An Analysis of the Condition of Gravel and Stone Roads in Indiana

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Condition relationships for gravel and stone roads were determined using road condition variables of roughness number, average rut depth, and Clegg Impact Value (a measure of in situ pavement strength). The studies were undertaken in Bartholomew, Huntington, Jasper, Tippecanoe, and Warrick Counties in Indiana. Roughness was measured at 20 mph (32 kph) over 1-mi test sections using a PCA roadmeter from the Indiana Department of Highways, Division of Research and Training. The independent variables of roadway geometry, material, and use characteristics in the regression analysis included average road width; percentage of surface camber; terrain (indicator or dummy variable); surface material parameters [P200, P40, P10, D95 (in), fineness modulus, liquid limit, and plasticity index]; and average daily traffic volume. In each 1-mi section, one surface material sample was collected for testing and other measurements were taken at 0.1-, 0.3-, 0.5-, 0.7-, and 0.9-mi locations. Most correlation coefficients were considered significant at α = 0.1 during the regression analysis. After the covariance and variance were analyzed, suitable equations were determined for each of the three condition variables. Two equations, including and excluding fineness modulus as a measure of coarseness of surface material, were determined. The coefficients of the determination of the six equations ranged from 0.52 to 0.69. The regression analysis, combined with degree of corrugation, strength, and surface rutting, provided a basis for the evaluation of the performance and maintenance management of low-volume gravel and stone roads in Indiana.

In the state of Indiana, as in many other countries with similar levels of development, gravel and stone roads are predominant in local highway networks. County and other local highway agencies, often with limited resources, are responsible for their maintenance. Road condition is usually assessed during routine or special road inspections by applying a visual assessment and personal judgment to recommend maintenance or major improvements. The condition of gravel or stone roads changes rapidly and is usually affected by a number of factors including road materials, environmental effects, traffic volume, and maintenance. An understanding of these factors can help establish suitable gravel road maintenance levels and simplified procedures for local highway agencies.

Relationships are presented between the road condition variables of roughness number, average rut depth, Clegg Impact Value, and unpaved road surface material and other roadway variables. The measurements that were taken of corrugations and the material characteristics of corrugated, weak, and rutted surfaces are also discussed to provide further insight into the factors that affect the performance and maintenance of gravel and stone roads.

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STUDY LOCATION AND EXPERIMENTAL DESIGN

Unpaved roads of a variable total length were selected from five counties in Indiana (Figure 1). The statistical experimental design adopted was a nested factorial design with unequal cells. Roads were nested in counties and sections were nested within roads. The unequal cells resulted from the inability of counties to select the same number and length of roads (Table 1).

VARIABLES ANALYZED

The three dependent variables that described road condition in the regression analyses were as follows:

- Roughness number (RN) measured in counts per mile using a PCA roadmeter at a measuring speed of 20 mph (32 kph),
- Average rut depth (ARD) measured in inches from surface to bottom of rut, and
- Clegg Impact Value (CIV), a measure of pavement strength using the Clegg Impact Tester (CIT).

The latter two variables were also analyzed as dependent variables. The independent variables used in this study are shown in Table 2 together with the limits of values that were measured and used in later equations. Previous research on unpaved roads also used most of these variables (*1-5*).

CONSIDERATIONS FOR FIELD MEASUREMENTS

Roughness

A PCA roadmeter supplied by the Division of Research and Training (DRT) of the Indiana Department of Highways (IDOH) was used to assess unpaved road roughness by divisional staff. The PCA roadmeter was chosen over the Mays ridemeter because of frequent cable failure on the Mays meter during initial trials. Roughness was measured at a speed of 20 mph (32 kph). This speed was selected because it reduced these cable problems. A speed of 50 mph (80 kph) was normally used for roughness measurements on paved roads using the PCA roadmeter. Roughness was measured over an entire 1-mi (1.6-km) section following the normal practice by the DRT of

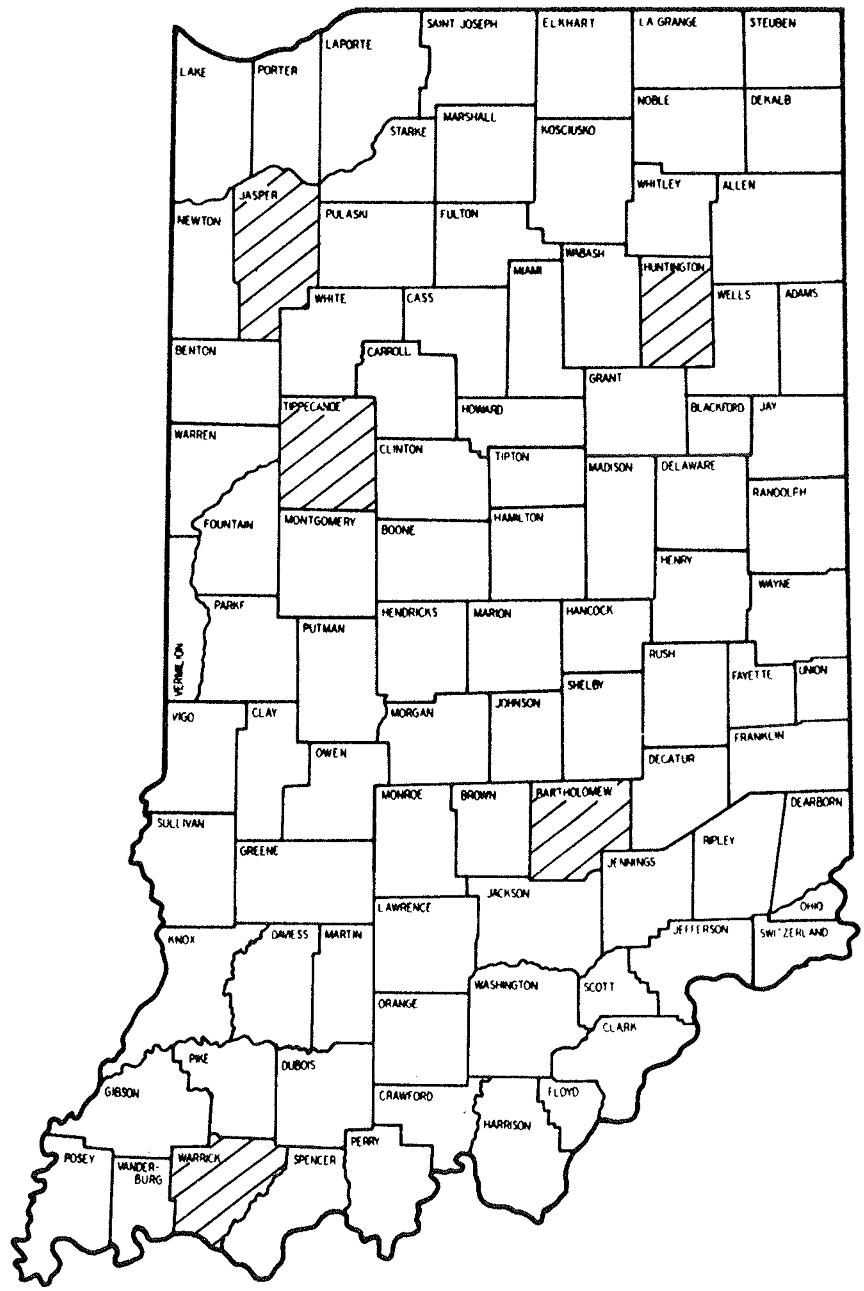

FIGURE 1 Location of study counties in the state of Indiana.

measuring roughness on 1-mi sections of the state highway network. Instrument calibration was provided from measurements by the DRT on an existing paved road section and other measurements that related roughness at various measuring speeds and measurements on the gravel road sections (*6*). However, roughness measured in counts per mile was not related to units such as inch per mile or quarter-car index that were used in other studies (*1, 4, 5, 7*).

Terrain, CIV, Rut Depth, and Roadway Characteristics

The effect of road vertical gradient and alignment was considered by applying a dummy or indicator variable (G) in the regression relationships (Table 2). CIV, rut depth, and other roadway characteristics, such as road width and camber, were measured at 0.1- , 0.3- , 0.5- , 0.7- , and 0.9-mi locations on each section (*6*). The CIV at each cross-section was measured at the centerline and transversely every 2.5 ft for the entire cross-sectional width. This procedure was first used in previous research at Purdue University in which the highest CIV readings occurred about 2.5 ft from the centerline (*8, 9*). The potential full range of CIV values on the cross-section was included in calculating average CIV by using 2.5 ft intervals.

Road Surface Materials Sampling and Testing

A representative sample of road surface material was obtained from each section down to a depth of 4 in (10 cm) from the

TABLE 1 DISTRIBUTION OF COUNTY ROADS AND SECTIONS IN REGRESSION ANALYSIS

County	Road Number	Number of Sections
Bartholomew	1	3
	2	1
	3	1
Huntington	1	1
	2	1
	3	1
	4	1
	5	1
	6	3
	7	2
	8	2
Jasper	1	1
	2	2
	3	1
	4	1
	5	2
	6	2
	7	2
Tippecanoe	1	2
	2	2
	3	2
	4	2
	5	1
	6	1
	7	2
Warrick	1	1
	2	1
	3	1
	4	2
	5	2
	6	2

surface. Additional samples were obtained from locations with identifiable corrugations or weak and deeply rutted surfaces. As a result, material characteristics of corrugated and weak spots were determined.

Gradation and liquid and plastic limits were determined for each sample. However, all of the surface gravel samples tested were found to be nonplastic; therefore, only the liquid limit was used in the regression analysis.

STATISTICAL ANALYSIS

Relationships for three dependent variables (*RN, ARD,* and *CIV*) were determined by applying analysis of variance or covariance followed by multiple regression analysis. The results from the analysis showed that the "county" factor was not significant for the dependent variables of roughness and average rut depth but was significant for CIV. As a result, the data for all five counties were combined for roughness and average rut depth and "county" was applied as a dummy variable in the regression equation for CIV (*6*). The coefficient of multiple determination, R^2, and the adjusted coefficient of determination, R_a^2, are presented for all the regression equations. Because the R^2 value usually increases with the number of independent variables in the equation, the R_a^2 value given in Equation 1 accounts for the effect of the number of independent variables in the equation (*10*).

TABLE 2 VARIABLES MEASURED OR CALCULATED FOR USE IN THE ANALYSES

Variable	Limits on Value in the Analysis	Description
1. Road width, (W ft) (Independent Var.)	15.0 - 26.8	Average section unpaved roadway width.
2. Surface Camber (CA %) (Independent Var.)	1.1 - 5.6	Average crossfall in the section.
3. Grade or Terrain (G) (Dummy Var.)	0 or 1	Gradient/Terrain Flat/Rolling = 0 Rolling to Hilly = 1
4. Soil parameters Surface gravel		(Independent Vars.)
(i) P#200 (%)	3.0 - 18.0	Percent passing ASTM #200 sieve (.075mm)
(ii) P#40 (%)	11.0 - 35.0	Percent passing ASTM #40 sieve (.425mm)
(iii) P#10 (%)	15.0 - 71.0	Percent passing ASTM #10 sieve (2.0mm)
(iv) D95 (in)	0.35 - 2.5	Equivalent sieve size passing 95% of the material.
(v) FM	3.05 - 6.7	Fineness Modulus - sum of cumulative percent retained on sieve sizes - 3/4 in. to #100, divided by 100.
(v) LL	4.8 - 20.0	Liquid Limit
(vi) PI	Non Plastic	Plasticity Index
5. ARD (in) (Dependent/Independent)	0.0 - 1.2	Average Rut Depth
6. CIV (Dependent/Independent)	24.9 - 73.1	Clegg Impact Value
7. Average Daily Traffic (ADT) (Independent Variable)	14 - 282	Average Daily Traffic Volume.
8. Roughness Number (Idependent Variable)	246 - 5903	Roughness in Counts/Mile at 20 mph (32 kph)

$$R_a^2 = 1 - \frac{(n - 1)}{(n - p)} (1 - R^2) \quad (1)$$

where

n = number of observations in the sample,
p = number of parameters, and
R^2 = coefficient of multiple determination determined from the least-squares procedure.

A correlation analysis between pairs of variables was undertaken to determine the significant independent variables for multiple regression analysis. Correlation coefficients for *RN, ARD, CIV*, and each independent variable, as well as their level of significance and the corresponding 95 percent confidence interval, are shown in Table 3. Variables with population correlation coefficients significant at α levels of less than 0.10 were included in the regression analyses.

Roughness Number

The negative correlation coefficients obtained imply that an increase in CIV, the percentage of surface gravel or stone passing a No. 40 (.425-mm) sieve (P40) and a No. 10 (2.0-mm) sieve (P10) is associated with lower roughness numbers. A higher CIV or higher in situ strength is logically related to a higher density. As a result, it could be concluded that well-compacted gravel or stone road surfaces would exhibit lower roughness levels. The positive correlation coefficients imply that gravel roads with deeper ruts, rolling to hilly vertical alignment (*G*), larger sieve size passing 95 percent of material (D95), higher fineness modulus (or coarseness), higher liquid limit, and higher ADT would tend to have surfaces with higher roughness numbers.

Equations 2 and 3 are the regression relationships obtained for surface roughness. Equation 3 uses the fineness modulus (FM) to describe surface material coarseness in place of variables P10, P40, and D95. All variables used in Equations 2 to 7 have been previously defined in Table 2.

TABLE 3 RESULTS OF CORRELATION ANALYSIS FOR ROUGHNESS, AVERAGE RUT DEPTH, AND CLEGG IMPACT VALUE RELATIONSHIPS

Variable	Correlation Coefficients		
	Roughness	Rut Depth	CIV
Average Rut Depth	.453* (.001)[1] .197/.651***	-- -- --	-- -- --
CIV	-.383* (.039) -.600/-.114	.007 (.371) -.275/.288	-- -- --
Gradient or Terrain (Dummy Var.)	.254* (.039) -.029/.500	.048 (.371) -.236/.325	.059 (.344) -.226/.335
Road Width	.179 (.110) -.108/.438	-.093 (.263) -.365/.193	.221** (.063) -.064/.473
Camber (%)	-.057 (.348) -.333/.228	.046 (.377) -.238/.323	-.096 (.255) -.367/.190
P#200	-.115 (.216) -.384/.172	.123 (.199) -.164/.391	.525* (.001) .286/.702
P#40	-.290* (.022) -.528/-.010	-.404* (.002) -.615/-.139	.063 (.335) -.222/.338
P#10	-.597* (.001) -.752/-.380	-.642* (.001) -.782/-.440	.080 (.292) -.206/.353
D95	.495* (.001) .248/.681	.682* (.001) .496/.808	.080 (.432) -.206/.353
FM	.589* (.001) .369/.747	.666* (.001) .473/.798	-.008 (.479) -.289/.274
Liquid Limit	.190** (.096) -.096/.447	.315* (.014) .037/.548	.076 (.303) -.210/.350
ADT	.217** (.067) -.068/.470	.151 (.151) -.136/.415	.081 (.291) -.205/.354

NOTES: 1. Numbers in parentheses denote significance level
* Coefficients significant at α = .05
** Coefficients significant at α = .10
*** 95 percent confidence limits for the coefficient.

$$RN = 4595.23 - 66.03\ P10 - 37.35\ CIV + 7.36\ ADT + 603.5\ G - 89.62\ LL + 85.02\ P40 + 880.00\ D95 \quad (2)$$

$$R^2 = 0.649 \qquad R_a^2 = 0.589$$

$$RN = -547.87 + 1300.94\ FM - 60.60\ CIV + 8.24\ ADT + 633.08\ G + 114.09\ P200 - 155.53\ LL \quad (3)$$

$$R^2 = 0.686 \qquad R_a^2 = 0.641$$

The relative significance of the added contribution of each variable to the total R^2 is shown in Table 4. All of the variables, significant at $\alpha = 0.10$, in both equations make contributions to the R^2.

Average Rut Depth

From the correlation analysis, ARD showed a negative correlation with P40 and P10. This implies that larger quantities of smaller coarse sizes (P40 and P10) and the sand sizes contribute to decreasing average rut depth. On the contrary, ARD tends to increase with increasing coarse sizes as represented by D95, higher values of fineness modulus that represent an overall coarseness, and increasing liquid limit. The tendency to rut more with coarser material is usually the result of instability in the material created by lack of adequate soil binder or smaller aggregate sizes that provide a keying function. Surface material deficient in smaller sizes is usually less dense and easily dispersed by vehicles. Coarser surfacing materials facilitate surface moisture penetration and also retain moisture for longer periods of time. The moisture retained would affect finer, moisture-susceptible materials underneath the coarser surfacing, which would tend to rut under traffic. Although ADT was not significant at $\alpha = 0.10$, the low positive correlation shows only a slight tendency for ARD to increase or decrease with traffic volume.

Equations 4 and 5 describe relationships for ARD obtained from multiple regression analyses. In Equation 5, the fineness modulus replaces variables D95, P10, and P40 to describe the coarseness of the surface material.

$$ARD = -.018 + 0.457\ D95 + .014\ P200 - .010\ P10 + 0.001\ ADT + 0.008\ P40 - .009\ LL - .02\ G \quad (4)$$

$$R^2 = 0.577 \qquad R_a^2 = 0.504$$

$$ARD = -1.315 + 0.358\ FM + 0.019\ P200 + 0.001\ ADT - 0.0162\ LL - 0.039\ G \quad (5)$$

$$R^2 = 0.517 \qquad R_a^2 = 0.46$$

The significance of the contribution to R^2 made by the addition of each variable is shown in Table 5. In Equation 4, variables *D95, P200,* and *P10* make contributions to the R^2 significant at $\alpha = 0.10$ and explain up to 54.5 percent of the R^2. For Equation 5, variables *D95, P200,* and *ADT* explain about 54.1 percent of R^2. The rut depth values measured in the field were generally low; several locations registered zero rut depths. Therefore, average rut depth can only be predicted within a narrow range of values obtained in the field.

TABLE 4 CONTRIBUTIONS TO R^2 VALUE BY VARIABLES IN THE ROUGHNESS EQUATIONS

Independent Variables in Equation 2					
Step	Variable	R	R^2	R^2 Change	Significance
1	P#10	.5968	.3562	.3562	.000
2	CIV	.6849	.4691	.1129	.003
3	ADT	.7146	.5106	.0415	.057
4	G	.7406	.5485	.0379	.061
5	LL	.7636	.5830	.0345	.066
6	P#40	.7875	.6202	.0372	.049
7	D95	.8055	.6489	.0286	.075
Independent Variables in Equation 3					
Step	Variable	R	R^2	R^2 Change	Significance
1	FM	.5887	.3466	.3466	.000
2	CIV	.6998	.4897	.1431	.001
3	ADT	.7383	.5451	.0554	.024
4	G	.7608	.5788	.0338	.067
5	P#200	.7821	.6116	.0328	.063
6	LL	.8282	.6860	.0743	.003

TABLE 5 CONTRIBUTIONS TO R^2 VALUE BY VARIABLES IN THE AVERAGE RUT DEPTH EQUATIONS

Independent Variables in Equation 4					
Step	Variable	R	R^2	R^2 Change	Significance
1	D95	.6820	.4652	.4652	.0
2	P#200	.7168	.5138	.04862	.037
3	P#10	.7380	.5447	.0309	.087
4	ADT	.7511	.5641	.0195	.168
5	P#40	.7563	.5721	.0079	.377
6	LL	.7587	.5757	.0036	.553
7	G	.7593	.5765	.0008	.781
Independent Variables in Equation 5					
Step	Variable	R	R^2	R^2 Change	Significance
1	D95	.6820	.4652	.4652	.0
2	P#200	.7168	.5138	.0486	.037
3	ADT	.7356	.5412	.0274	.108
4	FM	.7444	.5541	.0130	.264
5	LL	.7466	.5574	.0033	.577
6	G	.7474	.5586	.0012	.743

Clegg Impact Value

The percentage of materials passing a No. 200 (.075-mm) sieve (P200) and the average road width, W, were two variables that had correlation coefficients significant at $\alpha = 0.10$ with CIV. This implies that gravel road sections with wider roadways and roads with a higher proportion of fines (P200) would usually exhibit higher CIVs. The latter is generally true because sufficient fines are required to obtain denser material with a higher CIV when compacted.

Although CIV did not show a significant correlation with ADT, average road width had a positive correlation of 0.22 with ADT significant at $\alpha = 0.06$. This level of correlation is only a slight indication that roads with higher ADT are wider. Because most gravel and stone roads in Indiana are not usually rolled after regraveling, but are allowed to be compacted by traffic, the wider roads with potentially higher traffic volumes may exhibit higher CIVs. This factor, however, requires further investigation.

Because "county" was significant at $\alpha = 0.05$ in the analysis of covariance, dummy or indicator variables Z1, Z2, Z3, and Z4 were introduced into the regression. The relationships derived for CIV are presented in the following equations.

$$CIV = 20.203 + 8.351\,Z1 - 14.345\,Z2 - 12.330\,Z3 - 1.359\,W - 5.645\,Z4 + 0.143\,P200 \quad (6)$$

$$R^2 = 0.681 \qquad R_a{}^2 = 0.635$$

$$CIV = -2.235 + 14.506\,Z1 + 4.452\,FM + 0.604\,P200 - 1.003\,W - 7.960\,Z2 - 4.875\,Z4 - 4.071\,Z3 + .003\,ADT \quad (7)$$

$$R^2 = 0.694 \qquad R_a{}^2 = 0.633$$

The significance of contributions made by the various independent variables to the R^2 obtained for each equation is shown in Table 6. In Equation 6, apart from county variables, road width makes a significant contribution to the R^2 coefficient. However, in Equation 7, the fineness modulus (FM), $P200$, and road width (W) make a total contribution to R^2 of 68.4 percent if county variable $Z2$ is included. Both equations are, however, applicable to the study areas only because the "county" variables are used.

DISCUSSION

Grading

In previous research in Kenya and Brazil, the number of days since the last grading or the cumulative traffic volume since the last grading were used as independent variables (*1, 2, 4, 5*). In this research, little variation was found in the data obtained to determine the number of days since last grading in any county. The differences between counties did not significantly affect relationships with road condition variables also; the grading variable was therefore omitted.

General county maintenance practice has been to avoid grading when the surface crust is well developed. Some study roads had not been graded for over 70 days and no significant effects on road condition were detected. Nevertheless, evidence from one road section that was graded the day of the measurements showed substantial reductions in roughness with grading. The average roughness on a lane in the same direction on four, unbladed 1-mi sections was 1,944 counts/mi compared to 741 on the opposite bladed lane, which is a 62 percent

TABLE 6 CONTRIBUTIONS TO R^2 VALUE BY VARIABLES IN THE CLEGG IMPACT VALUE EQUATIONS

Independent Variables in Equation 6					
Step	Variable	R	R^2	R^2 Change	Significance
1	z1	.6927	.4798	.4798	.0
3	z2	.7551	.5701	.0864	.002
4	z3	.7839	.6145	.0444	.029
5	W	.8166	.6668	.0523	.012
6	z4	.8243	.6795	.0128	.205
7	P#200	.8250	.6806	.0011	.708
Independent Variables in Equation 7					
Step	Variable	R	R^2	R^2 Change	Significance
1	z1	3.3511	.6927	.4798	.0
2	FM	.7743	.5996	.1198	.001
3	P#200	.8023	.6436	.0440	.023
4	W	.8156	.6652	.0216	.100
5	z2	.8276	.6849	.0198	.108
6	z4	.8317	.6917	.0068	.341
7	z3	.8331	.6940	.0023	.581
8	ADT	.8332	.6942	.0001	.898

reduction. Roughness on another 1-mi (1.6-km) section dropped by 52 percent to 1,076 counts/mi from 2,246 counts/mi after grading. On a 1-mi section, half of which had been graded, the average reduction in roughness was 24 percent from 1,974 to 1,501 counts/mi. This indicates that on the day of grading, roughness values are likely to fall by about 50 percent on a typical gravel or stone road.

These observations confirm results published by Carmichael et al. for similar measurements on gravel roads in Bolivia (*11*). During the dry season in Bolivia, which is similar to summer conditions in Indiana, same-day reductions in roughness measured with the Mays ridemeter were between 41 percent and 52 percent. In the wet season in Bolivia, however, same-day reductions were reported between 1 and 38 percent. Roughness generally returned to original levels, or higher, about 20 days after grading in Bolivia.

Surface Material Characteristics

In the absence of a maintenance variable such as grading, surface material characteristics of gradation and liquid limit explain between 35 and 52 percent of the variability in the road condition variables of roughness, average rut depth, and pavement strength (CIV). Average material characteristics identified on roads in the five counties studied are presented in Table 7 and Figures 2 to 6.

Gradation specifications for No. 53 and No. 73 crushed stone that are recommended for base construction and gravel or stone road surface courses in Indiana are also shown in Figures 2 to 6. Indiana specifications state that in addition to the gradation band, the fraction passing a No. 200 sieve should not exceed two-thirds of the fraction passing the No. 30 sieve. Liquid limit should not exceed 25 (35 if slag) and the plasticity index should not exceed 5. When used as unsurfaced gravel or stone base, the amount passing a No. 200 sieve should be between 5 and 12 percent and the plasticity index should not exceed 7. Although not stated specifically, the grading ranges limit top sizes of the required material to less than 1.5 in. for No. 53 stone or aggregate and less than 1 in for No. 73.

Indiana counties have often adopted less stringent material specifications for gravel and stone roads for economic reasons. The study counties appear to have differing practices regarding material used on unpaved roads (Table 7 and Figures 2 to 6). Some counties allow maximum aggregate sizes greater than 2 or 3 in, whereas other counties have adopted fine gradation requirements. However, in some cases the finer gradation is partly a result of the effect of traffic abrasion.

The facility with which a surfacing material develops a crust appears to be important to the amount of roughness. The lowest average roughness value of 959 counts/mi was measured on unpaved roads in Huntington County followed by 2,019 and 2,819 counts/mi on roads in Tippecanoe and Jasper counties, respectively. Using the CIV as a relative measure of crust development, Huntington County roads exhibited the highest average CIV of 57, whereas Tippecanoe and Jasper counties had the lowest average values of 35 and 33, respectively. It is likely that the well-developed surface crust found on most gravel roads in Huntington County contributed to the better road performance compared to the other four counties. Huntington and Tippecanoe counties apply crushed limestone of No. 53 or No. 73 specifications to unpaved road surfaces.

TABLE 7 SUMMARY OF AVERAGE COUNTY ROAD SURFACE GRAVEL AND CROSS-SECTIONAL CHARACTERISTICS

Variable Description	Material Property or Cross-Sectional Characteristic by Study County				
	Bartholomew	Huntington	Jasper	Tippecanoe	Warrick
Number of Sections of Road	5	12	12	12	9
Fineness Modulus	4.4	3.5	4.0	3.9	4.9
Liquid Limit (Range)	13 (12.5-14)	13 (12-14)	11 (7-15)	12 (7-17)	17 (14-20)
Roughness (Counts/Mile)	2858	958	2819	2012	3369
Roadway Width (in.)	16.3 (0.9)[1]	19.2 (1.5)	19.1 (2.3)	19.1 (1.6)	20.4 (3.8)
Camber (%) (Range)	3.4 (.7)[1] (2.3-4.7)	2.8 (.9) (1.4-4.7)	2.8 (.9) (.8-4.1)	4.5 (1) (2-6)	3.84 (1.4) (.6-6.2)

NOTES

1. Numbers in parentheses are standard deviation values

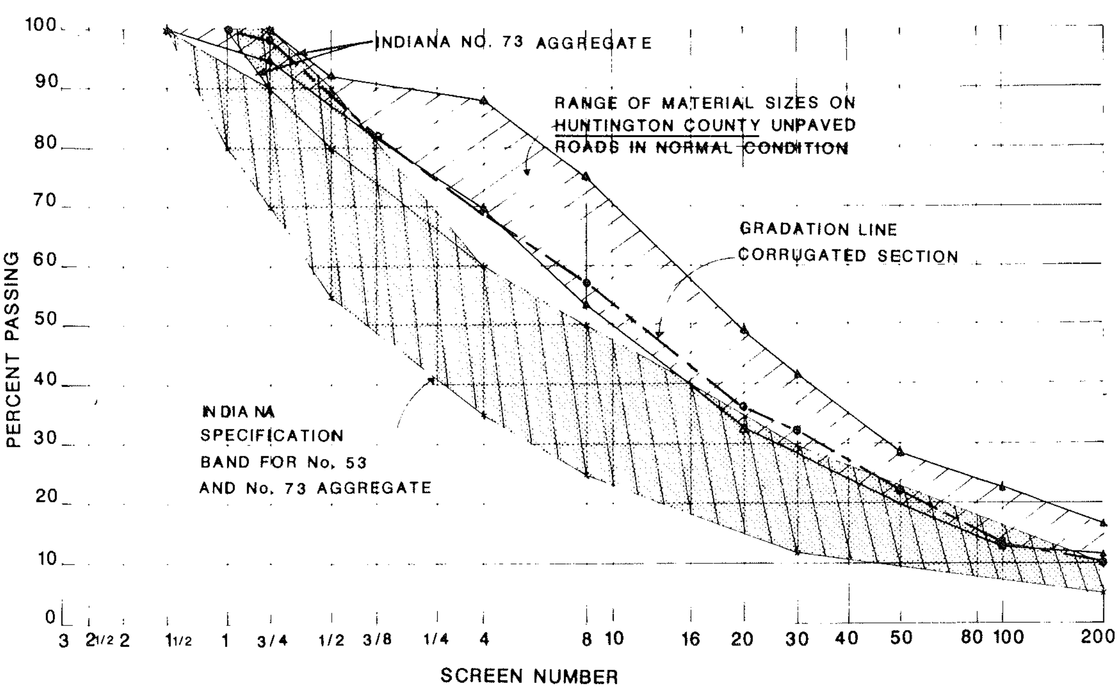

FIGURE 2 Surface gravel gradation characteristics in Huntington County.

Jasper County practiced the application of much coarser No. 5 crushed stone after the spring thaw to weakened areas and No. 73 aggregate at other times.

Both Bartholomew and Warrick counties in the southern part of the state use materials that are, on the whole, coarser than Indiana No. 53 or No. 73 aggregate. Warrick County applies No. 5 crushed limestone (Figure 5), whereas Bartholomew County applies No. 8 or No. 9 crushed limestone (Figure 6). Roads in those two counties had the highest average roughness of 2,858 and 3,369 counts/mi, respectively. The average CIV in both counties was 44. In Warrick County, some existing roads had been reconstructed as part of coal mining operations using coarse crushed rock.

No materials tested had a liquid limit above the recommended upper limit of 25 (35 for slag) (*12*). In order to gain further insight on road condition effects, surface material and other characteristics of corrugated, weak, and rutted road surfaces are discussed in the following sections.

Characteristics of Weakened and Rutted Sections

Gradation characteristics of four weak surface areas identified on two roads in Jasper County (250E and Division Road) and two roads in Tippecanoe County (850W and 1300S) are presented in Figures 3 and 4, respectively. The CIV values

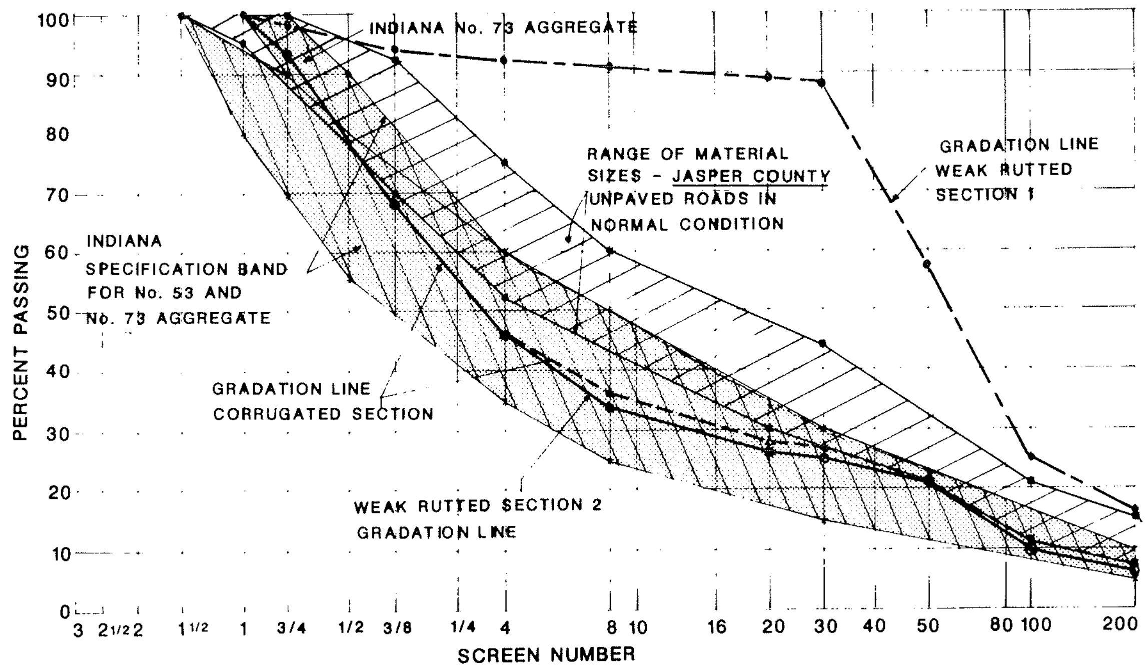

FIGURE 3 Surface gravel gradation characteristics in Jasper County.

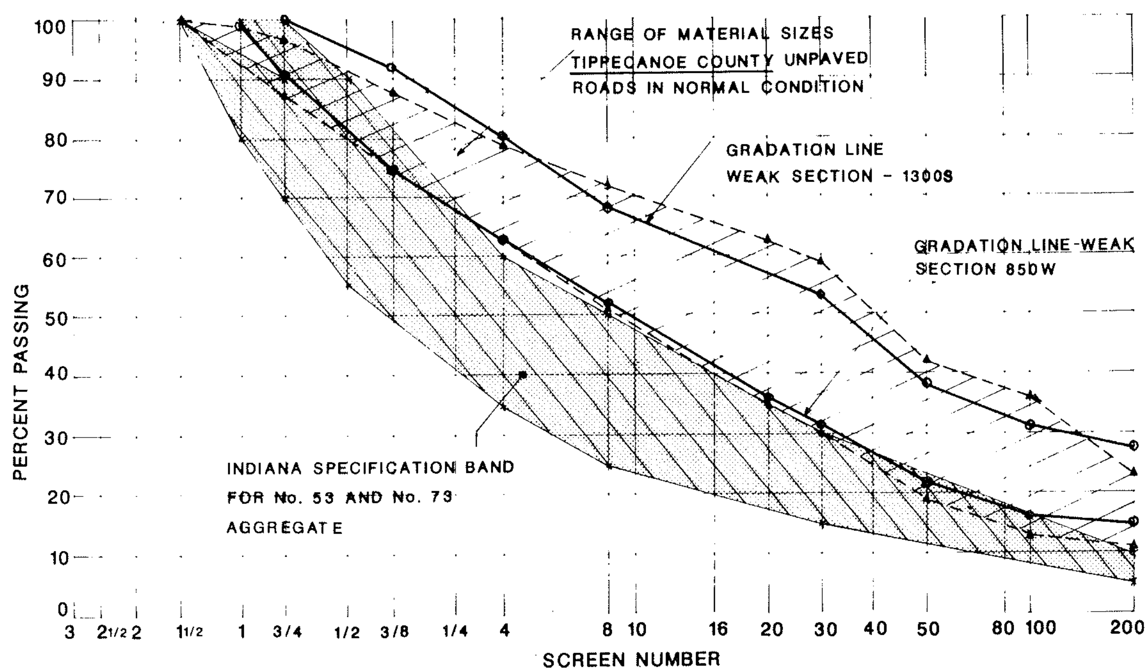

FIGURE 4 Surface gravel gradation characteristics in Tippecanoe County.

measured on these sections were 17, 25, 8, and 10, respectively. These CIV values were much lower than values measured on any road section that performed satisfactorily.

Weakened and rutting areas can also be identified by other characteristics. In the case of one road in Jasper County and another in Tippecanoe County, the surface material was loose and coarser than the county average. The surface exhibited a low CIV and rutting. Little compaction had taken place and the surfaces were prone to failure.

Weak areas can develop in cases in which the surface material is finer than average and is therefore sensitive to moisture. Loss of surfacing as a result of inadequate crust development can also expose a fine-grain subgrade to the detrimental effects of moisture. Moisture-sensitive subgrades combined with poor drainage likewise create weakened conditions.

Characteristics of Corrugated Surfaces

Corrugation or washboarding is a common type of gravel road distress; therefore, an understanding of its formation is essential in gravel road maintenance. Material gradation lines are

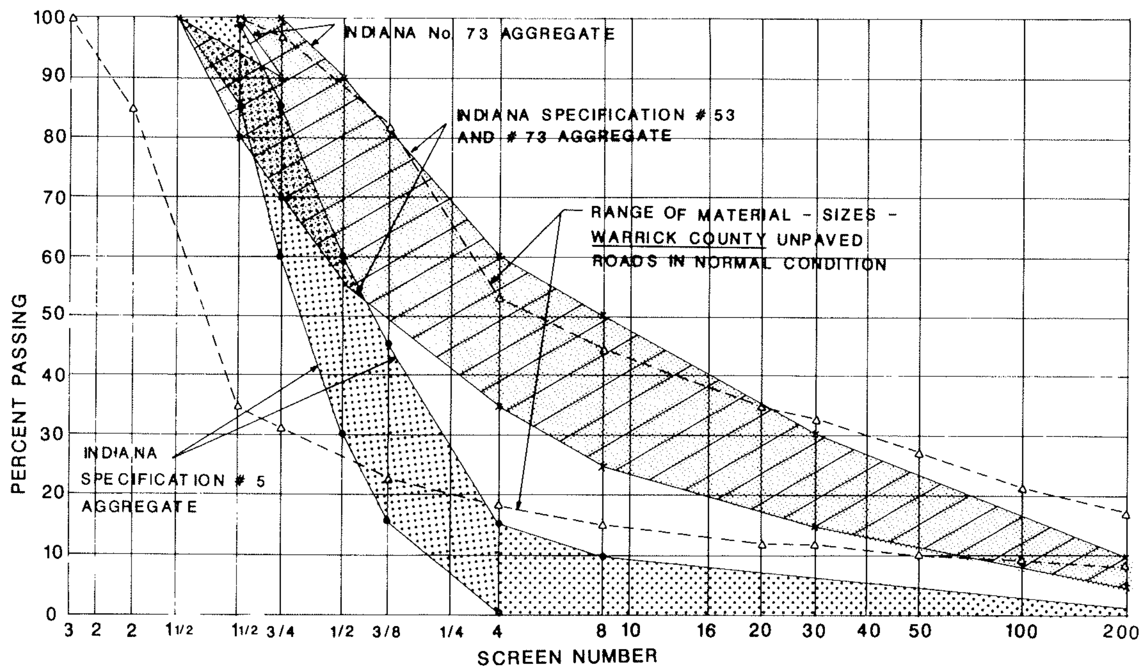

FIGURE 5 Surface gravel graduation characteristics in Warrick County.

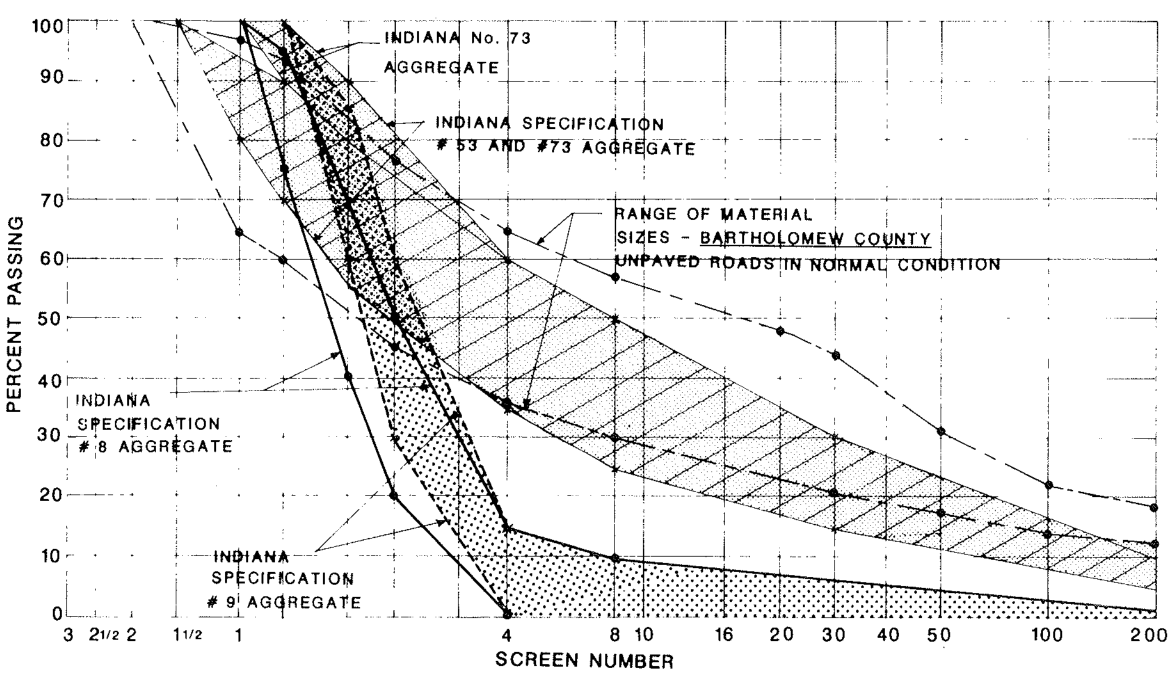

FIGURE 6 Surface gravel gradation characteristics in Bartholomew County.

presented in Figures 2 and 3 for two separate road locations with serious corrugation problems in Huntington and Jasper County, respectively. In both cases, the materials have coarser gradations compared to their county average although both gradations are on the finer side of the Indiana-specified gradation band. General characteristics of the corrugations measured are presented in Table 8. The characteristics include wavelength, or the distance between crests or troughs of corrugations; the depth from the top of the crest to the bottom of the trough; the CIV on the top of the crest and on the trough bottom; and a description of the location of the road in which corrugation occurred.

Wavelengths measured on corrugations varied from a low of 17 in (432 mm) to a high of 48 in (1220 mm), whereas depths varied from about 5/8 in (16 mm) to 1-1/4 in (32 mm) in different locations. From a review of past research studies on corrugations, Heath and Robinson reported a range of wavelengths between 12 in (300 mm) and 49 in (1250 mm) (*13*). The current study results also showed that shorter wavelengths may be associated with finer gravel materials and longer wavelengths with coarser materials. All material types are, however, susceptible to corrugation. Nevertheless, gravel and crushed rock with inadequate, nonplastic, or lost soil binder fines have been widely reported as susceptible to corrugation (*13-16*).

TABLE 8 SUMMARY OF AVERAGE CORRUGATION CHARACTERISTICS OF SELECTED ROAD SECTIONS IN THREE STUDY COUNTIES

County	Road Section	Clegg Impact Value			Wavelength (in.)	Depth (in.)	Location	
		Crest	Trough	Road			Description	Length (ft.)
Jasper	Div. 1	33	37	49	26	1.25	INT	150
	Div. 2	28	41	45	35	0.88	INT and SL	130
	400W	37	34	35	22	1.0	INT	150
	780W	52	36	54	29	0.8	INT	120
Huntington	300E 1	52	41	54	19	.63	INT and SL	180
	300E 2	50	45	50	18	0.88	SL	250
	100N	42	56	46	17	0.75	DW	150
Warrick	900W	47	49	60	32	0.75	SL	200
	475W	83	84	86	48	1.0	SLC	300

1. LOCATION DESCRIPTION
INT = Intersection ; SL = Slope ; SLC = Downslope before a curve
DW = Location near driveways

Because most surface materials found on Indiana county gravel roads were nonplastic and deficient in soil binder, corrugations are likely to be a continuing problem.

Locations and conditions on roads prone to corrugations include a downslope leading to an intersection and sloping road sections not near major intersections. In the latter case, the presence of a driveway accentuated the problem. This implies that gravel road locations in which vehicles are likely to decelerate and accelerate, usually to and from a stopped position, are likely to develop corrugations. The rate at which corrugations form, however, depends on the traffic volume. The 1-mi-grid local road network layout in Indiana, which requires frequent stops at intersections, provides the right conditions for formation of corrugations. Therefore, particular attention needs to be paid to maintenance of sections of road near intersections, on sloped sections, and sections with many driveways.

Previous studies have attributed the principal vehicle-related causes of corrugation to vehicle oscillation, and have suggested modifications to vehicle design to reduce this problem (*13*). The vehicle oscillation phenomenon could explain the differences in the CIV values on the crests and troughs of the corrugation waves measured in the current study. Both crests and troughs of corrugations in Table 8 exhibit equally high CIV values depending on which location is compacted the most by vehicle oscillation. The gravel or stone of uncompacted gravel material, such as that used by Indiana counties, is likely to be shoved and later compacted by decelerating or accelerating vehicles.

Recommended maintenance to improve corrugated gravel and stone road surfaces in the literature includes the application of granular materials with clay/silt binder, chemical treatment, watering, and more frequent maintenance consisting mainly of dragging or grading (*13*). Most Indiana counties increase the frequency of grading operations to overcome the problem of corrugations. However, based on this study, a review of county material use practices would be beneficial. An increase in the binder content in the surface gravel material could improve the general performance of gravel roads, especially near intersections and on slopes. Stones above 1 in. in size that may inhibit effective traffic compaction of the surface gravel and increase roughness should be avoided.

CONCLUSIONS

The results of the analysis presented in this paper show that material gradation properties represented by the percentage passing ASTM No. 10 and No. 40 sieves, sieve size passing 95 percent of the material, fineness modulus, and liquid limit are all significantly correlated with both roughness and average rut depth. However, average rut depth, road surface strength measured by the CIV, and the sloping characteristics of the road were also found to have significant correlation with roughness. There was a significant difference between the strength of the gravel surface courses in the counties studied. Average road width and the percentage of material passing a No. 200 sieve were also important variables.

Although counties usually apply surface gravel without rolling, the research results showed that well-compacted roads were less rough. If lowering roughness is considered important by local authorities, then it may be justified to roll the surface gravel immediately after application and before it significantly varies from an optimum moisture content. The higher density should facilitate the formation of a surface crust during drier weather. Such surface materials should contain an adequate soil binder to perform well.

Material properties provide some explanation for the formation of corrugations and ruts, and measured gravel and stone road surface condition such as roughness, average rut depth, and strength. Blading or grading can reduce roughness by over 50 percent. However, the frequency of grading should be increased on gravel roads at sloping locations with many driveways or sections near major intersections in which corrugations are likely to occur.

Although test sections of 1 mi (1.6 km) were used in this study, the results varied significantly within a section. Additional data would improve the accuracy of the results.

REFERENCES

1. J. W. Hodges, J. Rolt, and T. E. Jones. *The Kenya Road Transport Study: Research on Road Deterioration.* Laboratory Report 673. Transport and Road Research Laboratory, Crowthorne, England, 1975.
2. T. E. Jones. *The Kenya Maintenance Study on Unpaved Roads: Research on Deterioration.* Laboratory Report 1111. Transport and Road Research Laboratory, Crowthorne, England, 1984.
3. R. Robinson. *A Survey of Recent Research on Maintenance Criteria and the Deterioration of Unpaved Roads in Developing Countries.* PTRC Summer Annual Meeting, University of Warwick, United Kingdom, July 1980.
4. A. T. Visser. An Evaluation of Unpaved Road Performance and Maintenance. Ph.D. dissertation, University of Texas, Austin, May 1981.
5. T. Watanada, et al. HDM-III Model Description and User's Manual With Highway Expenditure Budgeting. *Highway Design and Maintenance Standards Study*, Vol. IV. Transportation, Water, and Telecommunications Department, The World Bank, Washington, D.C., July 1984.
6. J. D. N. Riverson. Unpaved Road Maintenance Management in Local Highway Systems. Ph.D. dissertation, Purdue University, West Lafayette, Ind., Dec. 1985, pp. 165-283.
7. C. A. V. Queiroz. Calibrating Response-Type Roughness Measurement Systems Through Rod-and-Level Profiles. In *Transportation Research Record 898.* TRB, National Research Council, Washington, D.C., 1984, pp. 181-188.
8. E. J. Yoder, D. G. Shurig, and B. Colucci-Rios. *Evaluation of Existing Aggregate Roads to Determine Suitability for Resurfacing.* Purdue University, West Lafayette, Ind., 1981.
9. N. W. Garrick. Field Evaluation of an Impact Testing Device for Measuring Base Course Strength. M.S.C.E. thesis, Purdue University, West Lafayette, Ind., May 1983.
10. J. Neter, W. Wasserman, and M. H. Kunter. *Applied Linear Statistical Models.* Regression Analysis of Variance and Experimental Design. Richard Irwin, Inc., Homewood, Ill., 1985.
11. R. F. Carmichael III, W. R. Hudson, and F. C. Sologuren. Evaluation of Highway Roughness in Bolivia. In *Transportation Research Record 702.* TRB, National Research Council, Washington, D.C., 1979, pp. 238-248.
12. *Standard Specifications.* Indiana Department of Highways, Indianapolis, 1985.
13. W. Heath and R. Robinson. *Review of Published Research into the Formation of Corrugations on Unpaved Roads.* Report SR 610. Transport and Road Research Laboratory, Crowthorne, England, 1980.
14. E. Y. Huang. A Study of Occurrence of Potholes and Washboards on Soil-Aggregate Roads. *Bulletin 282.* HRB, National Research Council, Washington, D.C., 1961.
15. J. Stoddart, R. B. L. Smith, and R. M. Carson. Gravel Road Corrugations. *Transportation Engineering Journal*, Vol. 108, No. TE4. American Society of Civil Engineers, July 1982, pp. 376-382.
16. J. S. Tanner. Corrugations on Earth and Gravel Roads: Their Formation, Treatment, and Prevention. *Roads and Road Construction*, Vol. 36, Nos. 421 and 422. Colonial Section, Road Research Laboratory, United Kingdom, Jan. and Feb. 1958, pp. 4-10 and 32-35.