# Procedure to Develop Index Quantifying Transverse Profile and Rutting of Flexible Pavements

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The amount of rutting on flexible pavements is an important distress parameter to consider when making judgments about rehabilitation of the riding surface. Because severe rutting is dangerous and uncomfortable to the riding public, millions of dollars are spent each year in the United States on rehabilitation of pavements that show such structural deterioration. Thus, network-level decisions about which pavements to rehabilitate should be based on a quantitative rut index that best uses available dollars while protecting the safety of the driving public. The methodology used to develop such a quantifiable rut index for Texas is presented. The Texas Department of Transportation has been collecting rut information by means of survey teams that manually read and record rut-depth information at selected sites throughout the state. The recent purchase of an Automatic Road Analyzer (ARAN) unit (and its associated rut bar) now allows them to collect rut information under traffic conditions and at normal highway speeds. The Center for Transportation Research was contracted to evaluate the ARAN unit and help implement the study findings. The methodology used in developing a rut index based on data collected by the ARAN unit is presented. The conclusions are based on the ARAN's output, but the methodology and index can be applied to any rut-depth instrument that collects and presents rut data in a similar fashion.

Development of a rutting index for use in evaluating Texas highways has been a concern for years. Accordingly, the Texas Department of Transportation (DOT) purchased an instrument for network-level evaluation of the state's highway system. This instrument captures and processes data from its sensors. Data are reported as a transverse profile and summarized into a rut index for the left and right wheelpaths.

This paper presents an approach for developing models to process transverse profile information and thus quantify rut-depth information. These models are then correlated with several summary statistics. Results of the correlations identify a preferred model to quantify transverse profile data captured by the instrument's rut sensors. In this paper, the terms "transverse profile" and "rutting" are used interchangeably. The formulas and resulting calculations are specific to the Texas Automatic Road Analyzer (ARAN), but the methodology can be applied to any rut bar depth-monitoring system as long as the reported information is similar, including number of sensors and the measurement principle.

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## BACKGROUND

Pavement rutting is defined as the longitudinal depressions left in wheel tracks after repeated load applications (*1*); it results from compaction under load combined with the sideways shoving of pavement material. It has long been considered a measure of performance of flexible pavements, and its characteristics can be used as an indication of structural deterioration and road surface deformation (*2–4*). Excessive rutting directly affects the safety and comfort of the traveling public (*5*). Instrumentation to study pavement rutting has developed significantly in the past few years. Studies have focused on development and evaluation of techniques to measure and predict road roughness and rutting (*6–9*).

The Texas DOT has been using condition survey teams to collect rut-depth data for several years. The process involves placing a straightedge across a travel lane and physically measuring the depth of individual ruts. Because this method is slow and dangerous, the DOT purchased the ARAN unit manufactured by Highway Products International (HPI). This instrument can collect several types of pavement distress information under normal traffic conditions. The ARAN's roughness, rutting, and gyro subsystems have been evaluated over the past 2 years. The Center for Transportation Research (CTR) was contracted to perform this evaluation and help implement the study findings.

One of the ARAN's instrumentation subsystems is used to determine the amount of pavement rutting, as previously stated. Rutting data are acquired from ultrasonic sensors mounted on a rut bar attached to the ARAN's front bumper. This bar can be configured in any of three ways. The bumper itself has seven sensors spaced 1 ft apart from one end to the other. Additionally, one of two sets of extension wings can be attached to the main bumper. Each set has two wings—a left wing and a right wing. For a smaller set, each wing contains two sensors, and for a larger set, each wing has three sensors. The smaller wings allow 11 sensors to be active, providing for the evaluation of the entire width of a 10-ft travel lane. This configuration was chosen for this study.

Sensor data are processed and presented to the user in two formats. Individual sensor readings from a survey section are stored and presented as transverse profile data. They are reported in inches with a resolution to 1/10 in. and can also be viewed in a summary report representing the mean value of each sensor through the length of the survey section. Finall· a rut index for each wheelpath is calculated and reported a percentage of rutting for that wheelpath.

During CTR evaluation of the rut-depth subsystem, two operational characteristics were evaluated for their effects on reported rut data: selectable report interval and vehicle speed of operation. Repeatability of reported rut information was analyzed when these operational characteristics were changed. Findings indicate that operating speed did not significantly affect output from the ARAN's rut subsystem. The user must chose either 0.005 or 0.01 mi as a report interval to obtain the best subsystem repeatability. Additionally, the subsystem has a statistical output, called rut-depth index, that statistically summarizes readings from some, not all, of the sensors. During this study, it was found that the reported rut-depth index was not repeatable, no matter what the operational parameters, because the index is not resulted from the whole profit. Therefore, this index cannot practically be used to report rut depth.

These facts led CTR staff to investigate and develop a useful rut-depth index based on transverse profile data produced by the ARAN unit. It should be pointed out that a test section length of 0.2 mi was used in developing the rut index models. This length was selected because it was also used by the Texas DOT in calibrating its high-speed pavement roughness instrumentation. It was thus convenient, well marked, and readily available.

## MEASUREMENT OF RELATIVE TRANSVERSE PROFILES

Pavement transverse profiles can be measured using a rut bar similar to the one shown in Figure 1, having 11 ultrasonic sensors to measure distance between pavement surface and each individual sensor. Horizontal distance between any two adjacent sensors is 1 ft. If a right-angle coordinate is defined as shown in Figure 1, then

$$\{X_i,\ i = 1, 2, \ldots, 11\} = \{-5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5\} \quad \text{(ft)}$$

and

$$Y_i + W_i = C \qquad (\text{all } i) \tag{1}$$

where

$C$ = a constant,
$\{X_i,\ i = 1, 2, \ldots, 11\}$ = transverse distance sequence in $x$-axis,
$\{Y_i,\ i = 1, 2, \ldots, 11\}$ = discrete transverse profile sequence, and
$\{W_i,\ i = 1, 2, \ldots, 11\}$ = measured data sequence by the individual ultrasonic sensors.

Thus,

$$Y_i = C - W_i \qquad (\text{all } i) \tag{2}$$

To obtain $Y_i$, a transverse profile reference level should be given. If the mean value of the transverse profile sequence $\{Y_i,\ i = 1, 2, \ldots, 11\}$ is taken as the reference level, the relative discrete transverse profile sequence $\{T_i\}$ can be defined as follows:

$$T_i = Y_i - \overline{Y} \qquad (\text{all } i) \tag{3}$$

where

$$\overline{Y} = \frac{1}{11}\sum_{i=1}^{11} Y_i = \frac{1}{11}\sum_{i=1}^{11} (C - W_i) = C - \overline{W} \quad \text{and}$$

$$\overline{W} = \frac{1}{11}\sum_{i=1}^{11} W_i \tag{4}$$

By combining Equations 2, 3, and 4, the relative transverse profile sequence can be obtained by Equation 5:

$$T_i = C - W_i - C + \overline{W} = -(W_i - \overline{W}) \tag{5}$$

Statistical characteristics of transverse profiles on a given pavement section are of interest when transverse profile smoothness and associated rutting are evaluated. In this study, all sampled transverse profiles at each sampling station were averaged to obtain a mean transverse profile statistically representing transverse profile characteristics of a given pavement section.

Figure 2 shows a mean relative transverse profile, which was measured by the ARAN unit on Austin Test Section

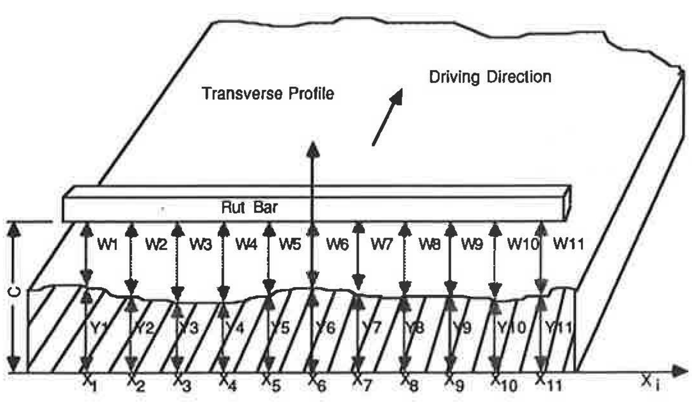


**FIGURE 1 Transverse profile measurement by rut bar.**

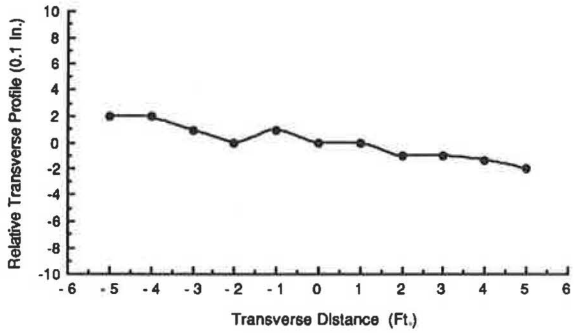


**FIGURE 2 Relative transverse profile at ATS28.**

ATS28 near Austin, Texas. Relative transverse profile was plotted as seen here.

## POLYNOMIAL TRANSFORM OF RELATIVE TRANSVERSE PROFILES

Although relative transverse profiles cannot quantitatively characterize transverse profile smoothness and rutting, they can demonstrate it graphically. In a practical engineering sense, the purpose of measuring transverse profiles is to obtain objective statistics to evaluate transverse profile smoothness and associated rutting.

A transverse profile can be approximately fitted by the mathematical function

$$T_i = F(X_i) \qquad (6)$$

where $F(X_i)$ is a continuous function of transverse distance $X_i$. One of the suitable models of $F(X_i)$ is the polynomial function

$$F(X) = A_0 + A_1X + A_2X^2 + \cdots + A_mX^m \qquad (7)$$

where $A_j(j = 0, 1, \ldots, m)$ is the constant coefficient, and $m$ is the order of the polynomial function. In this study, $m = 5$ was chosen. Then, by the notation shown in Figure 1, Equation 7 can be represented as

$$T_i = A_0 + A_1(X_i) + A_2(X_i)^2 + A_3(X_i)^3 + A_4(X_i)^4 + A_5(X_i)^5 \qquad (8)$$

The explanation of Equation 8 is that the transverse profile shown in Figure 1 is the weighted summation of polynomials with weights ($A_0$, $A_1$, $A_2$, $A_3$, $A_4$, and $A_5$). The coefficients $A_0$, $A_1$, $A_2$, $A_3$, $A_4$, and $A_5$ thus approximately reflect the geometrical or graphical characteristics of the transverse profile and rut depth. In fact, this approach could be considered a "transformation" of the variables $\{T_i\}$ in the "space domain," to the variables $\{A_j\}$ in the "polynomial domain." Symbolically, this transformation is expressed as

$$\{T_i\} \Rightarrow \{A_j\} \qquad (9)$$

Only the magnitudes of the coefficients of the regression model in Equation 7 are of concern because the magnitude of the coefficient $A_j$ indicates weight of the content of the $j$th-order polynomial function in the associated transverse profile. The transformation shown in Equation 9 can be symbolically represented as follows:

$$\{T_i\} \Rightarrow \{a_j\} \qquad (10)$$

where

$$a_j = |A_j| \qquad (j = 0, 1, \ldots, 5) \qquad (11)$$

This transformation is defined as the "polynomial transform" in the following discussion, and the symbol "$\Rightarrow$" represents an irreversible polynomial transform.

It might be expected that one or more of the polynomial transform coefficients $a_j$ could be sensitive to transverse profile smoothness. For example, for a given test section if the fourth-order polynomial transform $a_4$ is relatively larger than that of other test sections, then $a_4$ indicates that transverse profile of the given section is relatively rougher than that of the others.

In an extreme case all the polynomial transform coefficients would be zero, denoting a corresponding transverse profile that would ideally be constant or perfectly smooth with no rutting. Some or all of the coefficients $a_j$ would be relatively large if the condition of the transverse profile rutting were relatively poor. But it should be mentioned that magnitudes of the coefficients $a_j$ depend on graphic characteristics of the associated relative transverse profile. That is, the larger $a_j$, the more $j$th-order polynomial content there is in the transverse profile.

Applying the polynomial transform to evaluate a pavement transverse profile condition would be helpful in understanding the idea just presented. Figure 3 shows two transverse profiles from Austin Test Sections ATS04 and ATS28. Experience tells one that transverse profile smoothness of ATS28 is better, with less rutting, than ATS04, but this evaluation is subjective. Some data should be obtained from these transverse profiles to substantiate this subjective evaluation. If the polynomial transform is applied to these two sections, poly-

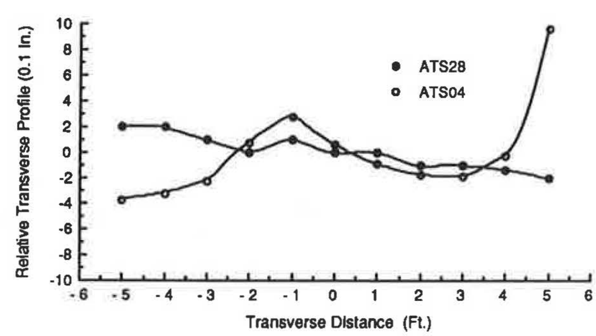


**FIGURE 3 Relative transverse profiles at ATS04 and ATS28.**

nomial transform coefficients of ATS04 and ATS08 can be listed as follows:

| *ATS04* | *ATS28* |
|---|---|
| $a_0 = 1.305$ | $a_0 = 6.434 \times 10^{-3}$ |
| $a_1 = 1.128$ | $a_1 = 0.2623$ |
| $a_2 = 0.610$ | $a_2 = 4.429 \times 10^{-3}$ |
| $a_3 = 0.110$ | $a_3 = 1.286 \times 10^{-2}$ |
| $a_4 = 2.695 \times 10^{-2}$ | $a_4 = 2.331 \times 10^{-4}$ |
| $a_5 = 5.128 \times 10^{-4}$ | $a_5 = 2.885 \times 10^{-4}$ |

From these coefficients it can be seen that all the polynomial transform coefficients of ATS04 are larger than those of ATS28. This example supports the statement that magnitudes of the coefficients $a_j$, to a certain degree, indicate the conditions of transverse profile smoothness and the associated rutting.

With substitution of the polynomial transform coefficients, the following linear multiple regression model adequately characterizes transverse smoothness and rutting (TSR):

$$TSR = K_1 + K_2a_0 + K_3a_1 + K_4a_2 + K_5a_3 + K_6a_4 + K_7a_5 \quad (12)$$

In this model, some of the coefficients ($K_n$ $n = 1, 2, \ldots, 7$) could be zero.

## INDEX DEVELOPMENT

A standard reference should be used to develop a new index characterizing transverse profiles. In evaluating pavement transverse profile smoothness and rutting, two statistics are often used: mean value and standard deviation of the measured transverse profile data. But these two statistics do not take into account the sequence of such data. In other words, graphic characteristics of transverse profiles do not affect the two statistics if data sequence values of the associated transverse profile are kept the same. In fact, the graphic characteristic of the transverse profiles is an important factor in evaluating highway safety and passenger comfort. It will affect transverse profile smoothness and rutting.

Graphic characteristics of pavement transverse profile can be obtained from the polynomial transform. The regression model shown in Equation 7 may be a good candidate for evaluating pavement transverse profile smoothness and rutting, although it does not have an obvious physical unit. The procedure of modeling and data analysis for developing indexes characterizing transverse profiles will be presented later. The Texas ARAN served as measuring equipment to collect pavement serviceability index and transverse profile data. Thus, the resulting models are based on the ARAN unit. But the methodology presented here can be applied to other rut-depth measuring equipment.

### Choice of Reference Statistics

Transverse profile standard deviation SD was chosen as one of the reference statistics in developing a new index to characterize transverse profiles. Another index, TD, was chosen as a reference statistic defined as

$$TD = \frac{(TDR + TDL)}{2} \quad (13)$$

where

$$TDR = \frac{(T_1 - 2T_3 + T_5)}{2}, \text{ and}$$

$$TDL = \frac{(T_7 - 2T_9 + T_{11})}{2} \quad (14)$$

It can be said that TDR is the second-order difference of the outside wheelpath transverse profile and TDL is the second-order difference of the inside wheelpath transverse profile. Although TDR and TDL do not cover the entire transverse profile, they reflect rutting characteristics in the outside and inside wheelpaths, respectively.

Serviceability index (SI) was also considered as a reference statistic. Because the roughness measuring subsystem of the ARAN unit is response-type, measured SI values are the responses of the measuring vehicle to longitudinal and transverse pavement roughness. The SI value thus should be correlated with transverse profile roughness and rutting.

### Data Collection and Processing

Field data were collected in the summer of 1989 using the ARAN unit. Table 1 presents measured transverse profile data collected from several flexible pavements. However, all raw data in Table 1 had to be subtracted from associated mean values to obtain the relative transverse profiles.

Table 2 gives the fifth-order polynomial curve-fitting coefficients of the relative transverse profile data, $R^2$-values of the curve fitting, and values of the reference statistics. Linear correlation between the reference statistics and coefficients can be conducted to evaluate sensitivity of reference statistics to coefficients. Correlation analysis results are as follows:

| *Statistics* | $a_0$ | $a_1$ | $a_2$ | $a_3$ | $a_4$ | $a_5$ |
|---|---|---|---|---|---|---|
| SI | .656 | .471 | .873 | .386 | .885 | .276 |
| SD | .765 | .439 | .794 | .322 | .644 | .192 |
| TD | .992 | .259 | .835 | .114 | .482 | .221 |

It is seen that the coefficients $a_2$ and $a_4$ correlate relatively well with SI. This further proves that measured roughness from a response-type roughness-measuring system has a certain correlation with transverse profile characteristics—that is, response of a vehicle is due not only to longitudinal roughness but also to transverse profile smoothness. However, this cannot be seen if the standard deviations SD of the transverse profiles are considered, because the $R^2$-value between SI and SD is relatively small.

### Transverse Profile Smoothness and Rut-Depth Index Specifications and Development

The multiple regression model in Equation 12 will be considered as the basis for index modeling. In modeling, specifi-

TABLE 1 TRANSVERSE PROFILE DATA AT AUSTIN TEST SECTIONS

| | Ultrasonic Sensors (0.1 Inch) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ATS | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
| 01 | 145.5 | 138.3 | 143.4 | 139.2 | 141 | 137.4 | 142 | 141.5 | 138 | 143.5 | 137.5 |
| 03 | 142.8 | 138.8 | 142.4 | 139.2 | 140.8 | 142 | 145.2 | 145 | 143.4 | 145.2 | 145.2 |
| 04 | 143.8 | 137.3 | 143.3 | 139.3 | 142.3 | 139.5 | 140.3 | 141.8 | 141 | 142 | 130.5 |
| 07 | 144 | 141.7 | 143.7 | 143 | 143 | 142 | 145 | 143.3 | 142 | 144 | 145.7 |
| 08 | 141.7 | 140.7 | 141.7 | 141.7 | 141.7 | 141.3 | 145 | 143 | 142 | 144 | 146 |
| 09 | 140.7 | 141 | 141 | 141 | 142 | 141.7 | 144.7 | 143.3 | 142.3 | 144 | 146 |
| 12 | 142.3 | 141.3 | 142.3 | 142.7 | 143 | 142 | 147 | 143.7 | 142 | 145 | 148.7 |
| 15 | 142.5 | 141 | 142 | 141 | 141 | 141.5 | 145 | 142.5 | 142 | 144 | 146.5 |
| 19 | 138.7 | 142 | 140.7 | 142 | 142 | 142 | 145.3 | 143.7 | 142.7 | 144.7 | 146.3 |
| 20 | 137.7 | 141 | 139.7 | 141 | 141 | 140.7 | 145.7 | 142.7 | 141 | 144 | 147 |
| 22 | 142.3 | 140.3 | 142.3 | 142 | 142.3 | 140.7 | 145 | 142 | 141 | 143.3 | 146 |
| 25 | 146 | 139 | 144 | 140 | 142 | 138.3 | 142.7 | 142 | 139.3 | 144 | 138 |
| 27 | 141.3 | 141.3 | 141 | 142.3 | 142 | 142 | 144 | 143 | 142.3 | 143.3 | 144 |
| 28 | 141 | 142 | 141 | 143 | 142 | 143 | 144.3 | 144 | 143 | 144 | 145 |
| 30 | 152.3 | 139 | 149.7 | 142 | 146.7 | 138.7 | 146 | 139.3 | 137 | 142.7 | 147.7 |
| 31 | 142.7 | 138.7 | 142.7 | 140 | 141.7 | 139.7 | 142.7 | 142.3 | 139.7 | 143.7 | 143.3 |
| 41 | 145 | 141.7 | 144 | 142.7 | 144 | 141 | 140.7 | 140 | 140 | 140 | 139.7 |
| 42 | 140.7 | 140.3 | 141 | 142 | 142 | 141 | 143 | 142 | 141 | 143 | 143 |
| 43 | 140 | 140 | 140 | 141 | 141 | 141 | 142.3 | 142 | 141 | 143 | 142 |
| 55 | 142.3 | 138 | 142 | 140 | 142 | 138.7 | 141 | 141 | 139 | 141.7 | 140 |

TABLE 2 TRANSVERSE PROFILE POLYNOMIAL TRANSFORM COEFFICIENTS AND REFERENCE STATISTICS

| | Coefficients of Polynominal Transform and $R^2$ Values | | | | | | | Reference Statistics | | |
|---|---|---|---|---|---|---|---|---|---|---|
| ATS | A0 | A1 | A2 | A3 | A4 | A5 | $R^2$ | SI | SD | TD |
| 01 | 3.009 | -0.5435 | -0.6773 | 1.338E-2 | 2.113E-2 | 1.619E-3 | 0.97 | 2.61 | 2.775 | -0.800 |
| 03 | 1.462 | -2.149 | -0.2341 | 0.1866 | 4.953E-3 | -4.423E-3 | 0.98 | 3.67 | 2.370 | -1.845 |
| 04 | 1.305 | -1.128 | -0.6103 | 0.1102 | 2.695E-2 | -5.128E-4 | 0.97 | 1.96 | 3.703 | -1.250 |
| 07 | 1.486 | -8.536E-2 | -0.2290 | -8.559E-3 | 4.516E-3 | 2.083E-4 | 0.97 | 4.40 | 1.257 | -1.725 |
| 08 | 1.287 | -0.4140 | -0.2027 | 4.050E-3 | 4.167E-3 | -1.923E-4 | 0.98 | 4.03 | 1.683 | -1.464 |
| 09 | 0.8155 | -0.5950 | -0.1449 | 2.674E-2 | 3.176E-3 | -9.776E-4 | 0.98 | 3.76 | 1.758 | -0.989 |
| 12 | 1.856 | -0.1118 | -0.2837 | -3.821E-2 | 5.536E-3 | 6.731E-4 | 0.98 | 4.37 | 2.334 | -2.127 |
| 15 | 1.285 | -0.4829 | -0.1307 | 7.503E-3 | 1.457E-4 | -1.603E-4 | 0.99 | 4.28 | 1.804 | -1.727 |
| 19 | 0.5372 | -0.3694 | -0.1628 | -7.233E-3 | 6.148E-3 | -3.365E-4 | 1.00 | 4.17 | 2.160 | -0.452 |
| 20 | 1.126 | -0.1454 | -0.2463 | -4.861E-2 | 7.488E-3 | 6.891E-4 | 1.00 | 3.57 | 2.695 | -1.216 |
| 22 | 1.862 | 1.867E-2 | -0.3016 | -2.899E-2 | 6.468E-3 | 5.289E-4 | 0.98 | 4.40 | 1.734 | -2.180 |
| 25 | 2.827 | -0.5363 | -0.6521 | 1.773E-2 | 2.075E-2 | 1.442E-3 | 0.99 | 3.12 | 2.653 | -3.068 |
| 27 | 0.4207 | -0.1398 | -8.814E-2 | -2.316E-2 | 2.593E-3 | 7.051E-4 | 0.91 | 4.29 | 1.049 | -0.332 |
| 28 | 6.434E-3 | -0.2623 | -4.429E-3 | -1.286E-2 | 2.331E-4 | 2.885E-4 | 0.92 | 4.43 | 1.328 | 0.223 |
| 30 | 6.137 | -0.9310 | -0.9022 | 4.458E-2 | 1.623E-2 | -1.026E-3 | 0.99 | 2.18 | 5.054 | -7.727 |
| 31 | 2.226 | -0.8512 | -0.4268 | 8.402E-2 | 1.145E-2 | -2.083E-3 | 0.93 | 3.58 | 1.721 | -2.443 |
| 41 | 0.9126 | -0.9509 | -0.1633 | 5.597E-2 | 4.050E-3 | -1.555E-3 | 0.99 | 3.93 | 1.914 | -1.107 |
| 42 | 0.8545 | -2.294E-2 | -0.2128 | -2.164E-2 | 7.168E-3 | 5.289E-4 | 0.84 | 4.24 | 0.988 | -0.720 |
| 43 | 0.4280 | -0.3217 | -0.1402 | -2.375E-3 | 5.478E-3 | 2.885E-4 | 0.86 | 4.42 | 1.010 | -0.232 |
| 55 | 1.957 | -0.4272 | -0.4403 | 5.570E-2 | 1.375E-2 | -1.166E-3 | 0.90 | 2.95 | 1.480 | -0.825 |

cations of the model are necessary because it is improper to use all of the polynomial transform coefficients. Specifications of models can be judged by factors such as $R^2$-value, sign of coefficient, absolute magnitude of coefficient, and simplicity.

Table 3 lists regression model specifications. The indexes SI, SD, and TD are dependent variables, and the polynomial transform coefficients $a_j$ ($j = 0, \ldots, 5$) are independent variables. Table 4 shows results of the multiple regression models specified in Table 3.

Several important factors must be considered to choose adequate models, as can be seen in Table 4. Factors of $R^2$-value, sign of coefficient, absolute magnitude of coefficient, and simplicity are concerned, as just stated. Model choices for the references SI, SD, and TD are now discussed individually.

TABLE 3 SPECIFICATIONS FOR MULTIPLE REGRESSION MODEL

| | Models | Dependent Variables: SI, SD, TD |
|---|---|---|
| Independent Variables $a_0\ a_1\ a_2\ a_3\ a_4\ a_5$ | 1 | $a_0\ a_1\ a_2\ a_3\ a_4\ a_5$ |
| | 2 | $a_1\ a_2\ a_3\ a_4\ a_5$ |
| | 3 | $a_1\ a_2\ a_3\ a_4$ |
| | 4 | $a_2\ a_3\ a_4\ a_5$ |
| | 5 | $a_0\ a_2\ a_4$ |
| | 6 | $a_2\ a_3\ a_4$ |
| | 7 | $a_2\ a_4$ |

TABLE 4 COEFFICIENTS AND $R^2$-VALUES OF ALL REGRESSION MODELS

| Dependent Variables | Independent Variables | Model 1 | Model 2 | Model 3 | Model 4 | Model 5 | Model 6 | Model 7 |
|---|---|---|---|---|---|---|---|---|
| | | Coefficients and R² Values of All the Regression Models | | | | | | |
| SI | Constant | 4.739 | 4.704 | 4.732 | 4.685 | 4.646 | 4.703 | 4.611 |
| SI | $a_0$ | 6.718 | | | | 6.626 | | |
| SI | $a_1$ | -0.552 | -0.600 | -0.423 | | | | |
| SI | $a_2$ | -68.70 | -1.395 | -1.139 | -1.593 | -67.68 | -1.411 | -1.365 |
| SI | $a_3$ | -2.383 | -1.153 | 0.742 | -5.192 | | -3.245 | |
| SI | $a_4$ | 1152.7 | -45.09 | -54.03 | -42.42 | 1125.4 | -48.09 | -54.12 |
| SI | $a_5$ | 234.96 | 216.42 | | 107.39 | | | |
| SI | $R^2$ | $R^2 = 0.912$ | $R^2 = 0.895$ | $R^2 = 0.875$ | $R^2 = 0.860$ | $R^2 = 0.839$ | $R^2 = 0.855$ | $R^2 = 0.822$ |
| SD | Constant | 0.919 | 0.933 | 0.860 | 0.971 | 1.006 | 0.894 | 1.016 |
| SD | $a_0$ | -2.966 | | | | -1.842 | | |
| SD | $a_1$ | 0.981 | 1.002 | 0.486 | | | | |
| SD | $a_2$ | 34.60 | 4.883 | 4.137 | 5.215 | 22.82 | 4.449 | 4.388 |
| SD | $a_3$ | 6.690 | 6.306 | -0.279 | 12.45 | | 4.300 | |
| SD | $a_4$ | -592.5 | -63.69 | -37.59 | -68.16 | -364.3 | -44.42 | -36.42 |
| SD | $a_5$ | -640.2 | -632.1 | | -450.0 | | | |
| SD | $R^2$ | $R^2 = 0.812$ | $R^2 = 0.810$ | $R^2 = 0.706$ | $R^2 = 0.751$ | $R^2 = 0.654$ | $R^2 = 0.688$ | $R^2 = 0.653$ |
| TD | Constant | 0.172 | 0.170 | 0.187 | 0.160 | 0.143 | 0.106 | 0.078 |
| TD | $a_0$ | 0.285 | | | | 0.143 | | |
| TD | $a_1$ | -0.274 | -0.276 | -0.158 | | | | |
| TD | $a_2$ | -16.20 | -13.34 | -13.17 | -13.44 | -14.69 | -13.13 | -13.11 |
| TD | $a_3$ | -1.235 | -1.198 | 0.301 | -2.888 | | -1.011 | |
| TD | $a_4$ | 314.9 | 264.1 | 258.2 | 265.3 | 283.6 | 259.5 | 257.7 |
| TD | $a_5$ | 144.7 | 143.9 | | 93.81 | | | |
| TD | $R^2$ | $R^2 = 0.999$ | $R^2 = 0.999$ | $R^2 = 0.997$ | $R^2 = 0.997$ | $R^2 = 0.995$ | $R^2 = 0.994$ | $R^2 = 0.993$ |

NOTE: SI, SD, and TD are dependent variables; $a_i$ (i = 0, 1, ..., 5) are independent variables.

### *SI*

Besides longitudinal profile roughness, pavement serviceability index SI measured by a response-type roughness-measuring system such as the ARAN unit is affected by transverse profile smoothness. The smoother the transverse profile, the better the serviceability, or the larger the SI. Mathematically, this logical relationship requires the coefficients of the regression model in Equation 12 to have negative signs according to the meaning of the polynomial transform coefficients. The multiple regression results in Table 4 indicate that only Models 6 and 7 are adequate if the signs are considered. However, the $R^2$-value of Model 6 is larger than that of Model 7. Model 6 was chosen for this study.

### *SD*

Transverse profile data standard deviation SD does not concern the sequence of transverse profile data, so graphic characteristics of the transverse profile do not significantly affect the SD value. Thus there is no strict requirement for signs of the coefficients of the multiple regression model in Equation 12. Model 1 was chosen for the multiple regression model of Equation 12 because it has the best correlation with SD (higher $R^2$-value).

### *TD*

According to the definition of TD, it does not consider the whole transverse profile. There is thus no strict requirement for the signs of the multiple regression model in Equation 12. Model 3 was chosen because of simplicity and the $R^2$-value.

On the basis of the three references SI, SD, and TD and the results of model choice, the three resulting multiple regression models are as follows:

*Based on SI*:

$$\mathrm{TSR}_{\mathrm{SI}} = 4.703 - 1.411a_2 - 3.245a_3 - 48.09a_4 \tag{15}$$

*Based on SD*:

$$\mathrm{TSR}_{\mathrm{SD}} = 0.919 - 2.966a_0 + 0.981a_1 + 34.60a_2 + 6.690a_3 - 592.5a_4 - 640.2a_5 \tag{16}$$

*Based on TD*:

$$\mathrm{TSR}_{\mathrm{TD}} = 0.187 - 0.158a_1 - 13.17a_2 + 0.301a_3 + 258.2a_4 \tag{17}$$

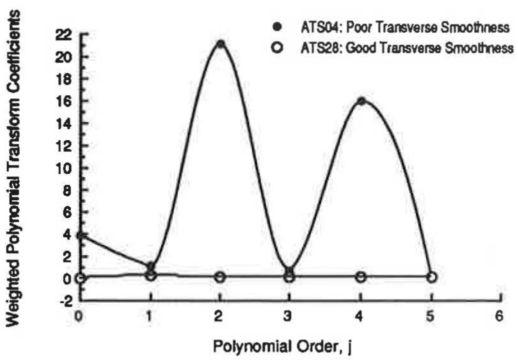


**FIGURE 4 Weighted polynomial transforms of transverse profiles at ATS04 and ATS28.**

The TSRs shown in Equations 15, 16, and 17 can be considered as the indexes characterizing transverse profile smoothness or rutting.

The following example may be useful in better explaining application of the polynomial transform described earlier. In this example, the model of Equation 16 will be used. The polynomial transform can be expressed by a curve. The horizontal axis ($x$-axis) is the polynomial order $j$, and the vertical axis ($y$-axis) is the weighted polynomial transform coefficient $|K_{j+2}|a_j$ ($j = 0, \ldots, 5$) as expressed in Equation 12, but the weights are the absolute values of the associated coefficients of the multiple regression models. From Equation 16, the weights can be listed as follows:

| *Polynomial Order* j | *Polynomial Transform Coefficient* | *Weights* |
|---|---|---|
| 0 | $a_0$ | 2.966 |
| 1 | $a_1$ | 0.981 |
| 2 | $a_2$ | 34.60 |
| 3 | $a_3$ | 6.690 |
| 4 | $a_4$ | 592.5 |
| 5 | $a_5$ | 640.2 |

Figure 4 shows the weighted polynomial transforms of Austin Test Sections ATS04 and ATS28. Conditions of transverse profile smoothness on ATS04 and ATS28 can be easily distinguished by use of the polynomial transform. It should be mentioned that the rutting judgment from Figure 3 is qualitative and that from Figure 4 is quantitative. The two judgments have essential differences.

Figures 5, 6, and 7 show correlation of the multiple regression models with the references SI (Equation 15), SD (Equation 16), and TD (Equation 17), respectively. The regression model shown in Equation 17 has a very good correlation with TD.

## DISCUSSION OF RESULTS

1. In developing indexes characterizing transverse profiles, three reference statistics (SI, SD, and TD) were selected. The purpose was to prove that the developed theoretical model concept and structure correlate with the chosen references. The correlations found also prove the implied use and applicability of the polynomial transform in evaluating pavement transverse profile smoothness. Of course, some better models could be found if the polynomial transform coefficients were directly correlated with subjective judgments on pavement safety and the passenger's degree of comfort. Judgments on rutting by a survey panel for a number of test sections could also be used to calibrate the model coefficients.

2. The presented multiple regression model for Equation 12 can quantitatively reflect the graphical characteristics of transverse profiles. The TSR indexes were developed to evaluate the transverse profile of an asphaltic pavement section. However, the resulting correlation analysis showed no good correlations among the reference statistics SI, SD, and TD. Their correlations are as follows:

| *Reference Pairs* | $R^2$-*Values* |
|---|---|
| SI–SD | 0.635 |
| SI–TD | 0.376 |
| SD–TD | 0.595 |

The indexes from Equations 15, 16, and 17 should have better correlations with SI, SD, and TD, respectively. They can be used to evaluate pavement smoothness and rutting conditions.

3. In new pavement construction, longitudinal roughness is usually used to evaluate whether the constructed pavement satisfies the design requirements. Research has been conducted on longitudinal roughness specifications (*10*). Trans-

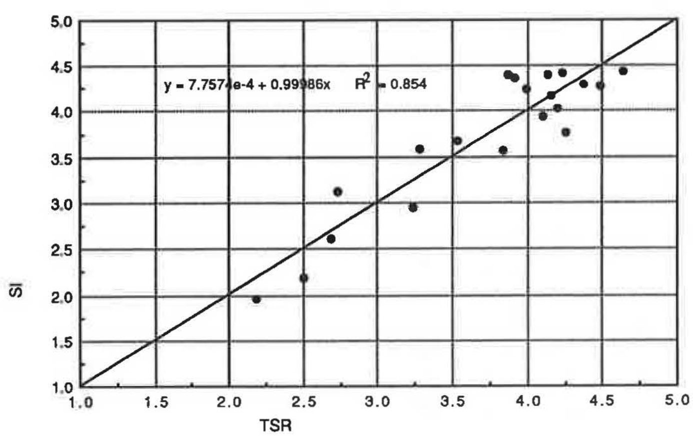


**FIGURE 5 Correlation between SI and TSR.**

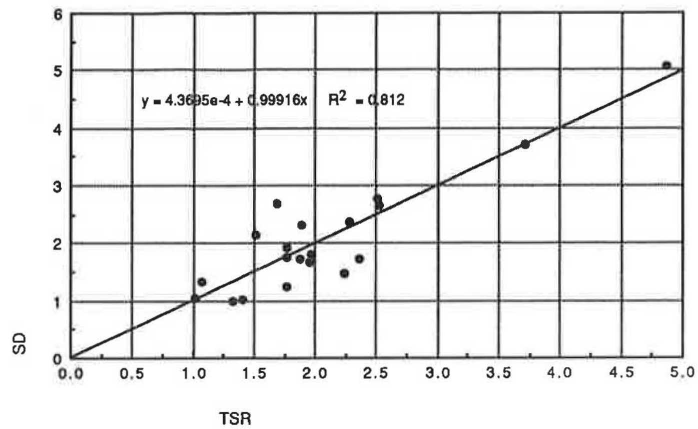


**FIGURE 6 Correlation between SD and TSR.**

verse smoothness of newly constructed pavement is also an important factor in determining if the constructed pavement satisfies the design requirements. In this case, the index TSR might be a good candidate for a quality-control statistic in evaluating newly constructed pavement. However, further research is needed for more effective application of the developed methodology.

4. Certain differences appear among the multiple regression models of Equations 15, 16, and 17. These models evaluate pavement transverse profile smoothness from different angles according to their associated references. For $TSR_{SI}$ from Equation 15, the larger the $TSR_{SI}$, the better the transverse profile smoothness because the model was derived from correlation with SI. But for $TSR_{SD}$ and $TSR_{TD}$ from Equations 16 and 17, the smaller the $TSR_{SD}$ and $TSR_{TD}$, the better the conditions of transverse profile smoothness, because the models were derived from correlations with SD and TD, respectively.

## CONCLUSIONS

The study used the rut-depth subsystem of the ARAN unit. The methodology in developing transverse profile smoothness and the rutting indexes can be applied to any system having a rut bar with sensor configuration as shown in Figure 1. All

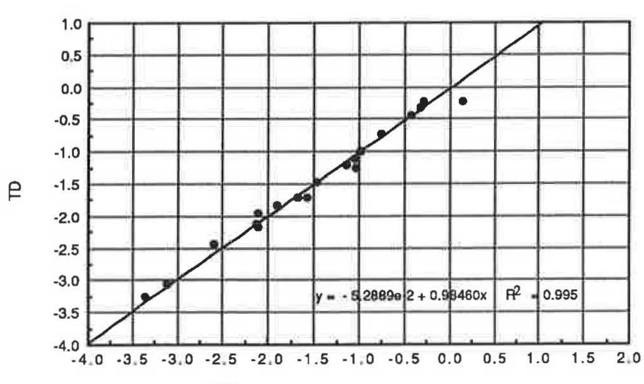


**FIGURE 7 Correlation between TD and TSR.**

the modeling coefficients must be found if a different system is used.

The index models shown in Equations 15, 16, and 17 characterize transverse profile smoothness from three different angles. Further research is needed to decide which index best correlates the safety factor and passenger's degree of comfort.

Relative transverse profile was obtained by averaging all the transverse profiles of a pavement section of a given length, thus smoothing the data. Research is needed to determine the most appropriate pavement length for calculating the TSR. For example, a 0.2-mi section could have the same TSR as a 4-mi section. Resolution of the TSR statistic must be determined by highway agencies for network- or project-level needs.

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