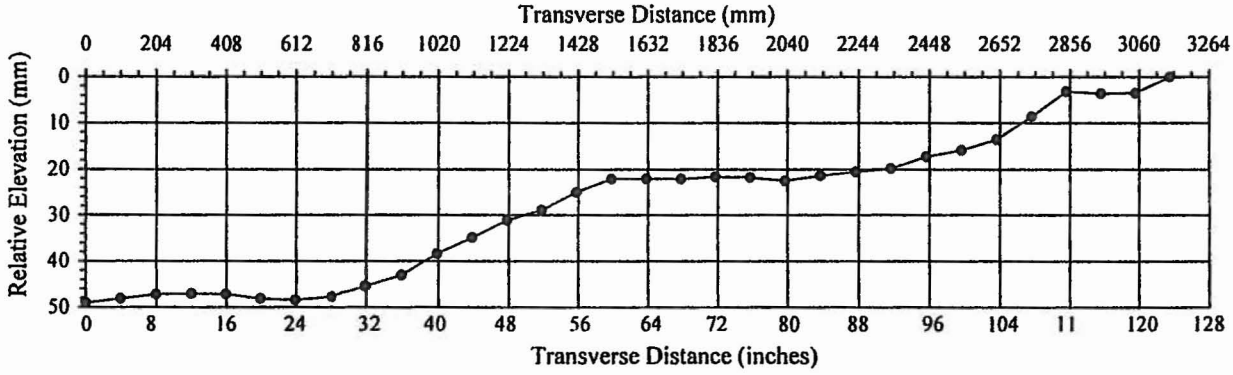
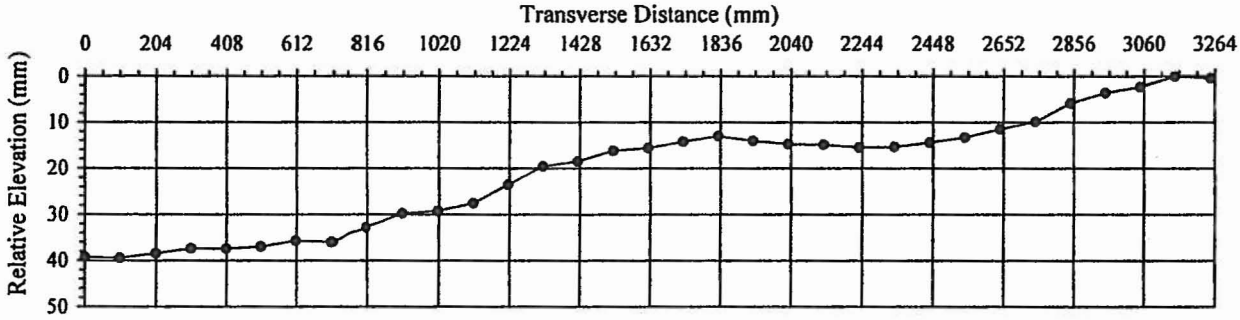


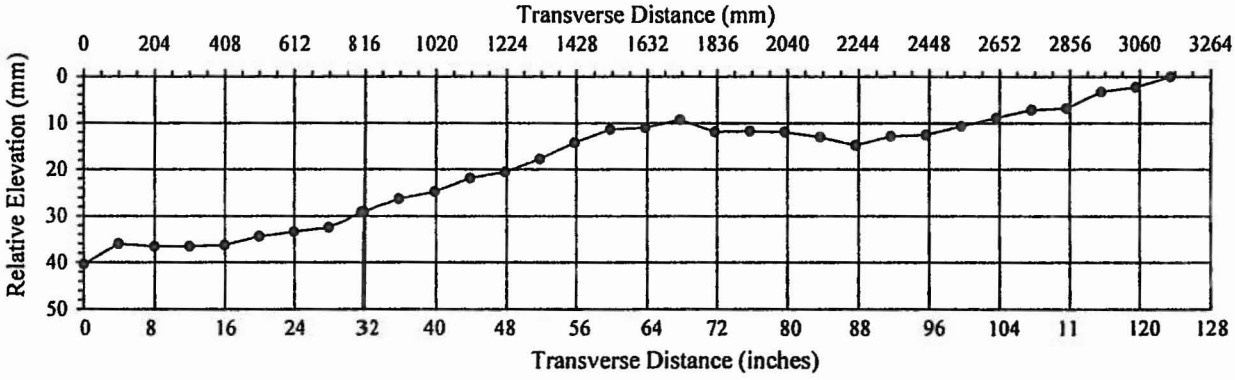
Profile 83.8, Test Section NM0185 P MP5.1 (May 14, 2009)



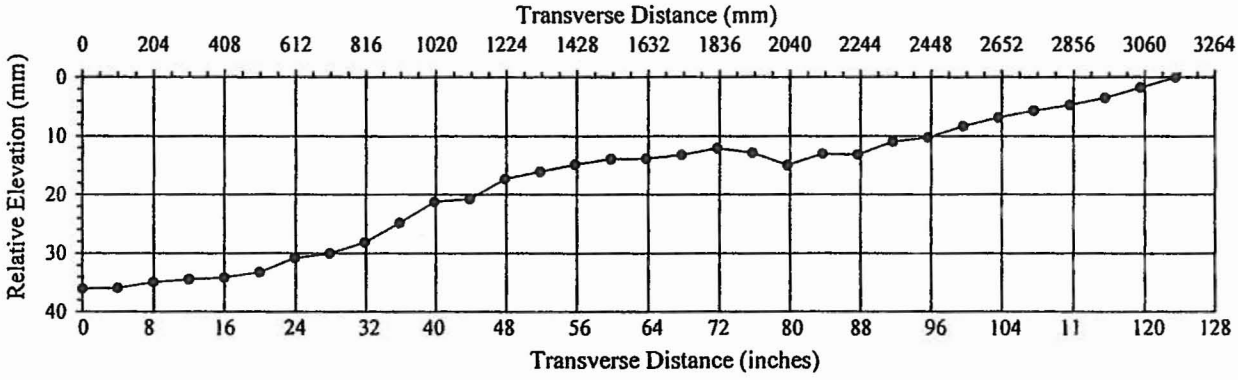
Profile 91.4, Test Section NM0185 P MP5.1 (May 14, 2009)



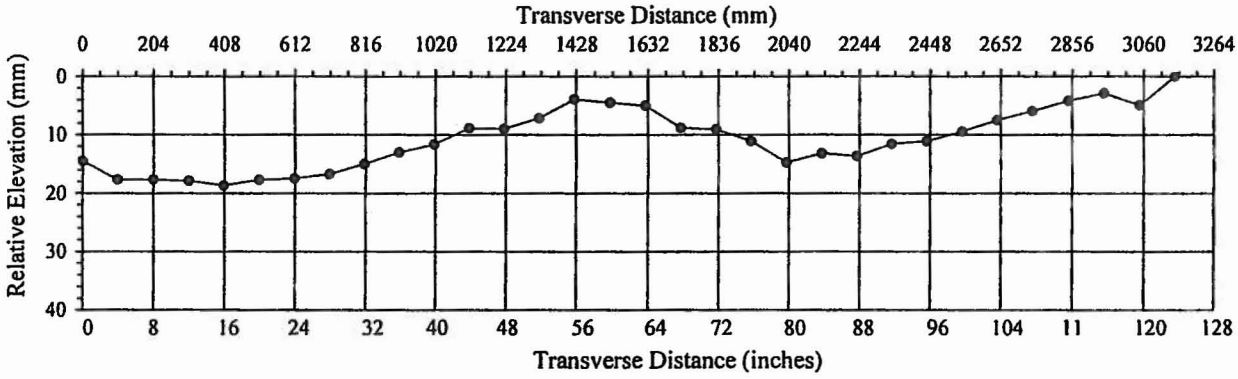
Profile 99.1, Test Section NM0185 P MP5.1 (May 14, 2009)



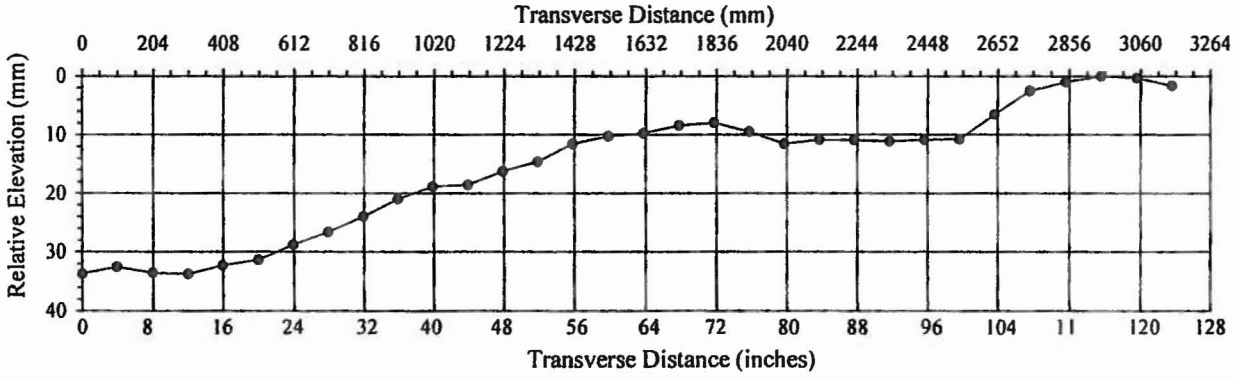
Profile 106.7, Test Section NM0185 P MP5.1 (May 14, 2009)



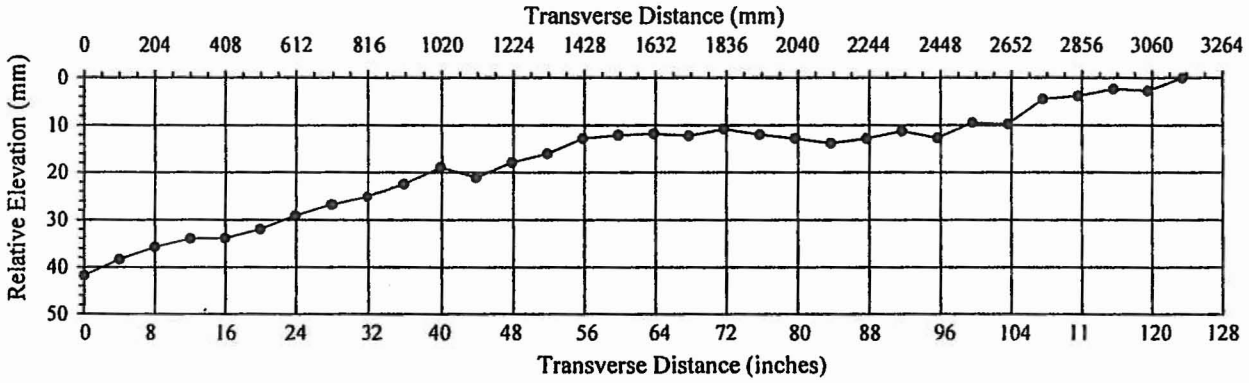
Profile 114.3, Test Section NM0185 P MP5.1 (May 14, 2009)



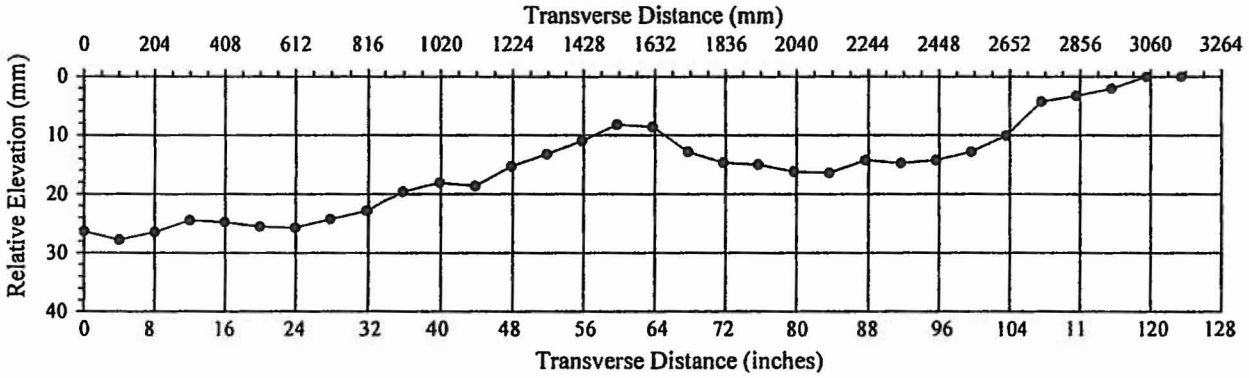
Profile 121.9, Test Section NM0185 P MP5.1 (May 14, 2009)



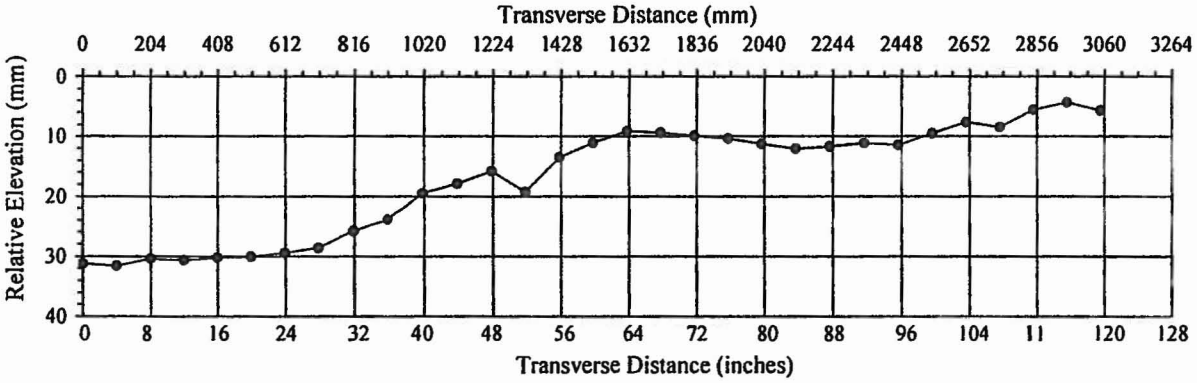
Profile 129.5, Test Section NM0185 P MP5.1 (May 14, 2009)



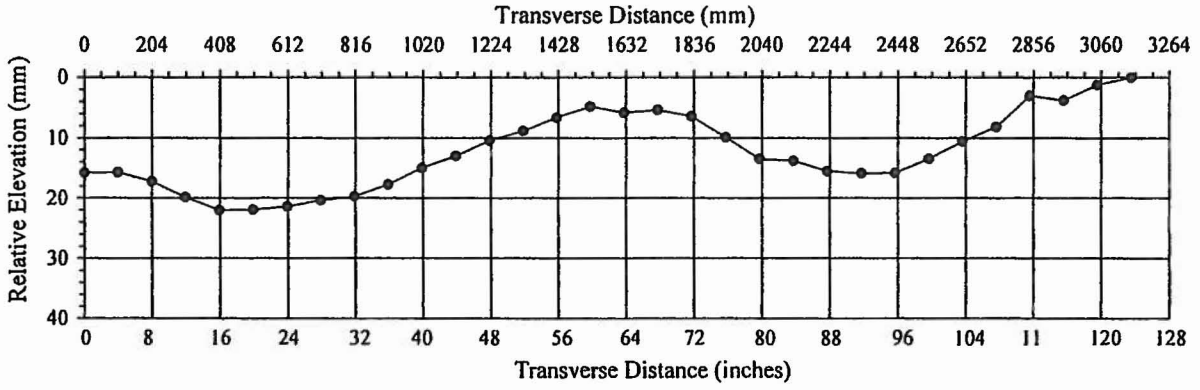
Profile 137.2, Test Section NM0185 P MP5.1 (May 14, 2009)



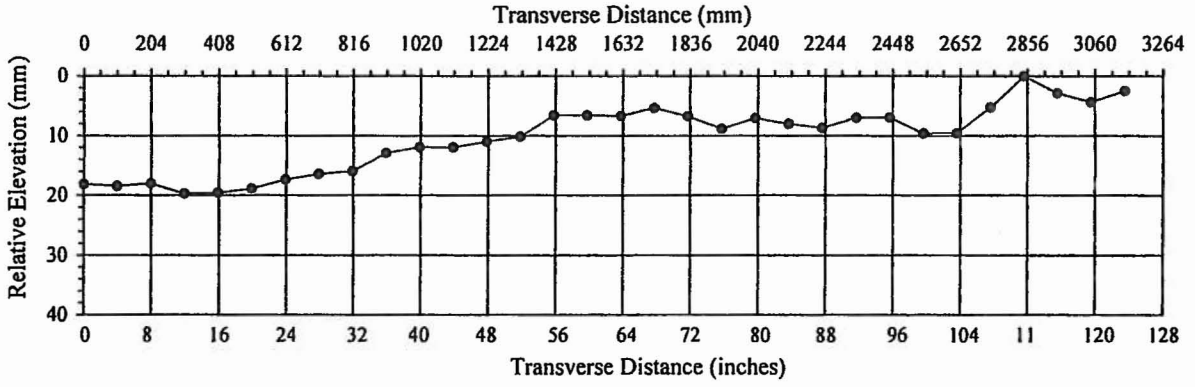
Profile 144.8, Test Section NM0185 P MP5.1 (May 14, 2009)



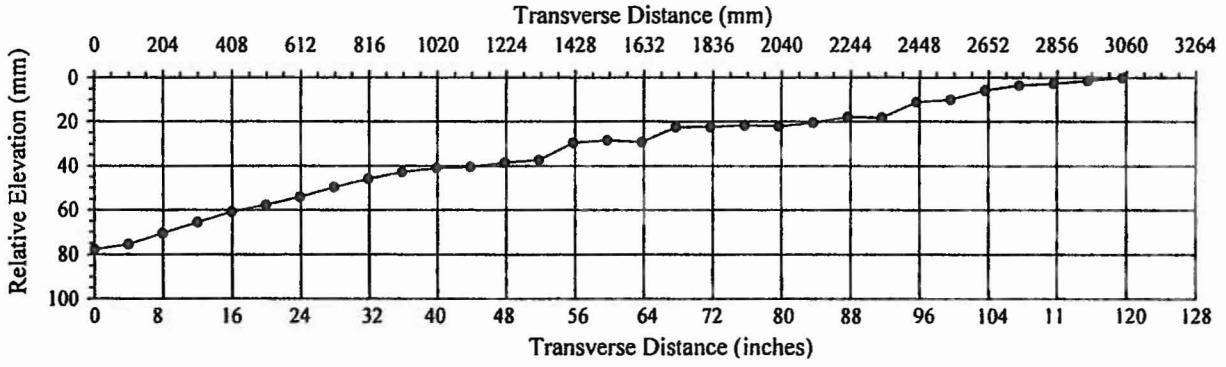
Profile 152.4, Test Section NM0185 P MP5.1 (May 14, 2009)



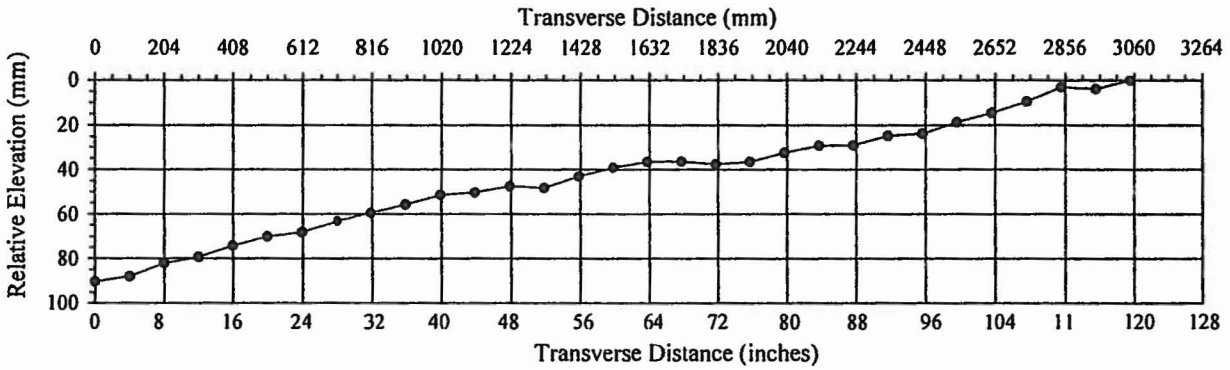
Profile 160, Test Section NM0185 P MP5.1 (May 14, 2009)



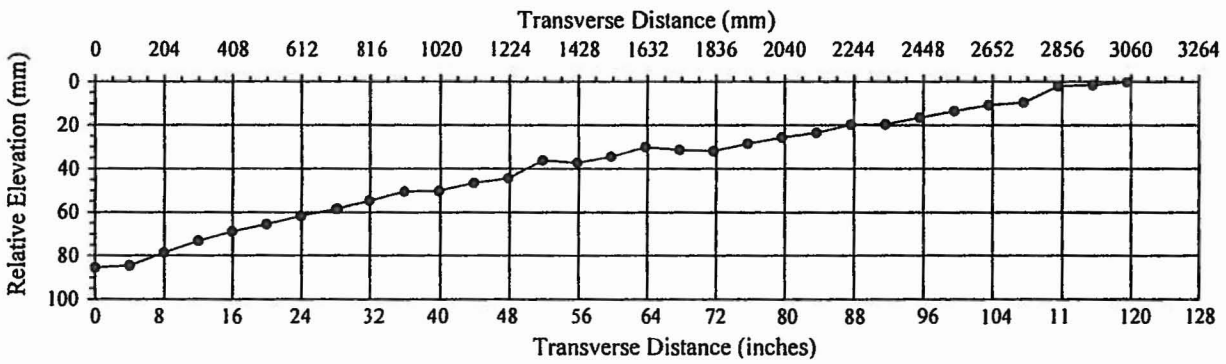
Profile 0, Test Section NM0185 P MP6.0 (May 14, 2009)



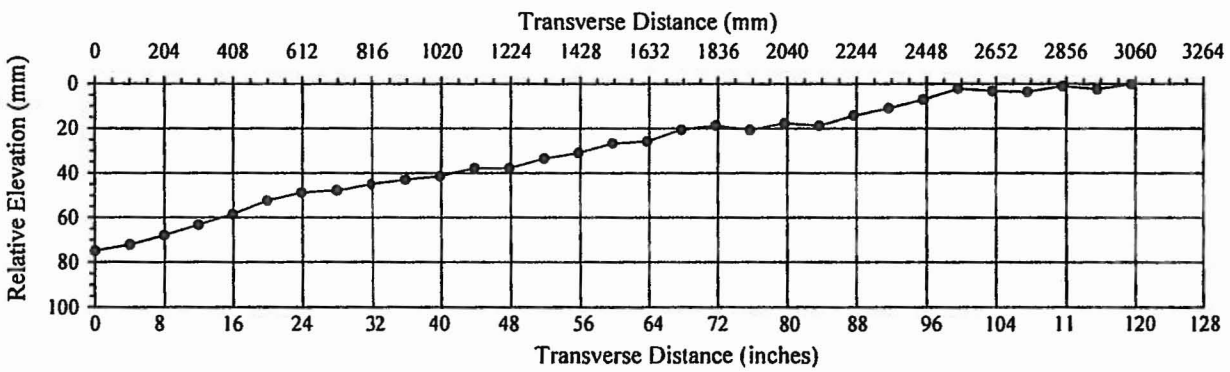
Profile 7.6, Test Section NM0185 P MP6.0 (May 14, 2009)



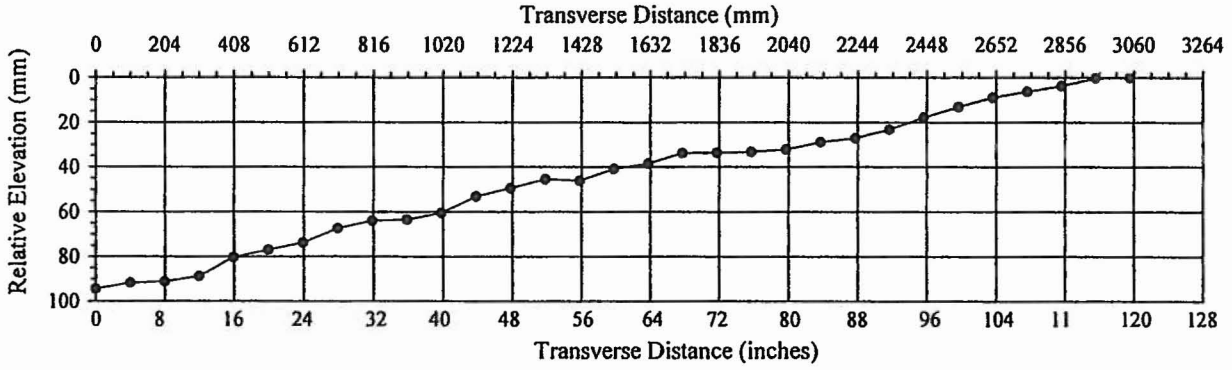
Profile 15.2, Test Section NM0185 P MP6.0 (May 14, 2009)



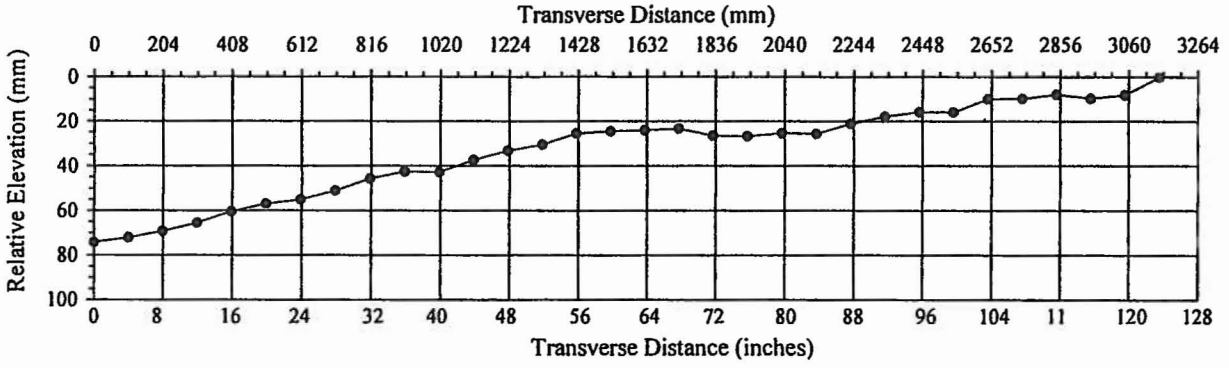
Profile 22.9, Test Section NM0185 P MP6.0 (May 14, 2009)



Profile 30.5, Test Section NM0185 P MP6.0 (May 14, 2009)



Profile 38.1, Test Section NM0185 P MP6.0 (May 14, 2009)



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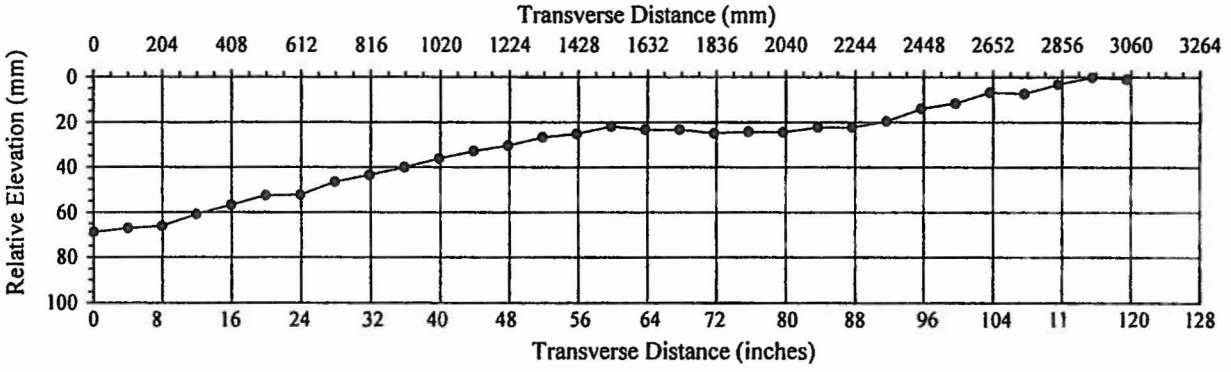

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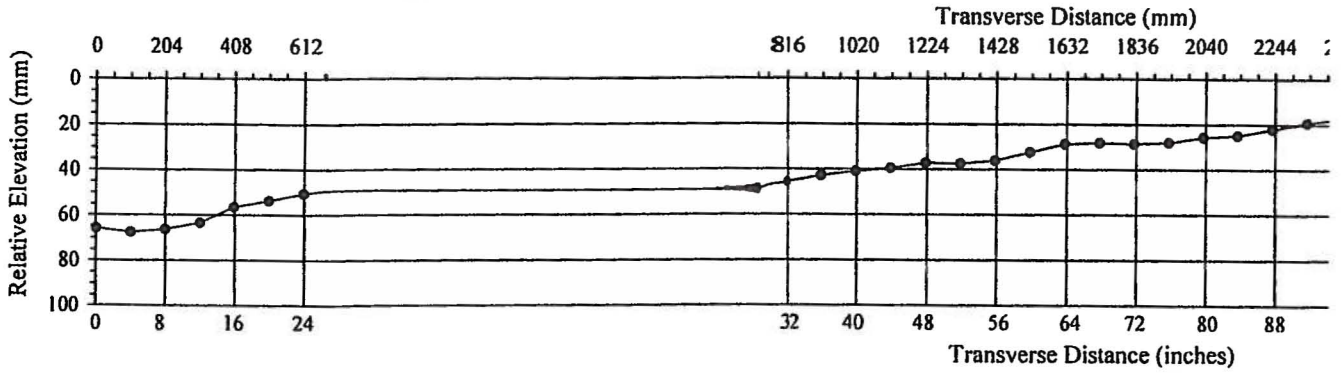

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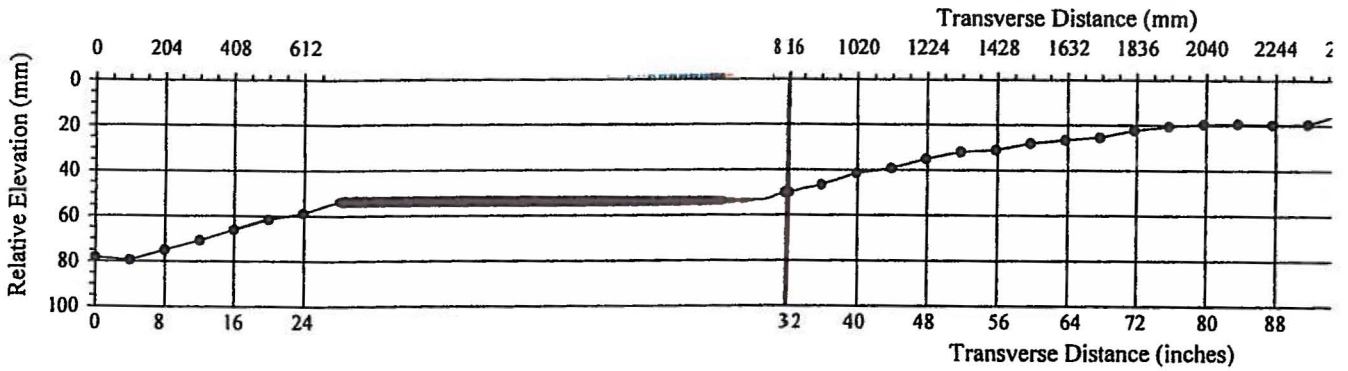

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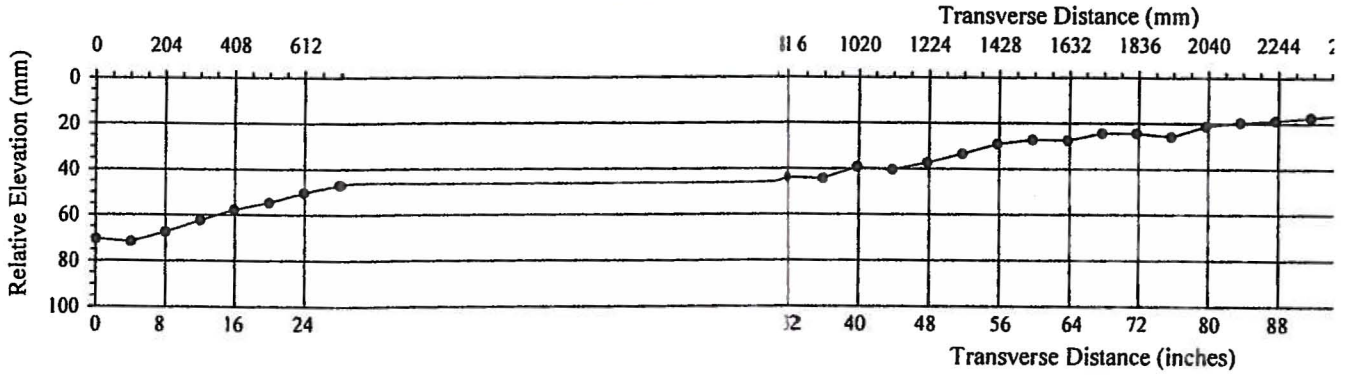

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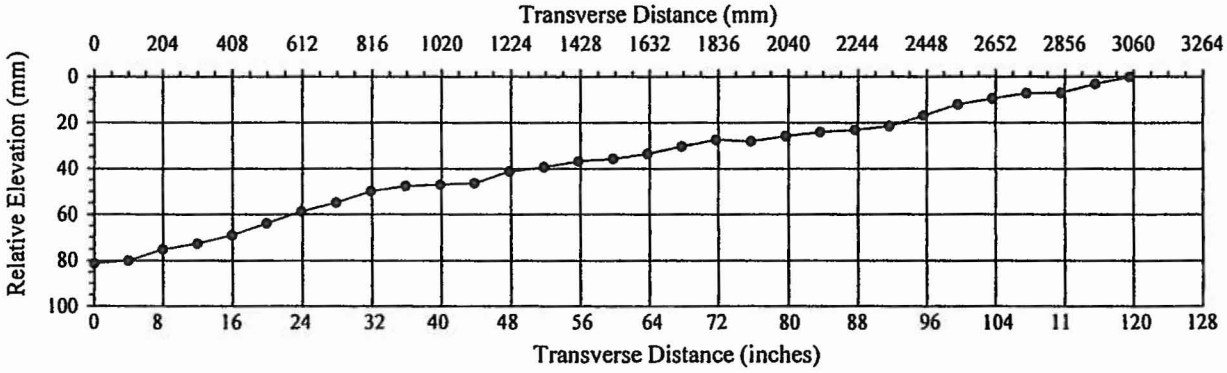

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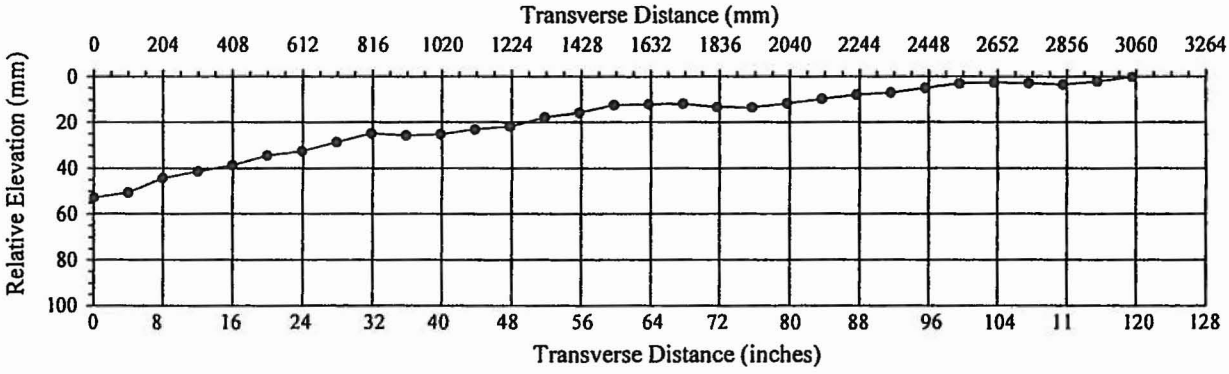

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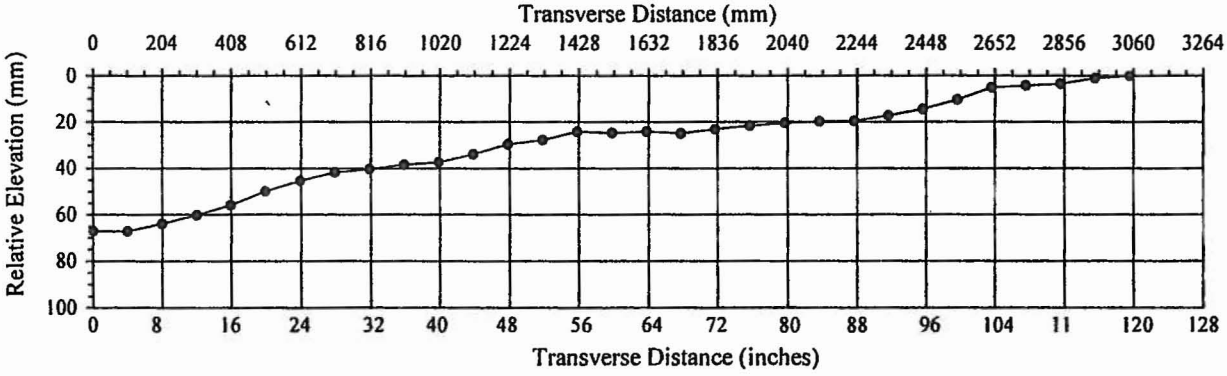

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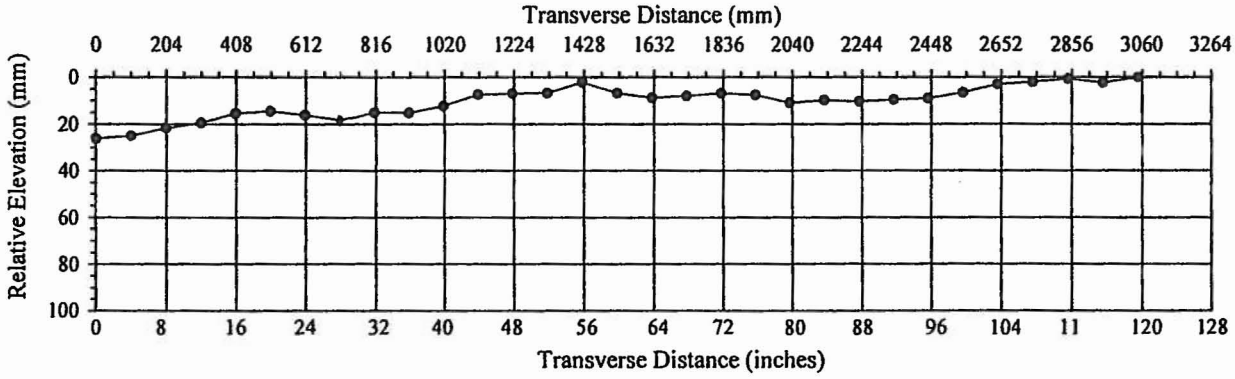

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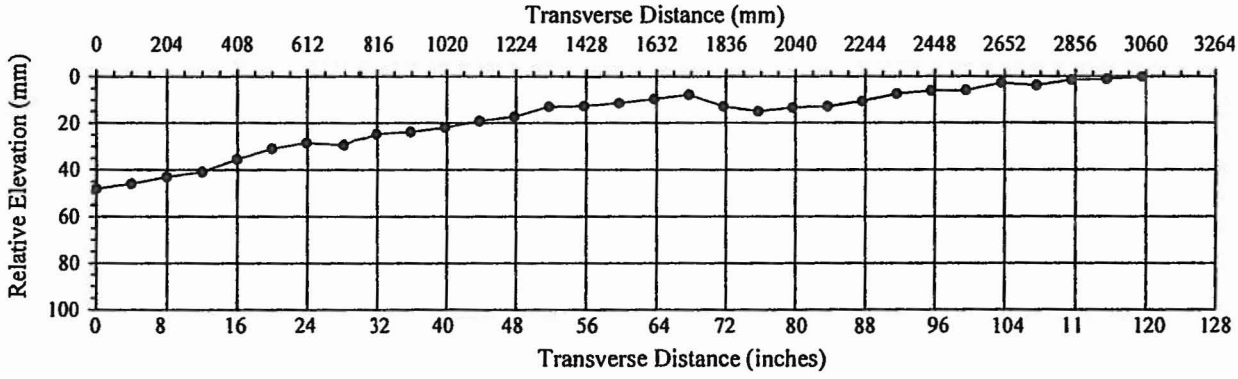

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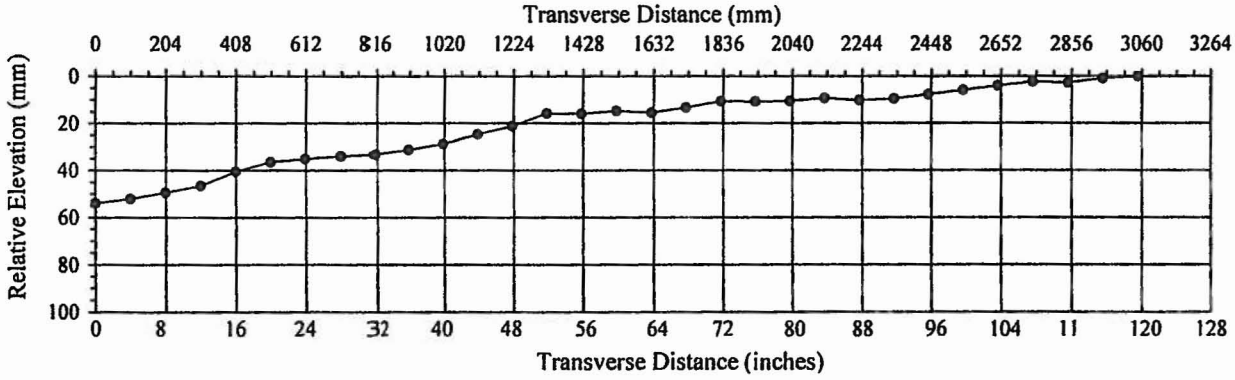

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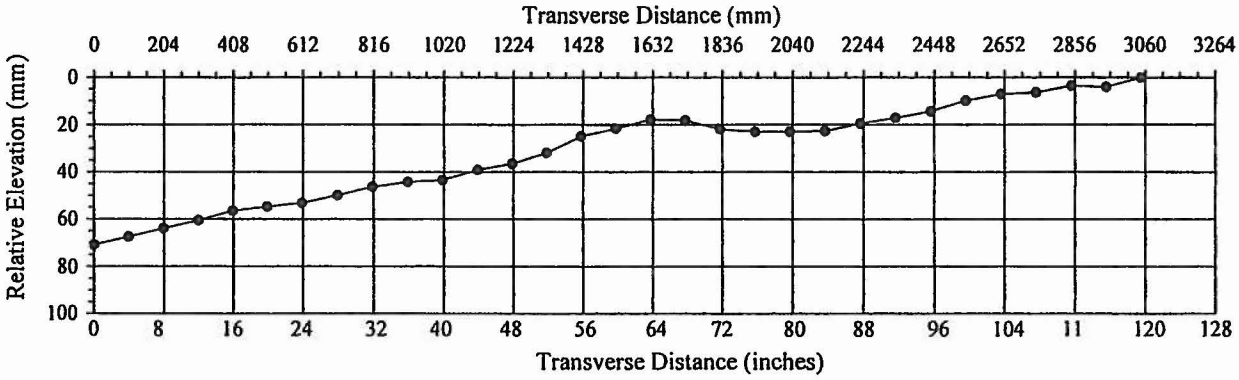

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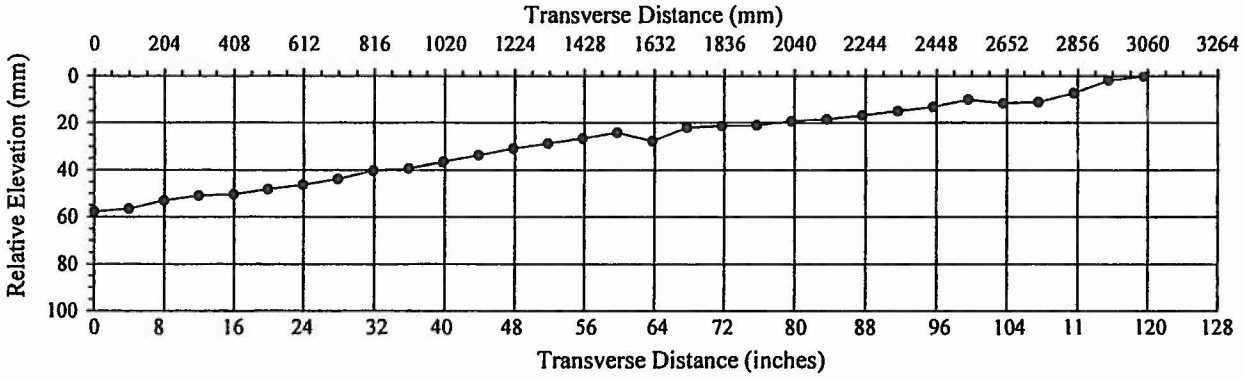

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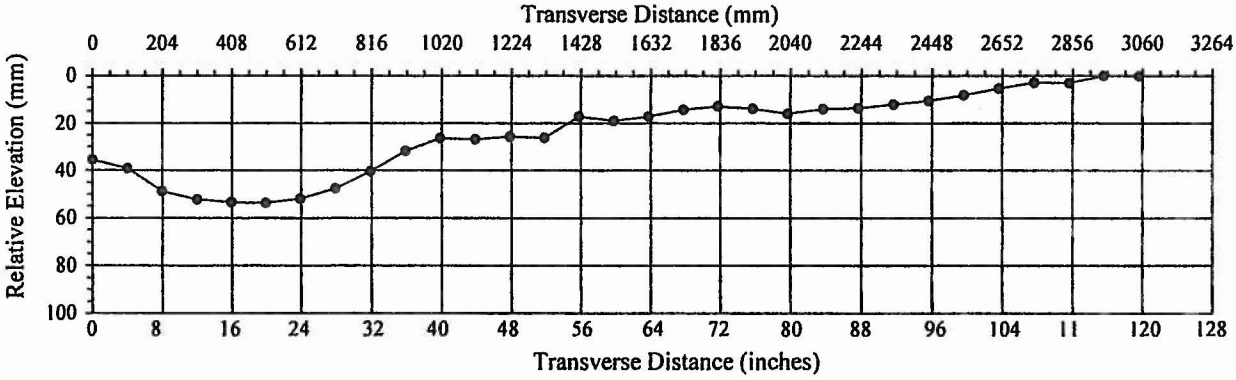

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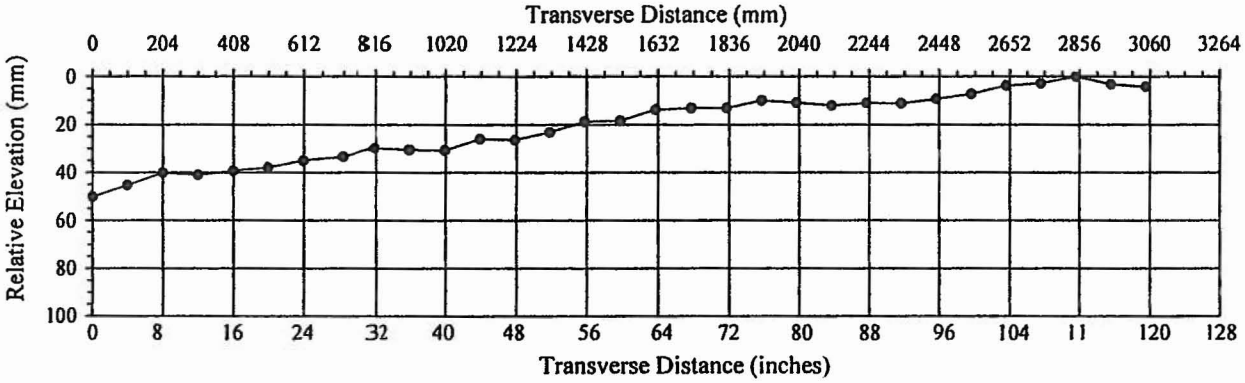

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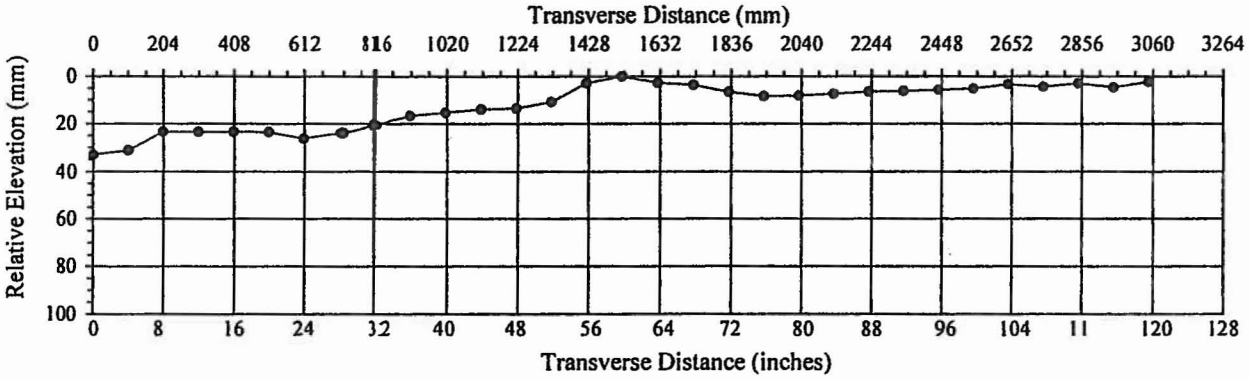

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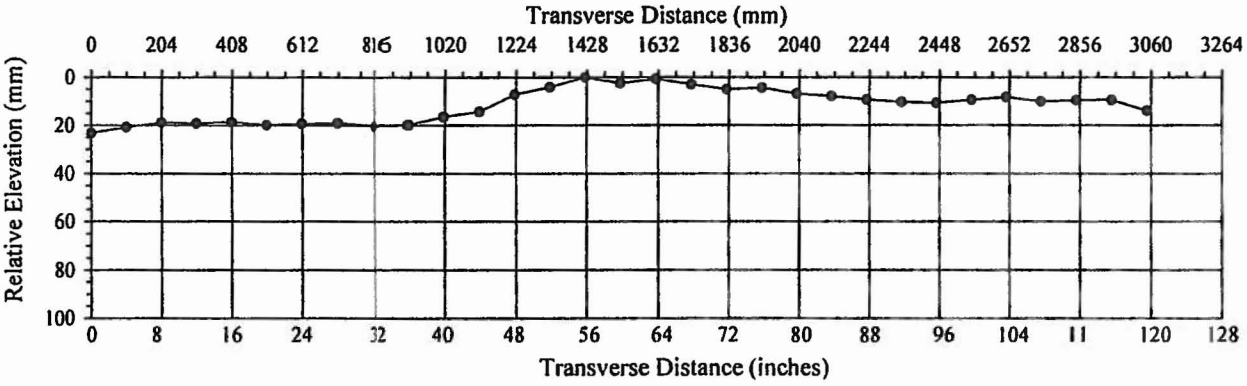

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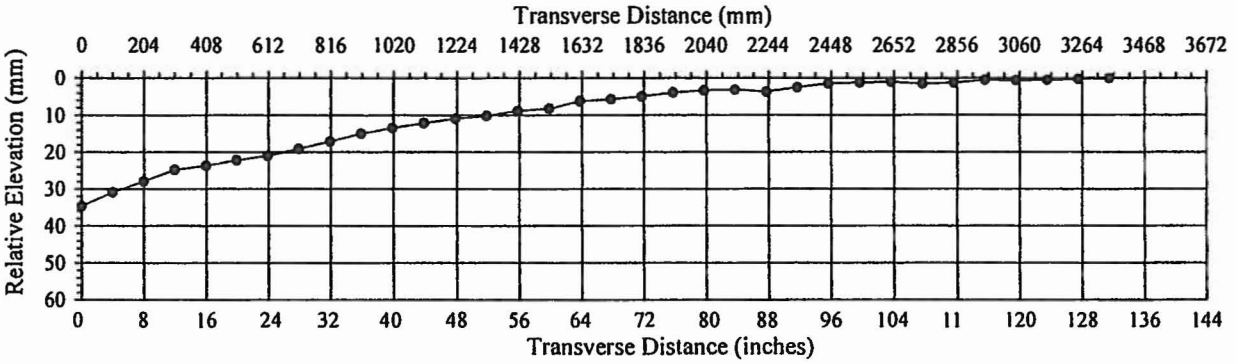

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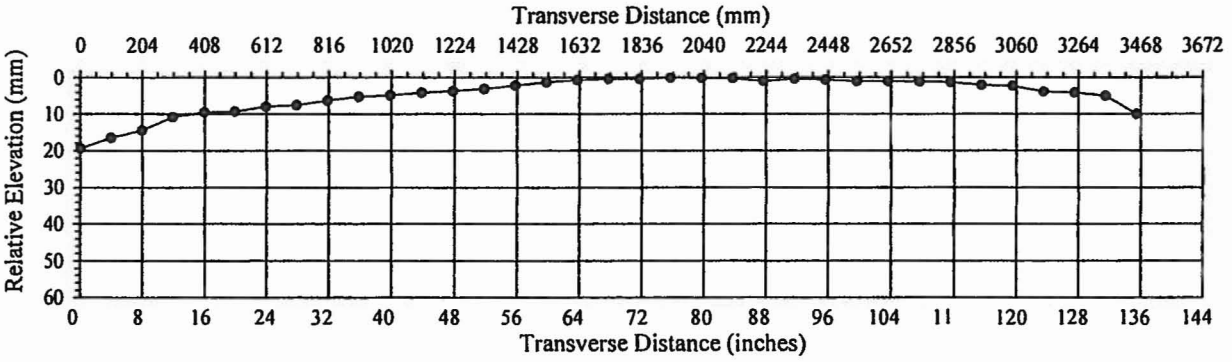

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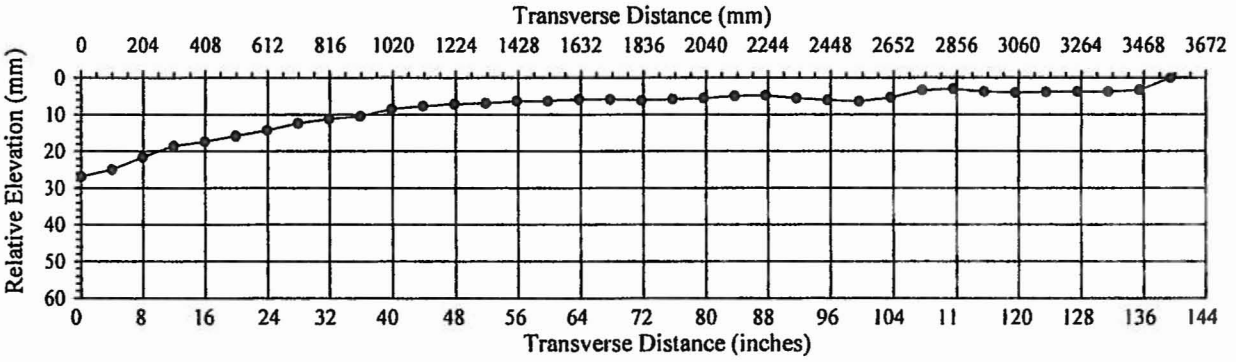

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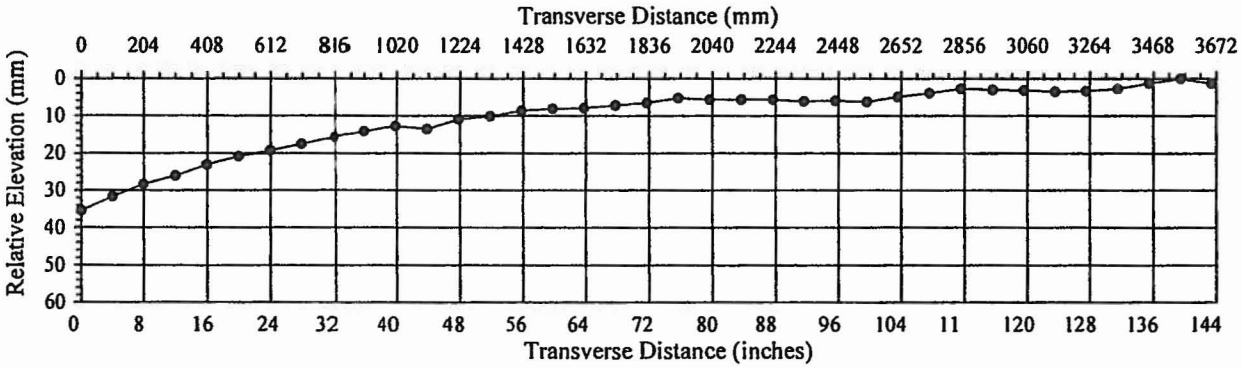

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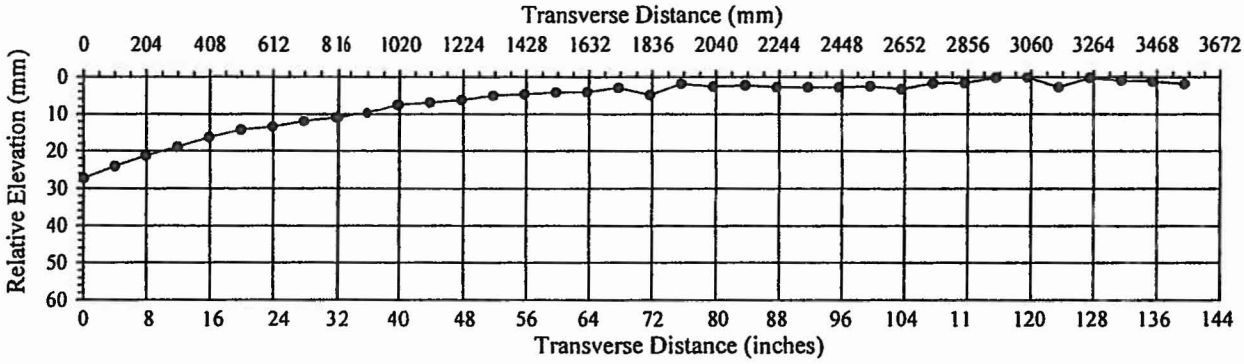

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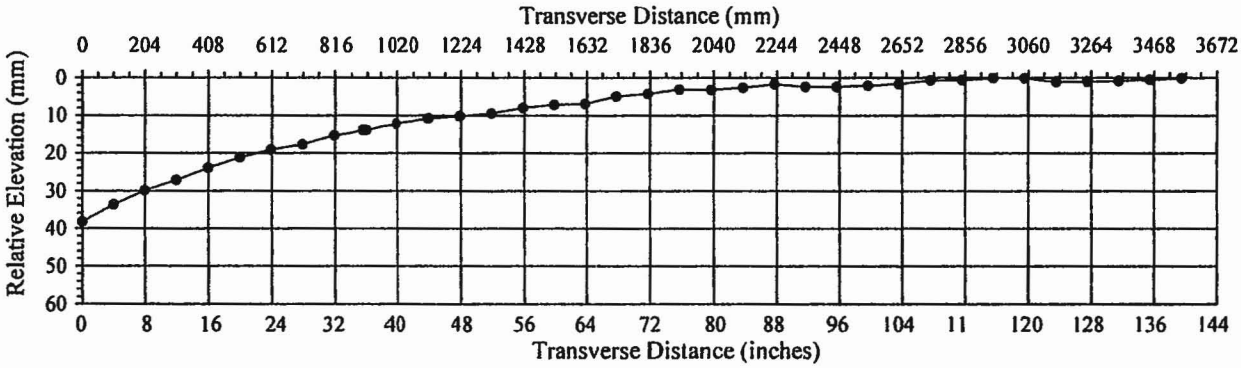

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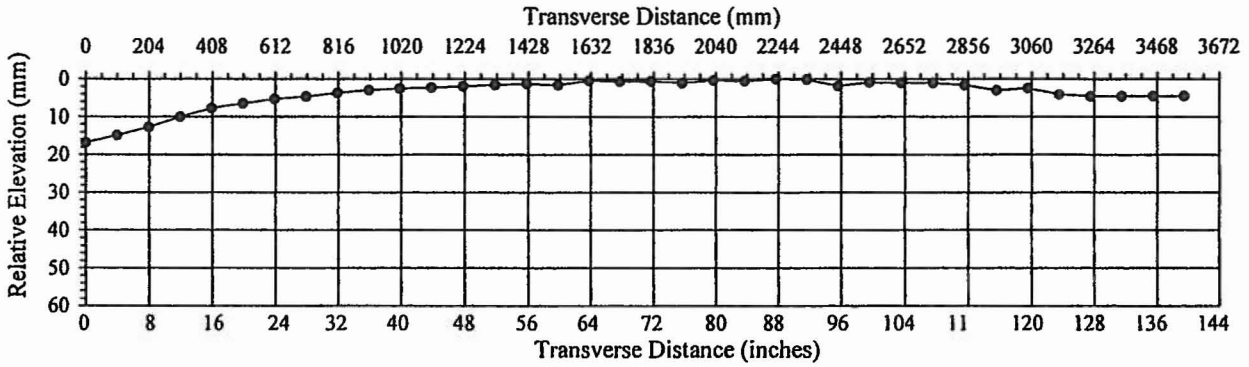

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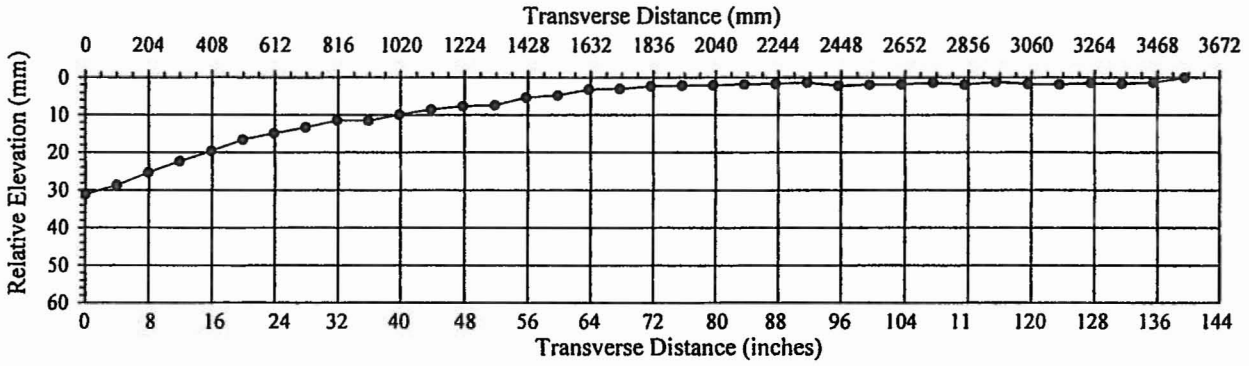

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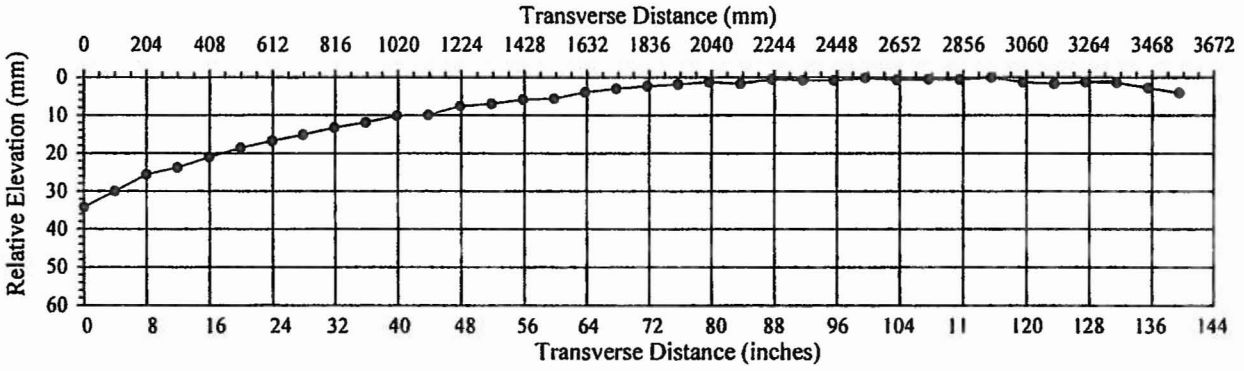

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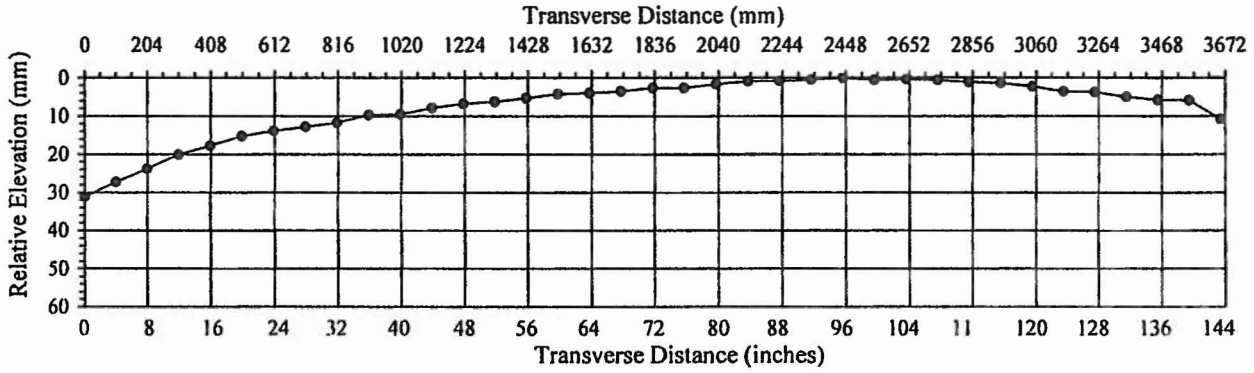

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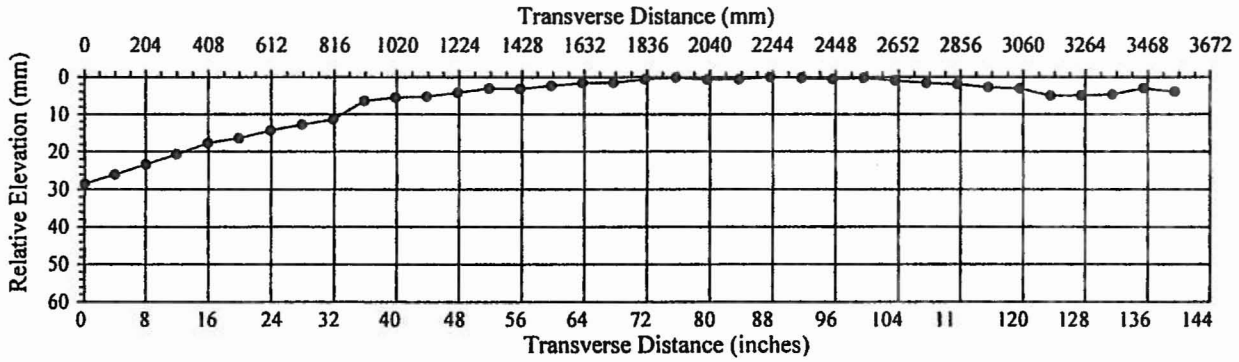

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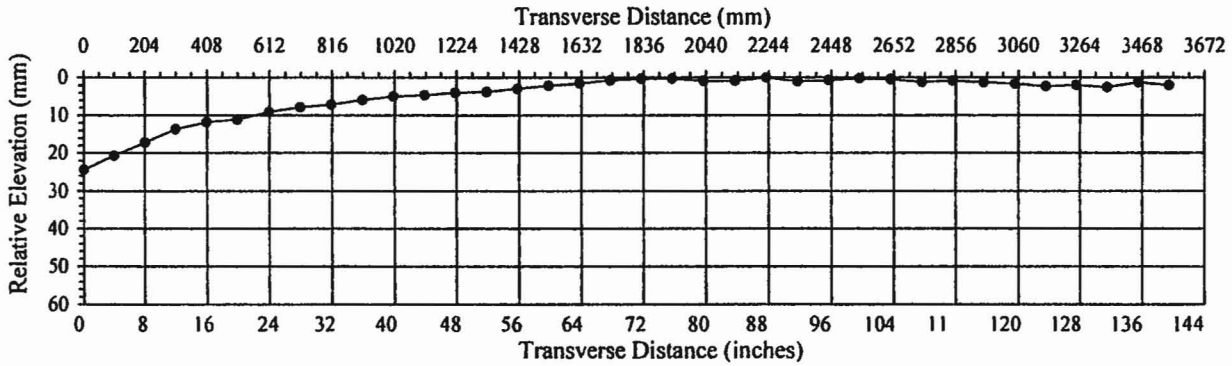

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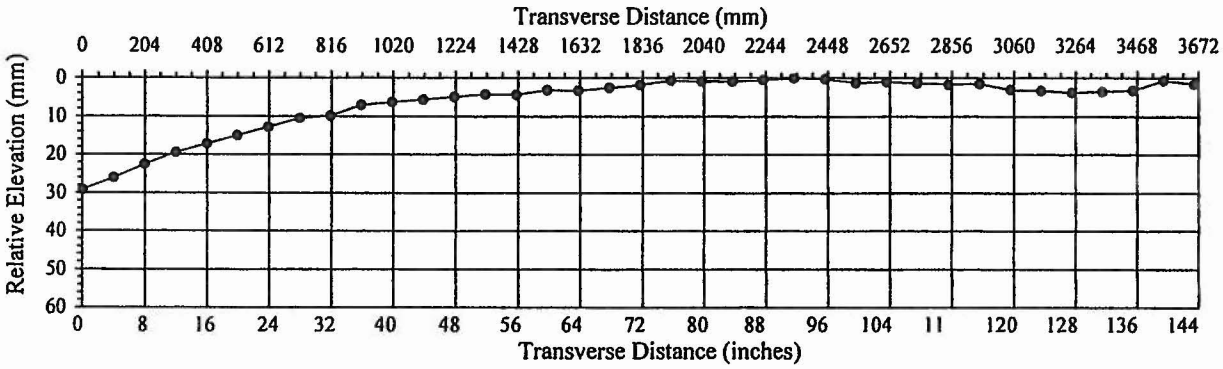

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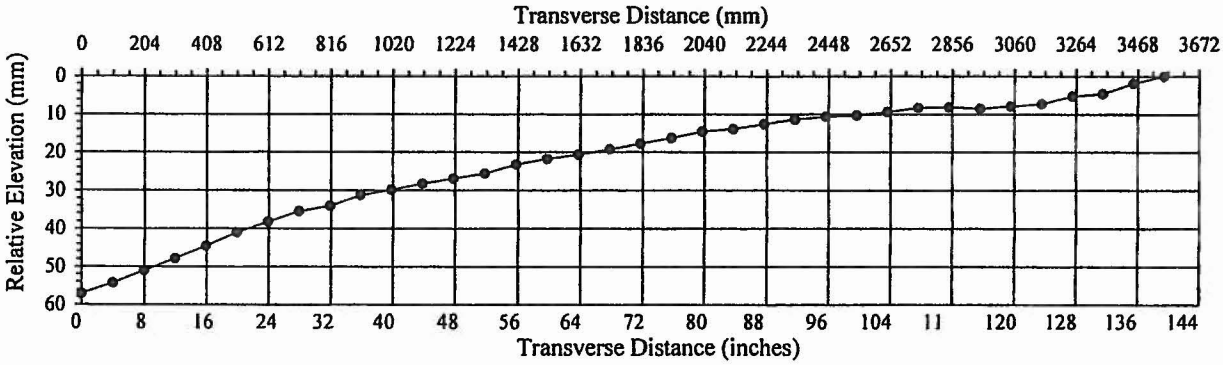

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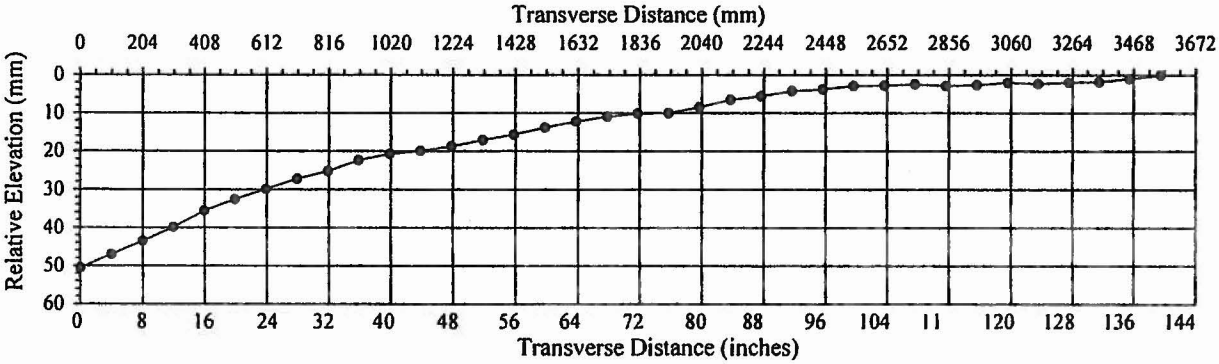

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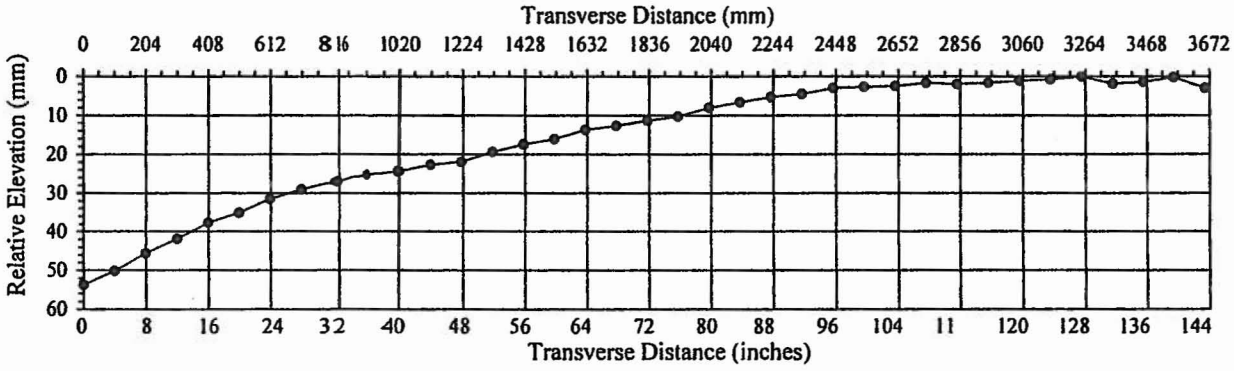

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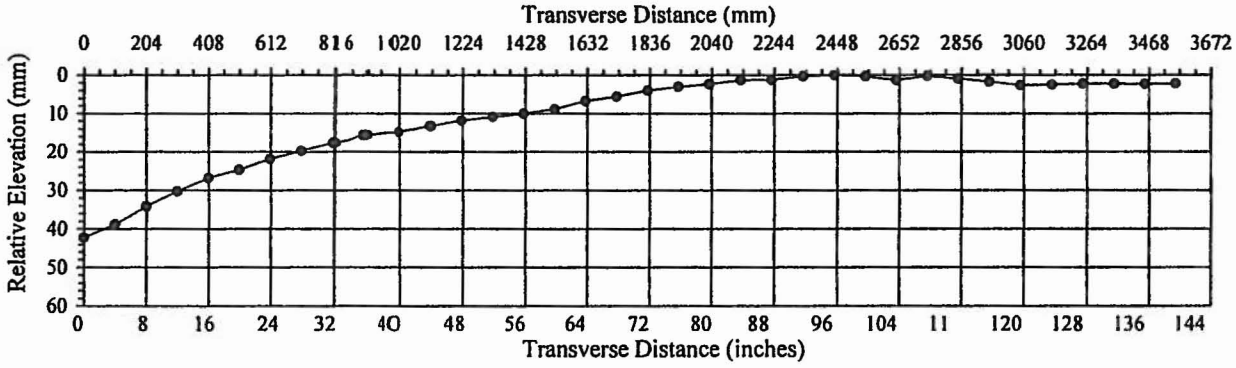

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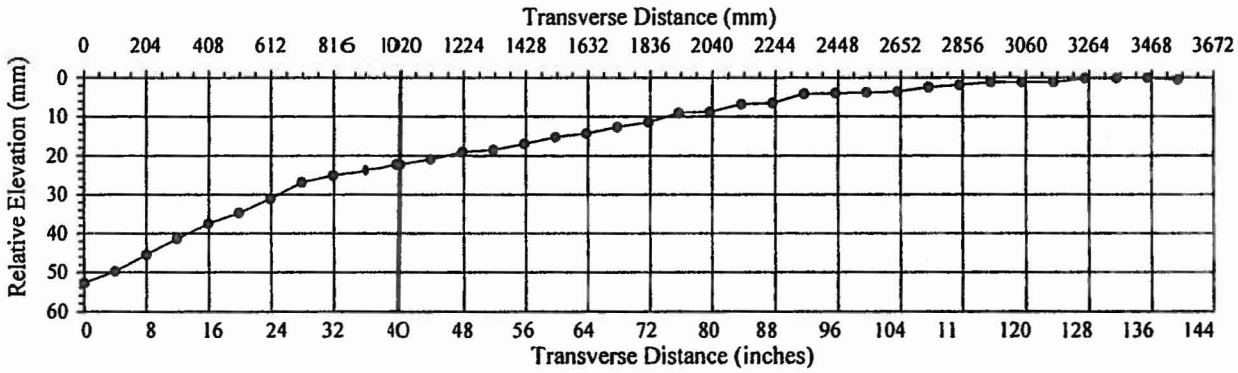

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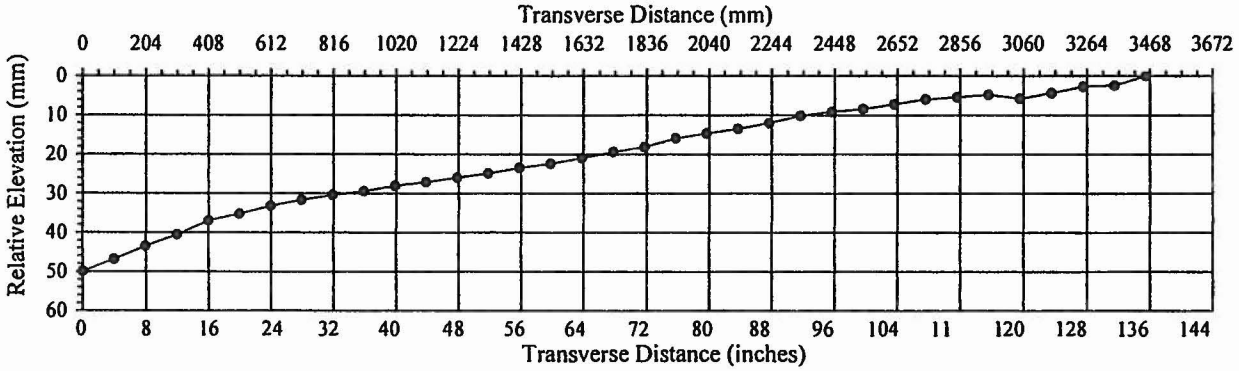

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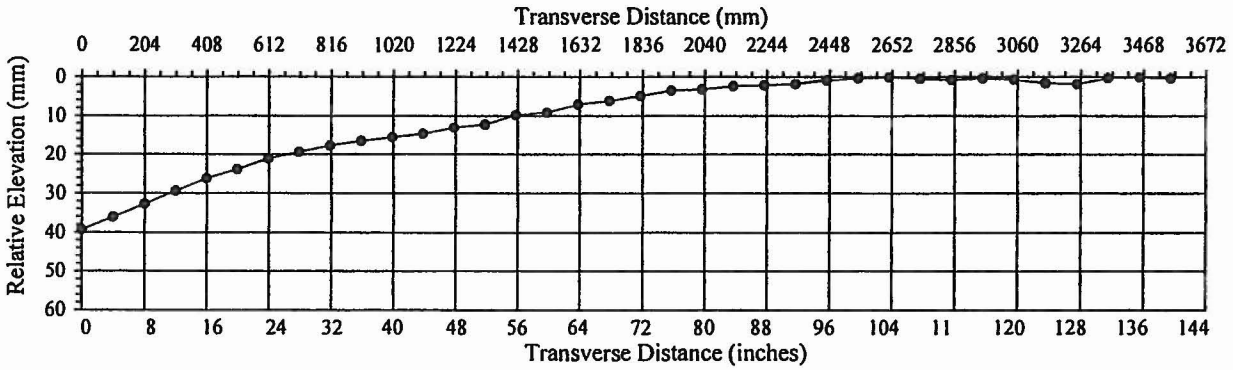

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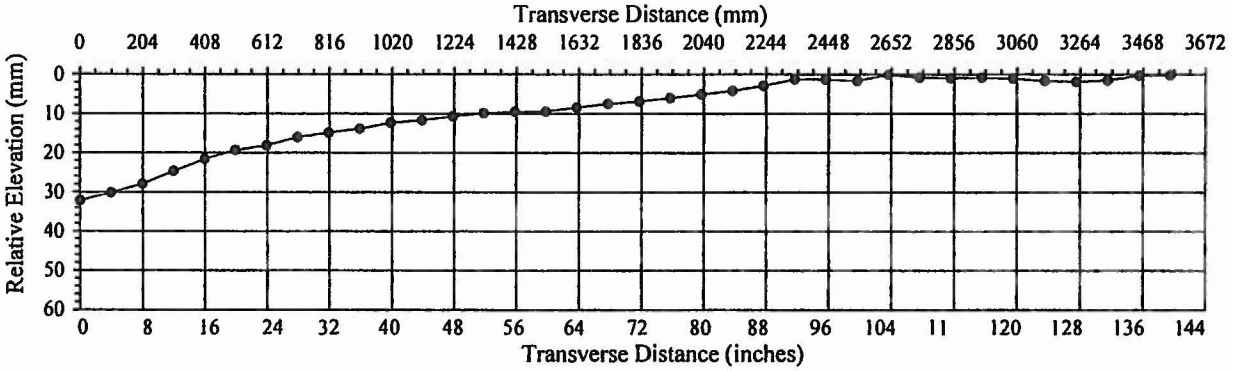

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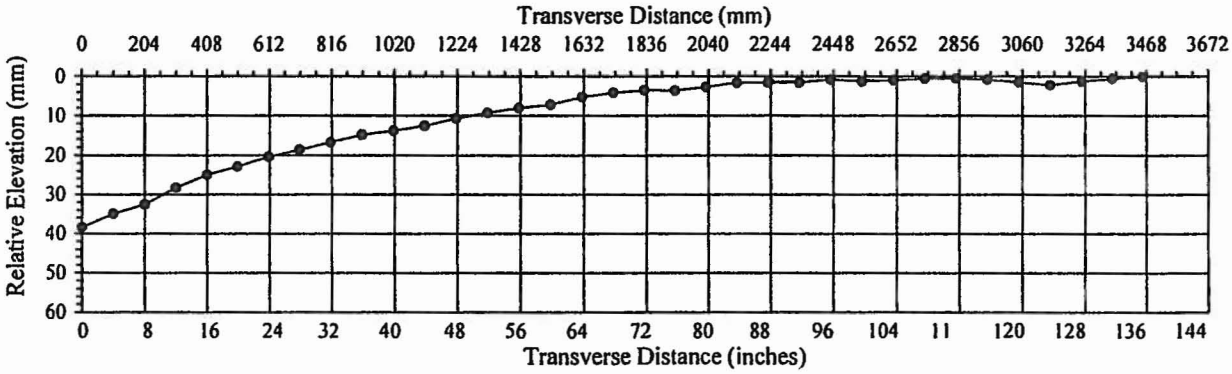

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APPENDIX F

Implementation Plan for Replacing Rutting Ratings from Manual Surveys with Automated Rut Depth Data

IMPLEMENTATION PLAN FOR REPLACING RUTTING RATINGS FROM MANUAL SURVEYS WITH AUTOMATED RUT DEPTH DATA

Paola Bandini, Ph.D., P.E.
New Mexico State University

SCOPE

The scope of this document is to describe the resources and steps needed to implement or apply the Recommended Approach (Approach A-Case 3) and the Alternative Approach B described in the body of this report. The target audience of this document includes NMDOT pavement presentation engineers, pavement management engineers, pavement condition data collection personnel and, most especially, computer and IT staff.

LIMITATIONS

The recommendations provided in this document were based on the results of statistical analysis of the data available to the authors. If concerns arise in the future about the quality of the automated rut depth data or other data used in this research, or new/different profilometer equipment is acquired by NMDOT, the results and recommendations of this report could be affected. The rating criteria and factors provided here may need to be refined or confirmed as new data become available. If, in a given year, automated rut depth data are not available for a number of test sections that are included in the distress surveys, the lack of data should be addressed; otherwise, inputting zero rut depth values when data are unavailable could produce erroneous results and misleading trends in the overall network condition.

CURRENT FORMULATION OF THE NMDOT'S PAVEMENT SERVICEABILITY INDEX (PSI)

The NMDOT's PSI is currently calculated from pavement roughness data and distress ratings (including rutting), through one of the following empirical expressions (restated here):

$$PSI = 0.041666\,X, \quad \text{if } X \leq 60 \tag{1}$$

or

$$PSI = [0.0625(X - 60)] + 2.4999, \quad \text{if } X > 60 \tag{2}$$

where the interim value X is given by

$$X = 100 - \left[\frac{0.6(IRI - 25) + (0.4DR)}{2.9}\right] \tag{3}$$

where IRI is International Roughness Index, and DR is the Distress Rate defined as

$$DR = \sum_{i=1}^{n} \left[(\text{Severity Rating}_i)(\text{Extent Factor}_i)(\text{Weight Factor}_i) \right] = \sum_{i=1}^{n} (DR_i) \quad (4)$$

in which i denotes one of the eight types of distresses of flexible or rigid pavements ($n = 8$), and DR_i is the component of the distress rate (DR) value corresponding to the distress type i for a given pavement section. The factors for the extent ratings and the weight factors used in Equation 4 for flexible pavements are given in Tables 2 and 3 (restated here).

TABLE 2 Factors for Extent Ratings for Flexible Pavements.

Extent Rating for Rutting and Shoving	Factor
0	0
1	0.5
2	0.8
3	1.0

TABLE 3 Weight Factors for Distresses in Flexible Pavements (14).

Distress Type	Weight Factor
Raveling and Weathering	3
Bleeding	2
Rutting and Shoving	14
Longitudinal Cracking	20
Transverse Cracking	12
Alligator Cracking	25
Edge Cracking	3
Patching	2

It is the current practice of NMDOT to use the automated pavement condition data (i.e., roughness data or the International Roughness Index, IRI) of the prior data collection cycle to calculate PSI values with the distress ratings of the current year.

IMPLEMENTATION OF RECOMMENDED APPROACH

The Recommended Approach (Approach A-Case 3) preserves the current PSI formulation, the equation of the interim X value (Equations 1 through 3), and the values of the extent rating factors and weight factor W_{Rut} (= 14). In this approach, the modification is made to the automated rut depth data. "Equivalent" severity and extent ratings are estimated from the

automated rut depth data for the entire length of each mile (test section). This means that the automated rut depth data are "converted" into equivalent ratings of rutting to be used in the current PSI formulation. To implement this approach, the following steps should be required.

Step 1: Evaluate Data Quality

1.1 Before the automated rut depth data are converted into equivalent ratings, the quality of the data should be evaluated and outliers must be investigated.

1.2 For quality control, it is recommended to perform rut-bar checks annually and systematically in a number of test sections to compare with the automated rut depth data.

1.3 Comparisons with data from previous years are also recommended.

Step 2: Convert Automated Rut Depth into Equivalent Rutting Ratings

2.1 Make all negative values of automated rut depth equal to zero. Positive values mean rutting; negative values mean no rutting or rutting with severity 0 (The quality of the data and the proper equipment calibration should be confirmed before making this assumption).

2.2 To determine the equivalent severity and extent ratings for rutting, a computer code should be written, with the following input and output:

INPUT: The inputs to the code are: 1) the automated rut depth data files (for the previous year or previous survey cycle), averaged at 0.1 mile intervals, and 2) the distress data files for the current year (8-distress type format). The example below is for automated rut depth corresponding to Interstate 10, positive direction, from milepost 100.0 to 100.1, survey performed 02-13-2008, and average rut depth of 0.27 in.

i00010p000-100_e01,XX,000.000,000.100,01302008,**0.27**

The example below is from a distress rating file (8-distress type format): Interstate 10, positive direction, test section from 100.0 to 100.1, survey performed 06-2009, rated by Crew 2. This type of distress file is produced by NMDOT's Oracle®-based Pavement Distress Feeder System. The ratings for rutting and shoving are shown in bold numbers.

I00010,P,100.000,F ,01,29,01,00000,06,2009, ,000000,000.000,13,31,**00**,12,13,12,13,21,11,16,06, ,Crew 2

OUTPUT: The outputs of the code are two digits per test section, corresponding to the equivalent severity and extent for rutting. Their possible values are: 0, 1, 2, or 3. The code should write these two digits in field "16" in the distress data file (8-distress type format), replacing the existing two digits in field "16". Fields are separated by comma.

2.3 For a given mile or test section of flexible pavement, the equivalent severity should be determined using the code by comparing the automated rut depth of each 0.1 mile interval with the modified criteria given in Table 20 (restated next). The greatest severity found in a given mile is taken as the equivalent severity rating for rutting for that mile.

Table 20 Recommended Approach (Approach A-Case 3): Rutting Rating Criteria Using IRI and Automated Rut Depth Data from Previous Year.

Rating	Criteria	
	Severity (Modified-Approach A Case 3)	Extent (NMDOT's criteria)
0	Rut depth less than 0.20 in.	Severity rating is 0
1	Rut depth between 0.20 in. and 0.28 in.	From 1% to 30% of the test section
2	Rut depth between 0.28 in. and 0.36 in.	From 31% to 60% of the test section
3	Rut depth greater than 0.36 in.	61% of the test section or more

2.4 The percentage of the 0.1 mile intervals with each severity level is calculated. The percentage with the highest severity rating in the entire mile is used to determine the equivalent extent rating for the test section with the criteria in Table 20.

Consider the following example of automated rut depth data (Input file):

i00010p000-100_e01,XX,000.000,000.100,01302008,**0.27**
i00010p000-100_e01,XX,000.100,000.200,01302008,**0.16**
i00010p000-100_e01,XX,000.200,000.300,01302008,**0.29**
i00010p000-100_e01,XX,000.300,000.400,01302008,**-0.05**
i00010p000-100_e01,XX,000.400,000.500,01302008,**-0.10**
i00010p000-100_e01,XX,000.500,000.600,01302008,**-0.10**
i00010p000-100_e01,XX,000.600,000.700,01302008,**0.09**
i00010p000-100_e01,XX,000.700,000.800,01302008,**0.12**
i00010p000-100_e01,XX,000.800,000.900,01302008,**0.40**
i00010p000-100_e01,XX,000.900,001.000,01302008,**0.39**

The negative rut depth values are first replaced with 0. To determine the equivalent severity and extent, apply the criteria in Table 20:

Start	End	Length (mile)	Automated Rut Depth (in.)	Equivalent Severity Rating (Table 20)
100.0	100.1	0.1	0.27	1
100.1	100.2	0.1	0.16	0
100.2	100.3	0.1	0.29	2
100.3	100.4	0.1	0.0	0
100.4	100.5	0.1	0.0	0
100.5	100.6	0.1	0.0	0
100.6	100.7	0.1	0.09	0
100.7	100.8	0.1	0.12	0
100.8	100.9	0.1	0.40	**3**
100.9	101.0	0.1	0.39	**3**

Number of segments with severity 0 = 6 (60% of the mile)
Number of segments with severity 1 = 1 (10% of the mile)
Number of segments with severity 2 = 1 (10% of the mile)
Number of segments with severity 3 = **2 (20%** of the mile)

Total number of segments = 10 (100% or entire mile)

The highest equivalent severity found is 3. There are two 0.1 mile intervals with severity 3 (from 100.8 to 100.9, and from 100.9 to 1001.0). Each of these segments represents 10% of the entire mile; therefore, 20% of the mile has rutting in the severity level 3. According to the criteria in Table 20, this percentage corresponds to low extent, or extent of 1. The equivalent severity and extent ratings for this test section are 3 and 1 respectively.

2.5 Finally, the ratings "31" are written into the distress file in the field "16" (replacing any existing data in this field). Fields are separated by comma. These changes are done for flexible sections only.

I00010,P,100.000,F ,01,29,01,00000,06,2009, ,000000,000.000,13,31,**31**,12,13,12,13,21,11,16,06, ,Crew 2

2.6 The distress data files are now ready, and the subsequent calculations and processes to compute PSI values can proceed as they are currently done. The new code and changes are done outside TIMS (Transportation Information Management System), as part of the data preprocessing. No further changes or modifications are necessary.

IMPLEMENTATION OF ALTERNATIVE APPROACH B

Alternative Approach B consists of applying a minor modification to the current NMDOT's Pavement Serviceability Index (PSI) formulation for flexible pavements, particularly to the equation of the interim value X (Equation 3).

Step 1: Evaluate Data Quality

1.1 Before the automated rut depth data is input in TIMS, the quality of the data should be evaluated and outliers must be investigated.

1.2 For quality control, it is recommended to perform rut-bar checks annually and systematically in a number of test sections to compare with the automated rut depth data.

1.3 Comparisons with data from previous years are also recommended.

Step 2: Modify Equation of the Interim Value X

2.1 The computer routine that currently calculates the PSI values in TIMS should be identified, particularly the one that calculates the interim value X (Equation 3).

2.2 Equation 3 should be replaced with Equation 11 in TIMS (restated here):

$$X = 100 - \left[\frac{0.6\,(\mathrm{IRI} - 25) + (0.4\,\mathrm{DR})}{2.9} + k_1 \exp^{k_2\,(\mathrm{Auto.Rut})} \right] \tag{11}$$

In this equation, the new input data are: Auto.Rut = automated rut depth (inches) for the section, k_1 = 0.73311, and k_2 = –2.80284; "exp" is the exponential function. There are no changes needed in the way how DR is calculated in TIMS (Refer to step 3.2).

2.3 Make changes to the READ statements in this routine: Read "Auto.Rut" from the automated rut depth files (at 0.1 mile intervals). Read the automated rut depth corresponding to the same test section (or 0.1 mile interval) as the distress ratings used to calculate DR, and <u>not</u> the rut depth averaged for the entire mile.

As an example, consider the following distress data file used to calculate Distress Rate (DR). Note that the severity and extent ratings for rutting should both be "0" in this file (shown in bold numbers below).

I00010,P,100.000,F ,01,29,01,00000,06,2009, ,000000,000.000,13,31,**00**,12,13,12,13,21,11,16,06, ,Crew 2

The corresponding automated rut depth data for the same mile are:

i00010p000-100_e01,XX,000.000,000.100,01302008,**0.27**
i00010p000-100_e01,XX,000.100,000.200,01302008,**0.16**
i00010p000-100_e01,XX,000.200,000.300,01302008,**0.29**
i00010p000-100_e01,XX,000.300,000.400,01302008,**-0.05**
i00010p000-100_e01,XX,000.400,000.500,01302008,**-0.10**
i00010p000-100_e01,XX,000.500,000.600,01302008,**-0.10**
i00010p000-100_e01,XX,000.600,000.700,01302008,**0.09**
i00010p000-100_e01,XX,000.700,000.800,01302008,**0.12**
i00010p000-100_e01,XX,000.800,000.900,01302008,**0.40**
i00010p000-100_e01,XX,000.900,001.000,01302008,**0.39**

Then, Auto.Rut = 0.27. This is the automated rut depth for the same 0.1 mile segment for which the distresses were collected.

Step 3: Data Preprocessing

3.1 During the data preprocessing, negative values of automated rut depth should be replaced with 0.

3.2 In the distress data files with 8-distress type format produced by NMDOT's Oracle®-based Pavement Distress Feeder System, make sure that the severity and extent ratings of rutting and shoving are equal to zero ("00") for all <u>flexible</u> sections. In this way, Equation 3 that calculates DR does not need to be modified in TIMS. The rutting component of Equation 3 will be equal to zero (DR_{Rut} = 0 in Equation 3). The following is an example:

Severity and extent equal to zero for
the third distress type

↓

```
NM0008,P,007.000,I ,02,25,04,00000,07,2009, ,000000,000.000,13,22,00,12,22,23,12,00,09,14,02,      ,Derek Boberg
NM0008,P,009.000,I ,02,25,04,00000,07,2009, ,000000,000.000,13,00,00,12,00,31,00,22,07,08,02,      ,Derek Boberg
NM0008,P,010.000,I ,02,25,11,00000,07,2009, ,000000,000.000,13,00,00,12,11,22,12,00,06,10,02,      ,Derek Boberg
NM0008,P,011.000,I ,02,25,04,00000,07,2009, ,000000,000.000,13,21,00,00,00,11,00,00,04,05,02,      ,Derek Boberg
NM0008,P,012.000,I ,02,25,04,00000,07,2009, ,000000,000.000,13,11,00,12,00,00,13,00,04,09,02,      ,Derek Boberg
```

↑

The format (or layout) of the distress data file with 8-distress types for flexible pavements (fields separated by commas, from left):

Position (separated by commas)	Field
1	Route
2	Direction (P or M)
3	Milepost
4	Type of route
5	District number
6	
7	
8	
9	Month when the survey was done
10	Year when the survey was done
11	(Blank)
12	
13	
14	Sev. & Ext. – Raveling and weathering (distress 1)
15	Sev. & Ext. – Bleeding (distress 2)
16	Sev. & Ext. – Rutting and shoving **(SET THIS EQUAL TO "00")** (distress 3)
17	Sev. & Ext. – Longitudinal cracks (distress 4)
18	Sev. & Ext. – Transverse cracks (distress 5)
19	Sev. & Ext. – Alligator cracks (distress 6)
20	Sev. & Ext. – Edge cracks (distress 7)
21	Sev. & Ext. – Patching (distress 8)
22	Sum of the severity ratings
23	Sum of the extent ratings
24	
25	Comment
25	Name of rater

3.3 Also, confirm that the distress data files (converted to 24-distress format) have the fields in positions 33 and 34 (which correspond to severity and extent of "rutting and shoving") equal to zero for all <u>flexible</u> sections.

```
080700I-25-P   024300002111000000000000001300000000031000003100000022000031000000
```

Field	Type of Data[a]	Position or column (from left)		
		Start	Length	End
Month	A	1	2	2
Year	A	3	2	4
Route type	A	5	3	7
Route number	A	8	3	10
Format (-)	A	11	1	11
Direction (P or M)	A	12	1	12
Format (blank spaces)	A	13	4	16
Milepost	N(9999)	17	4	20
Fraction	N(9.999)	21	4	24
(1) Sev. & Ext. Raveling & weathering **(distress 1)**	A	**25**	**2**	**26**
(2) Sev. & Ext. Bleeding **(distress 2)**	A	**27**	**2**	**28**
(3) Sev. & Ext. former distress – Input 00	A	29	2	30
(4) Sev. & Ext. former distress – Input 00	A	31	2	32
(5) Sev. & Ext. Rutting & shoving – Input 00 (distress 3)	A	**33**	**2**	**34**
(6) Sev. & Ext. former distress – Input 00	A	35	2	36
(7) Sev. & Ext. former distress – Input 00	A	37	2	38
(8) Sev. & Ext. former distress – Input 00	A	39	2	40
(9) Sev. & Ext. former distress – Input 00	A	41	2	42
(10) Sev. & Ext. Rutting & shoving – Input 00 **(distress 4)**	A	**43**	**2**	**44**
(11) Sev. & Ext. former distress – Input 00	A	45	2	46
(12) Sev. & Ext. former distress – Input 00	A	47	2	48
(13) Sev. & Ext. former distress – Input 00	A	49	2	50
Length, no longer recorded – Input 000	N(999)	51	3	53
(14) Sev. & Ext. Transverse cracks **(distress 5)**	A	**54**	**2**	**55**
Length, no longer recorded – Input 000	N(999)	56	3	58
(15) Sev. & Ext. former distress – Input 00	A	59	2	60
(16) Sev. & Ext. Alligator cracks **(distress 6)**	A	**61**	**2**	**62**
(17) Sev. & Ext. former distress – Input 00	A	63	2	64
(18) Sev. & Ext. former distress – Input 00	A	65	2	66
(19) Sev. & Ext. former distress – Input 00	A	67	2	68
(20) Sev. & Ext. Edge cracks **(distress 7)**	A	**69**	**2**	**70**
(21) Sev. & Ext. former distress – Input 00	A	71	2	72
(22) Sev. & Ext. former distress – Input 00	A	73	2	74
(23) Sev. & Ext. Patching **(distress 8)**	A	**75**	**2**	**76**
(24) Sev. & Ext. former distress – Input 00	A	**77**	**2**	**78**
End of record	A	79	5	83

[a] A: Alphabetic characters; N: Numeric (format in parentheses)

APPENDIX G

Multimedia Presentation (CD Enclosed)