A Study of Occurrence of Potholes and Washboards on Soil-Aggregate Roads

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This report presents the results of a study aimed at determining some of the circumstances associated with the occurrence of potholes and washboards on soil-aggregate roads. The study consisted of a statistical analysis of the qualitative data obtained from a road condition survey involving road surfaces of the coarse-graded aggregate type composed of mineral aggregate such as gravel or crushed stone and some binder material. Results of the study indicate that the occurrence of potholes and washboards was definitely associated with the volume of traffic, the type of surface material, and the drainage condition of the road surface. Although the findings are admittedly limited to the types and conditions of the roads studied, it is hoped that the data may be of value in further understanding the formation of potholes and washboards.

●THE OCCURRENCE of potholes and washboards has long been a serious problem in soil-aggregate surfaces. These formations, however, have not been fully explained. Potholes on road surfaces are irregularly occurring, well-defined holes consisting of fairly deep cavities up to about 5 in. (Fig. 1). Washboards are transverse or nearly transverse waves on road surfaces, generally about 1 to 1½ in. in amplitude and spaced about 2 or 3 ft apart (Fig. 2), regardless of the nature of material in which they occur. (Although typical formations of potholes and washboards are readily distinguishable, there are, however, numerous possibilities of transitional forms between these two typical forms.) Both potholes and washboards are conducive to surface impact and vibration, which contribute in a great measure to the rapid deterioration of the road surface as well as the vehicle itself. Driving on such roads, if not hazardous, is extremely unpleasant.

The purpose of this study was to determine some of the circumstances that were closely associated with the development and condition of potholes and washboards on soil-aggregate roads. The road surfaces studied were of the coarse-graded aggregate type composed of mineral aggregates such as gravel or crushed stone and some binder material. No chemical additives had been introduced into these surface courses, nor had they been surface-treated with bituminous material.

DEVELOPMENT AND SCOPE OF THE STUDY

The study was an outgrowth of a condition survey conducted during the summer of 1956 on soil-aggregate roads in Champaign County, Illinois, which was aimed at obtaining general information regarding road conditions in this area so that sections for special studies might be selected. This survey consisted of a field study of 749 separated road sections. A visual inspection was made of each road section noting the condition of the surface, type of the surface material, condition of the shoulders and side ditches, and other important features.

The methods and procedures employed in this area with respect to general maintenance of these roads were more or less uniform. Therefore, the effect on road conditions due to maintenance was considered insignificant and has not been included in this study.

Figure 1. Typical potholed road surface.

Figure 2. Road surface with washboard formations developed.

Traffic volume of these roads was obtained later from traffic volume maps supplied by the Illinois Division of Highways Bureau of Research and Planning. Information regarding subgrade soil conditions was obtained from engineering soil maps prepared by the Illinois Cooperative Project IHR-12, Soil Exploration and Mapping.

When the large amount of data was reviewed, it was noted that some of the recorded road characteristics appeared to be interrelated. In an effort to ascertain these relationships, the present investigation was instituted.

This study consists of a statistical analysis of the qualitative data obtained in the road condition survey. However, only those road sections which produced adequate data were used in the analysis. Consequently, the total number of road sections used in individual analyses may be less than 749.

This report is devoted mainly to the presentation and analysis of the data as well as the interpretation and discussion of the findings. To explain the method of analysis, the principle and procedure of chi-square test are briefly described in the early part of the report.

METHOD OF ANALYSIS

General

The association or independence of any two characteristics of road sections observed in the field was studied by a technique known as chi-square test. The procedure of this test is outlined as follows:

1. A frequency table is constructed classifying the observed data according to both characteristics.
2. Under the hypothesis that the two characteristics are independent, the frequencies which can be expected to occur in the various cells of the table are computed.
3. These expected cell frequencies are compared with the corresponding frequencies which are actually observed.
4. Decision is made on the basis of the criterion of chi-square distribution as to whether the discrepancies between the two sets of frequencies are large enough to permit a rejection of the hypothesis. If the hypothesis can be rejected, a significant relationship between these two characteristics is indicated.

Observed Frequencies

The first step toward studying the relationship between two characteristics of road sections by the chi-square test consists of constructing a frequency table where the observed data are classified according to both characteristics and arranged in compartments or cells. Such a table is commonly called a contingency table. Let two characteristics A and B be considered, each of which permits a certain number of alternative descriptions. The characteristic A, for instance, may be subdivided into n categories, while the characteristic B may be subdivided into m categories. The contingency table, therefore, will consist of mn cells. The data can be set out in the form of m rows and n columns as shown in Table 1.

The observed cell frequencies are represented by the letters 0_{11}, 0_{12}, ...and in general by the symbol 0_{ij}, where the subscript i refers to the row and the subscript j refers to the column to which the respective cell belongs. For example, the frequency (or the number of observed road sections) which belongs to the cell which is contained in the second row and fourth column is written as 0_{24} The totals at the end of the rows and at the bottom of the columns give the total frequencies of subclasses. The total of the first row is denoted as $0_{1.}$ and in general, the total of the ith row is given as $0_{i.}$. Similarly, the total of the jth column is written as $0_{.j}$. The whole number of observations, N, is given as the grand total in the bottom right-hand corner of Table 1.

Expected Frequencies

The expected cell frequencies are calculated on the basis of the following assumptions:

TABLE 1

TYPICAL CONTINGENCY TABLE

		Characteristic A								Row Totals
		A_1	A_2	A_3	A_4	—	—	A_{n-1}	A_n	
Characteristic B	B_1	0_{11} (e_{11})	0_{12} (e_{12})	0_{13} (e_{13})	0_{14} (e_{14})	—	—	$0_{1(n-1)}$ $(e_{1(n-1)})$	0_{1n} (e_{1n})	$0_{1.}$
	B_2	0_{21} (e_{21})	0_{22} (e_{22})	0_{23} (e_{23})	0_{24} (e_{24})	—	—	$0_{2(n-1)}$ $(e_{2(n-1)})$	0_{2n} (e_{2n})	$0_{2.}$
	B_3	0_{31} (e_{31})	0_{32} (e_{32})	0_{33} (e_{33})	0_{34} (e_{34})	—	—	$0_{3(n-1)}$ $(e_{3(n-1)})$	0_{3n} (e_{3n})	$0_{3.}$
	B_4	0_{41} (e_{41})	0_{42} (e_{42})	0_{43} (e_{43})	0_{44} (e_{44})	—	—	$0_{4(n-1)}$ $(e_{4(n-1)})$	0_{4n} (e_{4n})	$0_{4.}$
	—	—	—	—	—	—	—	—	—	—
	B_{m-1}	$0_{(m-1)1}$ $(e_{(m-1)1})$	$0_{(m-1)2}$ $(e_{(m-1)2})$	$0_{(m-1)3}$ $(e_{(m-1)3})$	$0_{(m-1)4}$ $(e_{(m-1)4})$	—	—	$0_{(m-1)(n-1)}$ $(e_{(m-1)(n-1)})$	$0_{(m-1)n}$ $(e_{(m-1)n})$	$0_{(m-1)}$
	B_m	0_{m1} (e_{m1})	0_{m2} (e_{m2})	0_{m3} (e_{m3})	0_{m4} (e_{m4})	—	— —	$0_{m(n-1)}$ $(e_{m(n-1)})$	0_{mn} (e_{mn})	$0_{m.}$
Column Totals		$0_{.1}$	$0_{.2}$	$0_{.3}$	$0_{.4}$	—	—	$0_{.(n-1)}$	$0_{.n}$	N

1. The two characteristics A and B are independent, that is, the probability that an individual road section falls in any particular row in the table is unaffected by the particular column to which it belongs, and
2. The totals of rows and columns are fixed.

In accordance with the above assumptions, it is evident that the proportion (or fraction) of observations which fits description A_j is given by the ratio $0_{.j}/N$, whereas the proportion which fits description B_i is given by the ratio $0_{i.}/N$. Consequently the proportion of the total number of observations which, under the above assumptions, should fit both of these descriptions is given by the product

$$\left(\frac{0_{.j}}{N}\right)\left(\frac{0_{i.}}{N}\right) = \frac{\left(0_{.j}\right)\left(0_{i.}\right)}{N^2}$$

The above value is then multiplied by the whole number of observations N to obtain the expected frequency of the cell which belongs to the ith row and the jth column. The expected frequency e_{ij} which corresponds to the observed frequency 0_{ij}, is given by the formula

$$e_{ij} = \frac{\left(0_{.j}\right)\left(0_{i.}\right)}{N}$$

In other words, the expected frequency of a given cell is obtained by simply multiplying the totals of the respective row and column and dividing this product by the whole number of observations.

The expected cell frequencies, represented by the letters e_{11}, e_{12}, ...and in general by the symbol e_{ij}, are then entered in the cells of the frequency table to compare with the observed frequencies. The expected frequencies are written in parenthesis below the observed frequencies. It may be noted that the totals of the rows and columns of the expected frequencies must equal those of the original table.

The Chi-Square

The comparison of the observed and the expected cell frequencies of the contingency table is made by the use of the statistic chi-square (X^2) which was originated by Karl Pearson in 1900 as a criterion for testing hypotheses about frequency distributions (8). It is defined by the equation

$$X^2 = \sum_{i=1}^{k} \frac{\left(0_{ij} - e_{ij}\right)^2}{e_{ij}}$$

where k is the number of pairs of frequencies to be compared (k=mn), 0_{ij} and e_{ij} the observed and the expected frequencies, respectively, and

$$\sum 0_{ij} = \sum e_{ij}$$

Chi-square is a discrete variable. It is always a positive number, since each denominator is a positive number and each term in the numerator is a square. If the observed frequencies should agree completely with the expected, chi-square would be zero. Chi-square increases in size as the observed frequencies depart more and more from the expected. It is evident that the statistic chi-square affords a measure of the correspondence between fact and theory.

In using chi-square to test the compatibility of a set of observed and expected frequencies, there is always a question as to what extent the discrepancies between expectation and observation can be regarded as significant. Since chi-square is calculated on the basis of a set of data, it is subject to the chance variation which is displayed by its sampling distribution. If the use of chi-square is to be satisfactory, it is necessary to distinguish significant values from those which may have arisen by sample fluctuations. This distinction is based on the probability of getting a particular value of chi-square from a set of data chosen at random, or, in other words, on the sample distribution of chi-square given as follows:

$$f(X^2) = \frac{1}{2^{v/2}\Gamma\frac{v}{2}} (X^2)^{\frac{v}{2}-1} e^{\frac{-X^2}{2}} \qquad 0 \leq X^2 \leq \infty$$

in which the parameter v is called the number of degree of freedom and Γ represents the gamma function. (It may be noted that the equation is an approximation to the distribution function of chi-square obtained by using multinominal distribution and making certain approximations. The exact distribution of chi-square has not yet been established.)

Since f (X^2) depends only upon the parameter v, there will correspond a X^2 curve to each value of v. When a random set of data is taken and chi-square is calculated, the probability of getting a value of chi-square as great as, or greater than, this particular value is as follows:

$$P = \int_{X^2}^{\infty} f(X^2)\,d(X^2).$$

Thus for any value of v, there corresponds a certain value of P to every value of chi-square. As chi-square is increased from zero to infinity, P diminishes from 1 to zero. Equally, there corresponds a certain value of chi-square to any value of P in this range. In applying the chi-square distribution to a test of significance, it is customary to select a critical P value to provide an approximate line of demarcation between acceptance and rejection of the significance of the observed deviations. If the computed chi-square is larger than the chi-square associated with the critical P, the computed value is regarded significant, and the hypothesis that the two characteristics are unrelated must be rejected. Otherwise, the discrepancy between the observed and expected frequencies can be regarded as entirely due to chance, and no significant relationship can be proven to be of existence between the two characteristics. In this study the demarcation line has been drawn, as a matter of personal opinion, at $P = 0.01$. In order to evaluate critically the reliability of the conclusions drawn from the study, the actual values of P, expressed to three decimal places, are also presented in the individual analyses.

For the interpretation of the values of computed chi-square, use has been made of the tables prepared by Elderton (9). With the aid of these tables, the value of P for a computed chi-square and a given value of v has been determined.

Number of Degrees of Freedom

The number of degrees of freedom v in the equation of chi-square distribution is the number of cells for which expected frequency values can be assigned without restriction. In computing the expected frequencies the sum of the frequencies in each row is set up to equal the total observed cell frequencies in that row, and similarly for the columns. Since the frequencies in that row or column must add up to the total observed frequency in that row or column, one of the expected cell frequencies in a given row or column is defined by the knowledge of the total cell frequency and of the remaining cell frequencies in that row or column. Hence each row or column imposes a constraint, and for a contingency table of m rows and n columns the total numer of constraints is $m+n$. However, as the sum of the frequencies in the rows equals the sum of those in the columns, and since these are not algebraically independent, one must be subtracted from $m + n$ to give the actual total number of constraints. Thus the number of degrees of freedom for a contingency table of m rows and n columns is expressed by the equation

$$
\begin{aligned}
v &= mn - (m + n - 1) \\
&= (m - 1)(n - 1)
\end{aligned}
$$

Example — Condition of Crown vs Pothole Formation

To illustrate the method described above, the analysis of the relationship between the condition of crown and pothole formation is taken as an example. The numbers of

TABLE 2

CLASSIFICATION OF ROAD SECTIONS ACCORDING TO CONDITION OF CROWN AND POTHOLE FORMATION

Pothole Formation	Number of Sections Having Stated Pothole Formation for Crown Condition of:			Row Totals
	High Crown (½ in. or more per ft)	Low Crown (¼ in. per ft)	No Crown	
No potholing	131 (94)	38 (57)	11 (29)	180
Slightly potholed	211 (220)	145 (132)	63 (67)	419
Severely potholed	51 (79)	54 (48)	45 (23)	150
Column totals	393	237	119	749

Note: Expected frequencies are shown in parentheses below the observed frequencies.

cases observed with regard to these two characteristics are represented by the figures not in parentheses in the cells in Table 2. The expected frequencies are calculated in the manner described in Section 7 and written in parentheses in the contingency table.

The chi-square is calculated on the basis of the observed and the expected frequencies by simply taking each cell in turn, squaring the difference between the observed and expected value, and dividing the result by the expected frequency. This is conveniently done by means of the following scheme:

The total of the last column in Table 3 gives the value of chi-square which is equal to 65.66. The contingency table has three rows and three columns, and hence the number of degrees of freedom

$$v = (3-1)\,(3-1) = 4$$

Entering these values in the chi-square table, a probability value less than 0.01 is indicated (P=0.000). On this evidence, the hypothesis that the condition of crown and pothole formations are unrelated is rejected, and an inference that the two characteristics are associated is drawn.

To determine the sense of association the difference between observed and expected

TABLE 3

COMPUTATION OF CHI-SQUARE (CONDITION OF CROWN VS POTHOLE FORMATION)

(1) 0_{ij}	(2) e_{ij}	(3) $0_{ij}-e_{ij}$	(4) $(0_{ij}-e_{ij})^2$	(5) $\frac{(0_{ij}-e_{ij})^2}{e_{ij}}$
131	94	37	1369	14.56
38	57	-19	361	6.33
11	29	-18	324	11.17
211	220	-9	81	0.37
145	132	13	169	1.28
63	67	-4	16	0.24
51	79	-28	784	9.92
54	48	6	36	0.75
45	23	22	484	21.04
				65.66

TABLE 4

DIFFERENCE BETWEEN OBSERVED AND EXPECTED FREQUENCIES (CONDITION OF CROWN VS POTHOLE FORMATIONS)

	Difference, for stated pothole formation, between number of sections observed and number of sections expected for crown condition of:		
Pothole Formation	High Crown (½ in. or more per ft)	Low Crown (¼ in. per ft)	No Crown
No potholing	37	-19	-18
Slightly potholed	-9	13	-4
Severely potholed	-28	6	22

frequencies (0_{ij} - e_{ij}) in various cells are tabulated in Table 4. It is noted that on road sections with a high crown there were more cases of "no potholing" and less cases of "severely potholed" actually observed than expected. Contrarily, on road sections with no crown or a low crown there were more cases of severely potholed and less cases of no potholing actually observed than expected. It is evident that a soil-aggregate road surface with a high or an adequate crown would tend to have less pothole problems than those with no crown or a poor crown.

POTHOLE FORMATION

Road Characteristics Studied

In addition to the condition of crown, whose association with pothole formation is illustrated in the previous example, the road characteristics studied included type of surface material, width of road surface, condition of shoulders, condition of side ditches, and type of subgrade soil. The volume of traffic was also studied in connection with the formation of potholes. Not all these factors, however, were found significantly associated with pothole formations.

Volume of Traffic vs Pothole Formation

The soil-aggregate roads investigated were located in rural areas providing adequate land service or access to every farm home not served by the primary or trunk line highways. The volume of traffic on these roads was rather light, most of which being below 100 vehicles per day. Table 5 shows observed and expected distributions of road sections according to their pothole condition and according to their average daily traffic.

From the data in Table 5 the chi-square computed is equal to 17.13. The contingency table has three rows and four columns, and hence the number of degrees of freedom is equal to 6. Entering these values in the chi-square table a probability value less than 0.01 is indicated (P-0.008). It follows that the relationship between the volume of traffic and pothole formation is significant. The differences between observed and expected frequencies indicate that road sections with a smaller volume of traffic appear to have less pothole problems than those with a larger volume of traffic.

Type of Surface Material vs Pothole Formation

Two major types of material, gravel and crushed stone, were used for road surfaces in the area investigated. All the gravel materials were pit-run, consisting of

TABLE 5

CLASSIFICATION OF ROAD SECTIONS ACCORDING TO AVERAGE DAILY TRAFFIC AND POTHOLE FORMATION

	Number of Sections Having Stated Pothole Formation for Average Daily Traffic of:				
Pothole Formation	0-24	25-49	50-74	75-99	Row Totals
No potholing	64 (57)	50 (58)	18 (17)	7 (7)	139
Slightly potholed	131 (121)	115 (124)	34 (35)	16 (16)	296
Severely potholed	25 (42)	60 (43)	12 (12)	6 (6)	103
Column totals	220	225	64	29	538

Note: Expected frequencies are shown in parentheses below the observed frequencies.

natural mixtures of gravel, sand, silt, and clay, and hence with a sufficient amount of fine material. The crushed stone used in the area was obtained from various sources as crusher-run product. It in general lacked sufficient binder and fines and was highly segregated in its particle size because of an incorrect method of handling and placing the material on the road. The contingency table classifying investigated road sections with respect to surface material and pothole formation is shown in Table 6.

From the data in Table 6 the chi-square computed is 16.38; the number of degrees of freedom is 2. Entering these values in the chi-square table, a probability value less than 0.01 is obtained (P=0.000). The result indicates that the relationship between the type of surface material and pothole formation is significant. The differences between observed and expected frequencies show that road sections surfaced with gravel appear to have less potholes than those surfaced with crushed stone.

TABLE 6

CLASSIFICATION OF ROAD SECTIONS ACCORDING TO TYPE OF SURFACE MATERIAL AND POTHOLE FORMATION

Pothole Formation	Number of Sections Having Stated Pothole Formation for the Two Types of Surface Material:		Row Totals
	Gravel	Crushed Stone	
No potholing	81 (76)	62 (67)	143
Slightly potholed	169 (156)	127 (140)	296
Severely potholed	33 (51)	64 (46)	97
Column totals	283	253	536

Note: Expected frequencies are shown in parentheses below the observed frequencies.

TABLE 7

CLASSIFICATION OF ROAD SECTIONS ACCORDING TO WIDTH OF ROAD SURFACE AND POTHOLE FORMATION

Pothole Formation	Number of Sections Having Stated Pothole Formation for Road Surface Width (ft) of:				Row Totals
	21-24	17-20	13-16	9-12	
No potholing	6 (14)	58 (61)	59 (52)	21 (17)	144
Slightly potholed	25 (28)	119 (119)	103 (101)	33 (32)	280
Severely potholed	21 (10)	47 (44)	28 (37)	6 (11)	102
Column totals	52	224	190	60	526

Note: Expected frequencies are shown in parentheses below the observed frequencies.

Width of Road Surface vs Pothole Formation

The road surfaces investigated were either two-lane or single-lane, with widths ranging from 9 to 24 ft. The contingency table giving observed and expected frequencies corresponding to width of road surface and pothole formation is shown in Table 7. The chi-square computed from the frequencies in Table 7 is 23.76. The number of degrees of freedom is 6. With 6 degrees of freedom, the computed chi-square shows a probability value less than 0.01 (P = 0.001). The result indicates a significant association between the width of road surface and pothole formation. Comparing the observed frequencies with the expected frequencies reveals that wider road surfaces were more severely potholed than narrower road surfaces.

TABLE 8

CLASSIFICATION OF ROAD SECTIONS ACCORDING TO CONDITION OF SHOULDERS AND POTHOLE FORMATION

	Number of Sections Having Stated Pothole Formation for Shoulders in:			
Pothole Formation	Good Condition	Fair Condition	Poor Condition	Row Totals
No potholing	44 (28)	22 (20)	96 (114)	162
Slightly potholed	48 (59)	39 (41)	252 (239)	339
Severely potholed	14 (19)	13 (13)	80 (75)	107
Column totals	106	74	428	608

Note: Expected frequencies are shown in parentheses below the observed frequencies.

TABLE 9

CLASSIFICATION OF ROAD SECTIONS ACCORDING TO CONDITION OF SIDE DITCHES AND POTHOLE FORMATION

	Number of Sections Having Stated Pothole Formation for Side Ditches in:			
Pothole Formation	Good Condition	Fair Condition	Poor Condition	Row Totals
No potholing	107 (95)	27 (30)	25 (34)	159
Slightly potholed	201 (206)	66 (66)	77 (72)	344
Severely potholed	68 (75)	27 (24)	30 (26)	125
Column totals	376	120	132	628

Note: Expected frequencies are shown in parentheses below the observed frequencies.

Condition of Shoulders vs Pothole Formation

The condition of shoulders as to drainage facility is arbitrarily classified as good, fair, and poor. The observed and expected frequencies with regard to condition of shoulders and pothole formation are shown in Table 8. The calculated chi-square is 16.68. The number of degrees of freedom is equal to 4. With four degrees of freedom, the calculated chi-square 16.68 shows a probability value less than 0.01 (P = 0.002). The result is thus significant. An inspection of the contingency table shows that road sections with good shoulders appear to have less pothole problems than those with poor shoulders.

Condition of Side Ditches vs Pothole Formation

The condition of side ditches is classified into three categories in accordance with their ability of removing water away from the road bed, and designated arbitrarily as good, fair, and poor. The contingency table classifying the road sections according to condition of side ditches and according to pothole formation is shown in Table 9. The calculated chi-square is 6.31; and the number of degrees of freedom is 4. Entering these values in the chi-square table, a probability value more than 0.01 is obtained (P =0.177). Inasmuch as the probability value associated with the computed chi-square is above the accepted level of significance, no ground is revealed by the test for supposing the hypothesis incorrect. In other words, the data do not suggest that the pothole formation varies with the condition of ditches, at least so far as this test is concerned.

Type of Subgrade Soil vs Pothole Formation

Subgrade soils in the area are predominantly of the DH, DM, and ZS groups, in accordance with the soil classification system used in Illinois Engineering Soil Maps (11). The classification system is based on a two letter system with reference to a soil profile divided into several horizons. The first letter of the symbol expresses the plasticity of the Horizon A (surface and subsurface), and Horizon B (or subsoil). The second letter indicates the character of Horizons C and D (or substrata). The details of the classification system have been reported previously by T.H. Thornburn (10).

Soils in the DH group have from slightly to moderately plastic horizons A and B, and highly permeable horizons C and D. Soils in the DM group have from slightly to moderately plastic horizons A and B, but moderately permeable horizons C and D.

TABLE 10

CLASSIFICATION OF ROAD SECTIONS ACCORDING TO SUBGRADE SOIL GROUP AND POTHOLE FORMATION

	Number of Sections Having Stated Pothole Formation for Subgrade Soil Group:			
Pothole Formation	DH	DM	ZS	Row Totals
No potholing	26 (25)	75 (77)	72 (71)	173
Slightly potholed	50 (56)	181 (172)	155 (158)	386
Severely potholed	25 (20)	56 (63)	60 (58)	141
Column totals	101	312	287	700

Note: Expected frequencies are shown in parentheses below the observed frequencies.

Soils in ZS group have highly plastic horizons A and B, and slowly permeable horizons C and D. The typical characteristics of these soils are given in the report accompanying the engineering soil map in detail in the form of soil data sheets.

The contingency table classifying road sections in accordance with the above subgrade soil groups and pothole formation is shown in Table 10. The data gives a chi-square of 3.37 and 4 degrees of freedom. Entering these values in the chi-square table, a probability value larger than 0.01 is obtained (P-0.498). This test gives no evidence to reject the hypothesis and does not prove that the two characteristics are related.

General Discussion

Among the various road characteristics the condition of side ditches and the type of subgrade soil have not been ascertained to be associated with pothole formation by the chi-square test. Both these characteristics gave a probability value above the accepted 0.01 level of significance, implying that any possible correlation between either one of these characteristics and pothole formation might be attributed to chance. It must be noted, however, that while the chi-square test provided no ground to relate the pothole formation with the characteristics mentioned above, the test did not prove that these characteristics were unrelated to the pothole formation. In the chi-square test, it is the disagreement between the observed data and hypothesis which is important, because this disagreement gives reason for thinking the hypothesis incorrect. Agreement, on the other hand, does not mean that the hypothesis is correct. Regarding these two road characteristics, therefore, all that can be said is that the chi-square test revealed no grounds for supposing incorrect the hypothesis that the pothole formation is independent of these characteristics. As far as the evidence is concerned, it is appropriate to assume that the drainage condition of side ditches and the particular types of subgrade soil were homogeneous with respect to pothole formation.

The circumstances that have been ascertained to be associated with the formation of potholes embrace (a) volume of traffic, (b) width of road surface, (c) type of surface material, (d) condition of crown, and (e) condition of shoulders. Of these circumstances the volume of traffic is perhaps the most remarkable, representing the cyclic stresses imposed by the wheels of moving vehicles upon the surface of a road.

Under the wheels of vehicles a road surface is imposed upon by a complex system of stresses. The weight of a wheel causes stresses in the surface course and tends to produce settlement or deformation of the loaded part of the surface in a vertical direction. Likewise, horizontal shear stresses are set up over the contact area of the tire due to the resistance offered by the road surface to lateral displacement of the tread. When the vehicle is accelerated, the horizontal shear tends to push the surface material backward. When brakes are applied, a similar tendency is produced in the opposite direction. In addition, rolling wheels produce vibratory or dynamic stresses which tend to loosen the surface material. The intensity of these stresses is determined by the magnitude of the total load, the rigidity of and the inflation pressure in the tire, the condition of road surface, the driving force and the braking force of the vehicle, and other dynamic effects of moving loads.

Each time a wheel passes, the above system of transient stresses is imposed on the road surface. If the process is repeated, the stresses set up by moving traffic ultimately exceed those that can be safely tolerated by the road material, and surface failures result. The greater the volume of traffic, the greater is the disruptive action of moving wheels, and thus more failures occur. Even though the forms of developed failure may be different, the above effect of traffic is common on all types of road surfaces.

While the destructive forces are always present, the serviceability and economic life of the surface vary in general with the structural strength of the surface material. Basically all road materials are composed of mineral aggregates which are bound together by a cementing agent. The strength of a material is generally ascribed both to the friction between aggregate particles and to the cohesion introduced by the cementing agent. The capacity to resist wear and tear of traffic on a surface system, however, is to a large extent represented by the binding power of the cementing agent.

It is generally recognized that mineral aggregate for most types of road construction must consist of a properly graded mixture of hard, tough, and durable particles to provide frictional resistance. For high type pavements carrying large volumes of traffic, a cementing agent capable of supplying a strong and relatively permanent bond between these mineral aggregates is in addition a matter of virtual necessity. Thus among the high type surfaces, a portland cement concrete pavement must employ a hardened cement paste to completely surround and strongly hold together the mineral aggregates. Similarly, a bituminous concrete pavement has to resort to a suitable bituminous binder for properly cementing the otherwise loose aggregate mass.

In a soil-aggregate road surface, the cementing is provided by the clay in the binder soil which derives its cohesion from the adsorbed moisture films of individual soil particles. Since the cohesion varies with the moisture content, the binder soil can be depended upon for cementing action only when the moisture content is within a certain desirable range. In dry weather the soil moisture is not sufficient to develop the cohesion required to prevent surface abrasion which results in loss of material and causes dust nuisance. Conditions in wet weather may be just as unsatisfactory, due to excessiv moisture. Under these conditions, the cohesion of the clay fraction may be completely vanished and the soil become a lubricant instead of a binder. In addition, the soil may expand the solid framework and cause a decrease in the mechanical contact between particles through excessive volume change. Thus the interlocking of granular particles and the mutual support so important to the frictional resistance of aggregate materials is readily, and in some cases, entirely eliminated.

Inasmuch as the binder soil, except under ideal conditions, does not act efficiently as a cementing medium, the capacity of the soil-aggregate mixture to resist wear and tear of traffic is essentially limited. Although a mixture of well compacted angular particles may withstand the action of a limited amount of traffic due to effective particle interlocking, a surface material that consists of rounded mineral particles in the absence of cohesion can hardly carry any appreciable amount of traffic without resulting in some kind of serious defect. As the vehicle crushes with its weight and tears and abrades with its moving wheels, the soil-aggregate material which is not firmly bound in the road surface will either be laterally displaced or be lifted and carried away, thus leaving small depressions or holes in the road surface. Following further actions of traffic, serious road failures will be developed. If the road material is not generally deficient in structural strength, the failure will be ordinarily localized at the points, in the form of potholes, where local weakness or injury takes place. Otherwise the surface failure will occur in a larger area, most commonly in the form of washboards where the weak surface material shapes itself into rhythmic undulations under the influence of traffic.

This depiction of the effect of volume of traffic and type of surface material on the development and condition of potholes on soil-aggregate road surfaces has been confirmed by the results of the present investigation. The chi-square test indicated convincingly that the formation of potholes was related to the volume of traffic. Although potholes were found in road sections in all classes of average daily traffic, it was noted that road sections with smaller volumes of traffic were less severely potholed than those with larger volumes of traffic. In addition, the effect of volume of traffic was evidenced by the correlation between the width of road surface and the pothole formation, in that wider road surfaces were more severely potholed than the narrower ones. Inasmuch as wider surfaces were also associated with larger volumes of traffic, the correlation between the width of road surface and pothole formation was, in effect, an indication of the relationship between the volume of traffic and pothole formation. Since larger volumes of traffic were carried by road sections with wider surfaces, the greater disruptive action of moving wheels resulted in more severe formations of potholes in these surfaces. (In the test of association between the width of road surface and the volume of traffic, the probability associated with the computed chi-square 91.70, for six degrees of freedom, is less than 0.01, (P = 0.000), indicating a significant correlation between the two.)

In regard to the two types of soil-aggregate material used for road surfacing, the chi-square test indicated that the pit-run gravel tended to be less associated with pothole formation than the crushed stone. Due to lack of detailed data concerning the properties and characteristics of these two materials, a complete account of the occurrence was not possible. It was noted in the field investigation, however, that the crushed stone was not only deficient in binder content, but also highly segregated in its particle size because of incorrect method of handling and placing the material on the road. It was speculated, therefore, that due to the above circumstances the road surface was seriously weakened in many spots becoming particularly susceptible to the development of potholes. The pit-run gravel, on the other hand, generally contained enough binder soil which would hold the soil-aggregate material in place under normal service conditions. The presence of enough binder soil in the pit-run gravel would not necessarily exempt the road material from the development of potholes or other types of defect. The formation of washboards might well be promoted if a slight excess of binder soil were present in the surface, since the binder soil would soften and swell when wet and tend to unseat the coarser materials under traffic.

Among the road characteristics that have been ascertained to be associated with pothole formation, both the condition of crown and the condition of shoulders have perhaps no occasion for elaborate explanation. The strength of a soil-aggregate mixture is decreased by the penetration of moisture into the voids. Consequently, a soil-aggregate surface must be equipped with adequate crown and sloped shoulders to facilitate fast removal of water from the road surface. If the crown and shoulders fail to function properly, the surface material becomes softened by water standing on the surface, and under traffic the surface develops small pits. Water held in these depressions during subsequent wet periods further softens the hard-packed surface, and the finer soil material suspended in the water is lost as traffic throws the water aside. The coarser residual material, no longer held together by a binder, is also partly removed later when the road is dry. In this manner the small initial pits produce the typical potholes.

Although the data brought out by the present investigation indicate clearly the trend discussed above, it is interesting to note that similar results were disclosed in 1935 by Burggraf. In a study of soil-aggregate roads in Kansas, Illinois and Indiana, Burggraf showed a very definite relationship to exist between the service behavior of the road and the amount of crown, the serviceability of the road surface decreasing as the crown is lowered (4). Based on field data he concluded that the average crown where potholing had been developed was 0.26 in. per ft, and that where no surface defects appeared was 0.41 in. per ft. It is noted in the present investigation that, somewhat unconformable to Burggraf's conclusion, potholing was observed in road sections with a crown greater than 0.41 in. per ft. However, the effect of surface drainage on the development and general condition of potholes is essentially in agreement with the findings reported by Burggraf. It is realized that there were definitely other factors than condition of crown and shoulders affecting the formation of potholes. It would not be possible, therefore, in this study to ascribe the pothole formation only to any arbitrary rate of crown or slope of shoulders.

WASHBOARD FORMATION

Road Characteristics Studied

The road characteristics which were tested for association with washboard formation were the same ones studied with pothole formation, including type of surface material, width of road surface, condition of crown, condition of shoulders, condition of side ditches, and type of subgrade soil. In addition, the volume of traffic was studied in connection with the formation of washboards.

Volume of Traffic vs Washboard Formation

The contingency table showing observed and expected distributions of road sections with respect to their washboard formation and volume of traffic is shown in Table 11. From the data, the chi-square computed is 30.04 and the number of degrees of freedom is 6. Entering these values in the chi-square table, a probability value less than 0.01 is obtained (P = 0.000). It follows that there was a significant correlation between the volume of traffic and washboard formation. The differences between the expected and the observed frequencies reveal that the road sections with smaller volume of traffic appear to have less washboarding problems than those with larger voume of traffic.

Type of Surface Material vs Washboard Formation

The contingency table classifying road sections according to two types of surface material, gravel and crushed stone, and according to washboard formation is shown in Table 12. The chi-square computed is equal to 36.13. The number of degrees of freedom is 2. For these values, a probability value less than 0.01 is noted in the chi-square table (P = 0.000), indicating a significant relationship between the type of surface material and washboard formation. The differences between observed and expected frequencies show that road sections surfaced with crushed stone appear to have less washboards formed than those surfaced with gravel.

TABLE 11

CLASSIFICATION OF ROAD SECTIONS ACCORDING TO AVERAGE DAILY TRAFFIC AND WASHBOARD FORMATION

Washboard Formation	Number of Sections Having Stated Washboard Formation for Average Daily Traffic of:				Row Totals
	0-24	25-49	50-74	75-99	
No washboarding	163 (144)	191 (190)	46 (57)	16 (25)	416
Slightly washboarded	27 (36)	43 (47)	19 (14)	14 (6)	103
Severely washboarded	19 (29)	42 (39)	17 (11)	7 (6)	85
Column totals	209	276	82	37	604

Note: Expected frequencies are shown in parentheses below the observed frequencies.

TABLE 12

CLASSIFICATION OF ROAD SECTIONS ACCORDING TO TYPE OF SURFACE MATERIAL AND WASHBOARD FORMATION

Washboard Formation	Number of Sections Having Stated Washboard Formation for the Two Types of Surface Material:		Row Totals
	Gravel	Crushed Stone	
No washboards	179 (211)	181 (149)	360
Slightly washboarded	77 (59)	24 (42)	101
Severely washboarded	56 (42)	16 (30)	72
Column totals	312	221	533

Note: Expected frequencies are shown in parentheses below the observed frequencies.

Width of Road Surface vs Washboard Formation

The contingency table giving observed and expected frequencies corresponding to width of road surface and washboard formation is shown in Table 13. The computed value of chi-square is 18.68. The number of degrees of freedom is 6. With six degrees of freedom, the computed chi-square shows a probability value less than 0.01 (P = 0.005). The result indicates a significant association between the width of road surface and washboard formation. Comparing the observed frequencies with the expected frequencies Table 13 shows that wider road surfaces had more severe formations of washboards than narrower road surfaces.

TABLE 13

CLASSIFICATION OF ROAD SECTIONS ACCORDING TO WIDTH OF ROAD SURFACE AND WASHBOARD FORMATION

Washboard Formation	Number of Sections Having Stated Washboard Formation for Road Surface Width (ft) of:				Row Totals
	21-24	17-20	13-16	9-12	
No washboarding	35 (43)	150 (165)	163 (149)	49 (40)	397
Slightly washboarded	17 (12)	56 (47)	35 (43)	6 (12)	114
Severely washboarded	12 (9)	41 (35)	25 (31)	6 (9)	84
Column totals	64	247	223	61	595

Note: Expected frequencies are shown in parentheses below the observed frequencies.

TABLE 14

CLASSIFICATION OF ROAD SECTIONS ACCORDING TO CONDITION OF CROWN AND WASHBOARD FORMATION

Washboard Formation	Number of Sections Having Stated Washboard Formation for Crown Condition of:			Row Totals
	High Crown (½ in. or more per ft	Low Crown (¼ in. per ft	No Crown	
No washboarding	284 (255)	105 (122)	50 (62)	439
Slightly washboarded	73 (88)	52 (42)	26 (21)	151
Severely washboarded	51 (65)	38 (31)	23 (16)	112
Column totals	408	195	99	702

Note: Expected frequencies are shown in parentheses below the observed frequencies.

Condition of Crown vs Washboard Formation

The relationship between the condition of crown and washboard formation is studied on the basis of the data contained in Table 14. From the data the chi-square computed is 21.77. With the number of degrees of freedom 4, a probability value less than 0.01 is indicated in the chi-square table (P = 0.000). The result shows the relationship between the condition of crown and washboarding is significant, the formation of washboards being aggravated as the crown is lowered.

Condition of Shoulders vs Washboard Formation

The observed and expected frequencies with regard to condition of shoulders and washboard formation are shown in Table 15. The computed value of chi-square is 9.87. The number of degrees of freedom is 4. Entering these values in the chi-square table, a probability value more than 0.01 is indicated (P = 0.043). Since the probability value is above the accepted level of significance, there is no reason to suppose that the hypothesis is incorrect, or postulate that washboard formation is related to the condition of shoulders.

Condition of Side Ditches vs Washboard Formation

The contingency table showing observed and expected distributions of road sections according to their washboard formation and according to the condition of side ditches is shown in Table 16. The calculated chi-square is 1.89; and the number of degrees of freedom is 4. Entering these values in the chi-square table, a probability value more than 0.01 is noted (P = 0.756). Since the probability value falls above the accepted level of significance, there is no cause to assume that the washboard formation varies with the condition of side ditches.

Type of Subgrade Soil vs Washboard Formation

The contingency table classifying road sections in accordance with three subgrade soil groups, namely, DH, DM and ZS, and washboard formation is shown in Table 17. The chi-square computed from the frequencies in Table 17 is 2.06. The number of degrees of freedom is 4. Entering these values in the chi-square table, a probability value more than 0.01 is indicated (P = 0.725). The result does not ascertain that washboard formation is related to the type of subgrade soil, since the probability value

TABLE 15

CLASSIFICATION OF ROAD SECTIONS ACCORDING TO CONDITION OF SHOULDERS AND WASHBOARD FORMATION

Washboard Formation	Number of Sections Having Stated Washboard Formation for Shoulders in: Good Condition	Fair Condition	Poor Condition	Row Totals
No washboarding	121 (107)	62 (61)	253 (268)	436
Slightly washboarded	22 (28)	14 (16)	79 (71)	115
Severely washboarded	10 (18)	11 (10)	52 (45)	73
Column totals	153	87	384	624

Note: Expected frequencies are shown in parentheses below the observed frequencies.

associated with the computed chi-square is above the accepted level of significance.

General Discussion

The circumstances that have been ascertained to be associated with washboard formation include (a) volume of traffic, (b) width of road surface, (c) type of surface material, and (d) condition of crown. Although all these circumstances have previously been found to be also related to pothole formation, their controlling influence upon the performance and serviceability of the roads investigated seems all the more evident.

Both the volume of traffic and the width of road surface, as noted in the discussion in connection with pothole formation, are indicative of the cylcic stresses imposed by wheels of moving vehicles upon a road surface. When the traffic volume is small and the total stresses are less than those that can be safely tolerated by the road material, the surface remains relatively intact. As the traffic increases, the weakest places in

TABLE 16

CLASSIFICATION OF ROAD SECTIONS ACCORDING TO CONDITION OF SIDE DITCHES AND WASHBOARD FORMATION

Washboard Formation	Number of Sections Having Stated Washboard Formation for Side Ditches in:			Row Totals
	Good Condition	Fair Condition	Poor Condition	
No washboarding	251 (246)	82 (83)	102 (106)	435
Slightly washboarded	73 (73)	25 (24)	30 (31)	128
Severely washboarded	49 (54)	19 (19)	28 (23)	96
Column totals	373	126	160	659

Note: Expected frequencies are shown in parentheses below the observed frequencies.

TABLE 17

CLASSIFICATION OF ROAD SECTIONS ACCORDING TO SUBGRADE SOIL GROUPS AND WASHBOARD FORMATION

Washboard Formation	Number of Sections Having Stated Washboard Formation for Subgrade Soil Group:			Row Totals
	DH	DM	ZS	
No washboarding	66 (63)	231 (237)	186 (183)	483
Slightly washboarded	13 (16)	70 (63)	45 (49)	128
Severely washboarded	12 (12)	44 (45)	36 (35)	92
Column totals	91	345	267	703

Note: Expected frequencies are shown in parentheses below the observed frequencies.

the road give way first and the surface begins to deteriorate. Since the destructive forces are inherent in the vehicles using the road, the developed failure, in whatever form it may occur, will be accentuated by increasing frequency of loading or growing traffic.

The effect of traffic on soil-aggregate roads, as far as washboard formation is concerned, has long been recognized. Ladd reported in 1924, for instance, in connection with his investigation concerning washboard formations in roads in Maine, New Hampshire, Connecticut, New Jersey, Michigan, Wisconsin, and Oregon that gravel roads subjected to a traffic of not more than 200 or 300 vehicles per day remained practically free from washboards if occasionally dragged. As soon, however, as traffic reached 400 to 450 vehicles per day washboards developed very rapidly (7).

Carpenter and Dana reported in 1927 in a discussion of the relation of volume of traffic to formation of washboards that a traffic of 300 or 400 vehicles per day did not usually cause serious formation of washboards (1). On the other hand, it has also been reported that, based on more recent experience, washboards might be encountered in some roads if the volume of traffic exceeded 50 vehicles per day, and that only by intensive maintenance could a greater number of vehicles be handled without serious washboards formed (5). While there were effects other than traffic upon the formation of washboards, the disagreement in reports regarding the critical amount of traffic effecting the formation of washboards would be expected. It is speculated, however, that considering that weights and speeds of vehicles have been considerably increased during the past 30 years, a traffic of 50 vehicles per day can probably be regarded at present as the average volume that would initiate the nuisance of washboarding in a fairly well constructed road even under favorable climatic conditions.

The washboard formations are characterized by the presence of transverse waves on the road surface with approximately equal amplitudes and uniform spacings. Just how the traffic causes or accentuates these formations has been a problem of interest for many years, and the indications are that the periodic vibrations and impacts of moving wheels have much to contribute to the problem. As described by Dana,

> ...a small obstruction, or uneveness in the road surface, the lurch of the vehicles, the vibrations of the engine, or any of a number of different circumstances, separately or combined, may cause the wheel ...to jump from the road surface....When it descends, the cushioning of the impact by the air pressure in the tire will cause the wheels to bounce again. This bouncing will continue until the original energy imparted to the system has all been absorbed....The wheels of the next vehicles, hitting the same obstruction, or being influenced by similar circumstances, will repeat the previous performance. Thus the impacts of successive tires in nearly the same spots will begin to break and loosen the....surface, and the air currents caused by the moving tires and by the car itself will lift part of the loosened binder and fine material and carry it away, at the same time shaping the remainder into successive waves ....which in turn promote still more and deeper washboards (3).

The fact that washboard formations occur in all sections of the country makes it evident that nearly all soil-aggregate roads, if they serve sufficient traffic, are subject to the development of this nuisance even though the methods of construction and kinds of material vary widely. However, the facility by which the washboard formations are formed appears to depend to a considerable extent upon the strength characteristics of the road material. From the experience gained with this type of construction, it is generally agreed that to resist adequately the periodic vibrations and impacts of moving vehicles, the surface material must be such that it would consolidate sufficiently by rolling or under traffic and remain relatively stable under all weather conditions. Such a material calling upon a combination of the high internal friction of the aggregates and the beneficial cohesion of the binder soil is generally attained through properly controlling the gradation or relative amounts of components of the mixture, and by controlling the binding properties of the binder soil. If a material is lacking in adequate binder soil, compacting the material to a desirable state of consolidation and maintaining it in this state are extremely difficult. The strength of the mixture has to resort primarily to the internal friction produced by the interlocking and mutual support of adjacent particles in the mass. Although a mass of angular particles may produce some resistance, a loose granular mass composed of rounded particles is evidently incapable of withstanding the destructive forces of traffic, and, in the words of Ladd, "washboards are formed by the kick-back of surface materials arising from the spin of...wheels of automobiles as they descend after a bounce over some obstacle or depression" (7, p. 18). On the other hand, if a mixture contains an excessive amount of binder soil, the material will become soft and plastic in the presence of water and, according to Ladd, washboards are formed by the squeezing action of wheels resulting from impact (7. p. 19).

It is evident that the type of surface material bears a definite relation to the formation of washboards. Ladd reported as early as 1924 that, in the opinion of some highway officials, washboard trouble would be reduced should angular aggregate materials be used. It was reported that in northern New Hampshire some roads that were built of a material which had resulted from the decomposition of granite rocks and was full of angular quartz were said to give better service, as far as washboards were concerned, than those built in the same area with glacial gravels. Highway engineers, according to Ladd, notably in Wisconsin and Oregon, objected to any clay binder in the gravel and preferred only the fines produced by crushing and from surface wear to prevent washboard formation (7, p. 18).

More recently Jahn in examining road failures in Flensburg, Germany, reported among other things that serious defects, either in the form of washboards or potholes, were observed in roads where the material showed either an excessive amount of binder soil or an excessive amount of aggregates (6).

The result of the present study agrees in general with the trends indicated above. Although washboards were found in road sections surfaced with gravel as well as crushed stone, the road sections surfaced with gravel showed definitely a closer association with washboard formation than those surfaced with the other material. It may be recalled that the gravel material was a pit-run product, consisting of rounded aggregate particles with more than enough binder material which tended to expand and to act as a lubricant when wet. Such a material would readily soften in the presence of water and be squeezed by the periodic vibrations and impacts of moving wheels, resulting in the formation of washboards. The crushed stone, on the other hand, consisted entirely of angular aggregates, highly segregated and in general deficient in binder content. It is postulated that the mechanical advantage due to the interlocking of angular particles enhanced the resistance of the material to the bouncing and squeezing action of traffic, and restrained more or less the formation of washboards. However, the segregated material automatically incorporated many weak spots in the road surface and invited localized destruction under traffic in the form of potholes which showed no apparent regularity as washboards.

Although a road material containing an excessive amount of binder is generally regarded unsatisfactory in soil-aggregate construction, the detrimental effects are often unsuspected if there is no excessive moisture present. Ladd has reported, for instance, that a section of road built of soft gravel which was high in clay-silt bond was practically free from washboards throughout summer, but later during the wet season became nearly impassable (7, p. 20). Because washboard formations in a soil-aggregate surface depend upon the strength characteristics of the road material and because the strength characteristics, as indicated previously, are adversely affected by increasing moisture content, the development of washboards can often be curbed by protecting the road material from moisture through effective drainage. As a road surface a soil-aggregate material may occasionally be weakened by ground water or capillary water, but more often it is weakened by uncontrolled rain and strom water standing upon the surface. Consequently, an effective crown must be provided to shed rapidly the surface water away from the traveled way so that the stability of the road material will be well preserved. As an important drainage factor, the condition of crown would be expected to bear a definite relationship to the development and condition of washboards. The pattern has been brought out by the result of the present investigation, in that road surfaces with good or adequate crowns were less associated with washboards than those which had poor or inadequate crowns for surface drainage.

Among the road characteristics studied in this investigation, three have not been ascertained to be associated with washboard formation, namely, (a) condition of shoulders, (b) condition of side ditches, and (c) type of subgrade soil. It must be again emphasized, in this connection, that the results give no indication that these characteristics are unrelated to washboard formation. Although washboard formations have been reported to be affected by the bearing value and drainage requirements of the subsoil (2) and the condition of shoulders has indeed been ascertained previously to be associated with pothole formation, it is within the bounds of possibility that one or more of these characteristics are related to washboard formation. However, all these characteristics gave a probability value above the accepted 0.01 level of significance, implying that any possible correlation could have arisen solely due to chance and giving no evidence to reject the hypothesis that these characteristics were unrelated to washboard formation. It is pertinent to conclude, nonetheless, that as far as the evidence is concerned, the condition of shoulders and side ditches and the type of subgrade soil were homogeneous with respect to the formation of washboards.

SUMMARY AND CONCLUSIONS

Results

In this investigation a number of road characteristics observed and noted in a condition survey of soil-aggregate roads were studied for association by chi-square test. Certain circumstances have been proved to be definitely associated with the development and condition of potholes and washboards in these roads. The results are summarized as follows:

1. Both the pothole formation and the washboard formation were associated with volume of traffic. Road sections with larger volume of traffic appeared to have more serious problems of potholes and washboards than those with smaller volume of traffic.
2. Both the pothole formation and the washboard formation were associated with the width of road surface. Road sections with wider surfaces were more severely potholed or washboarded than those with narrower surfaces. Inasmuch as wider surfaces were also associated with larger volume of traffic, the correlation was, in effect, an indication of the relationship between the volume of traffic and pothole or washboard formation.
3. Potholing was more severe in road sections surfaced with crushed stone than in those surfaced with gravel. Washboarding was more severe in road sections surfaced with gravel than those surfaced with crushed stone.
4. A very definite relationship was shown to exist between the condition of crown and shoulders as to drainage and the pothole formation. Road surfaces with poor or inadequate crowns and shoulders showed more severe potholing than well drained surfaces. A significant relationship was also found between the condition of crown and washboard formation. Road surfaces with poor or inadequate crowns tended to have more serious washboard problems than those with high or adequate crowns.

Conclusions

On the basis of the foregoing data, the following general conclusions have been drawn:

1. The service of soil-aggregate road surfaces is confined to roads carrying a relatively small volume of traffic, because the capacity of the surface material to resist wear and tear of traffic is much limited. When the traffic volume is relatively

low and the climatic condition favorable, the road surface is decidedly an economic type. As the traffic increases, potholes and washboards start to develop, and the cost of maintenance required to keep the road in serviceable condition begins to mount. When the traffic reaches a certain limit, potholing and washboarding will become incorrigible and the maintenance cost will approach the amount which is no longer economically justified to spend. Although conditions of local material, climate, and method of construction vary, the effect of traffic should be realized by the intensity of maintenance required and by its cost.

2. To minimize or to better control the nuisance of potholes or washboards in soil-aggregate road surfaces, attention must be exercised in selecting the proper material for surface construction. From this study it is difficult to state whether gravel or crushed stone was more desirable since crushed stone sections showed more severe potholing and gravel sections showed more severe washboarding. It is appropriate to conclude, however, that a soil-aggregate mixture with proper amount of aggregate and binder that combines the high internal friction of the aggregate with the beneficial cohesion of the binder soil should minimize the formation of either potholes or washboards.

3. Inasmuch as soil-aggregate surfaces are generally irregular and highly absorbent, a proper amount of crown and sloped shoulders to readily drain the surface water away from the traveled way is a virtual necessity to satisfactory performance of these surfaces. Both potholes and washboards are developed and accentuated if the surface material has been softened by standing water on the surface. It is evident that in order to get constantly rid of the water from the surface as quickly and fully as possible, adequate drainage must be provided which will largely minimize the formation of potholes and washboards.

Although the circumstances related to the formation of potholes or washboards may be many, this paper outlines only those that have been noted in a road condition survey. Since the primary objective of this survey was to locate road sections for special studies, much of the needed data for a correlation study was not collected. Consequently the scope of the study was limited. It is believed, however, that while the formation of potholes and washboards remains a problem of interest for future study, the findings of this investigation at the least provide certain information toward further understanding of these formations.

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The work reported herein was done under the general supervision of Ellis Danner, Director of the Illinois Cooperative Highway Research Program and Professor of Highway Engineering, University of Illinois; and Theodore F. Morf, Engineer of Research and Planning, and W.E. Chastain, Sr., Engineer of Physical Research, Illinois Division of Highways.

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Discussion

J.W. SPENCER, Highway Research and Extension Engineer, Department of Agricultural Engineering, Cornell University — Professor Huang's presentation of some relationships between various road characteristics and the occurrence of potholing and washboarding is very helpful — especially as these relationships serve to inspire deeper thinking about the causes of these rather common "diseases" of soil-aggregate roads.

Although there is some danger that lack of independence of a particular characteristic and a particular disease may lead the uninitiated to assume a cause-effect relationship, the chi-square test helpfully indicates where relationships appear definitely to exist. While the chi-square approach provides an objectivity not possible in more observation of data, there seems to be one contingency table (Table 5) where the indicated significance of relationship between volume of traffic and pothole formation is not readily apparent to the observer.

The author suggests that of the circumstances associated with the formation of potholes, the volume of traffic is perhaps the most remarkable. He amplifies this by stating, "The chi-square test indicated convincingly that the formation of potholes was related to the volume of traffic." The experience of those who have long observed the performance of soil-aggregate roads must confirm an apparent relationship between traffic volume and potholing, but it does not seem that the data in Table 5 indicate a strong relationship for roads carrying at least 50 vehicles per day. Comparing the observed frequencies with expected frequencies, it appears that for an average daily traffic of up to 50 vehicles, increasing traffic had a marked relationship to degree of potholing, but for increases beyond 50 vehicles per day, there appears to be little if any difference between expected and observed frequencies. Perhaps this observer has misinterpreted the data or perhaps the statements were based on data not included in the paper.

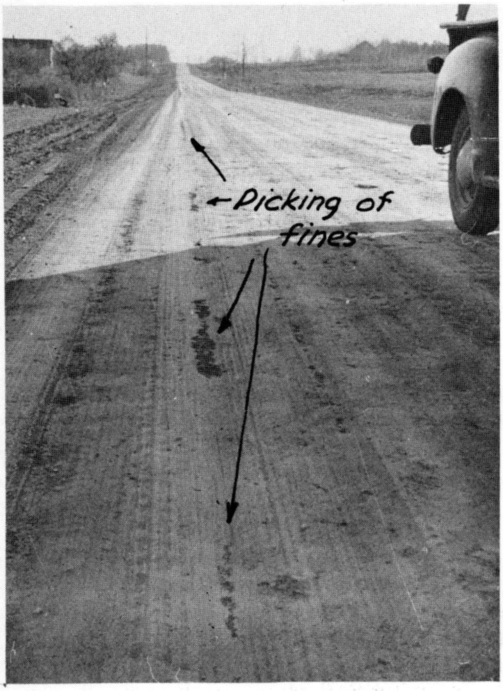

Figure 3. A beginning of potholes; fines at surface of road have picked up under traffic.

The paper helpfully discusses some actions of wheels on a soil-aggregate road which are responsible for the beginnings of potholes. Experience in New York suggests that there may be yet another action which is responsible for the start of many potholes. Figure 3 will help to explain the apparent picking or plucking of fines at the surface of soil-aggregate roads. The surface of many soil-aggregate roads becomes "plastered" with fines during wet weather. A concentration of finer particles at the road surface can result from several actions, but traffic compaction in rainy weather, especially where the soil-aggregate mixture has not previously been fully compacted at a reasonable water content, may contribute to a subsequent pumping of fines to the surface. Such an action cannot be completely controlled by compaction because freezing may slightly "fluff" a soil-aggregate road which has been previously well compacted. Regardless of the cause of a concentration of fines at the road surface, and recognizing that the fines may actually benefit dry-weather road performance, the presence of fines which are adhesive when wet may result in the beginning of potholes.

The section of road shown in Figure 3 had a silt and clay content of about 6 percent in the top 4 in. of the soil-aggregate mixture; the silt and clay content in the top ½ in. was about 14 percent. The photograph illustrates how tires had picked up or plucked out fines from the road surface while the material was at a water content which promoted adhesion. Experience indicated that such depressions quite rapidly developed into potholes. Observations have suggested that picking is more likely to result where fines at the surface overlay a rather clean gravel mixture than where the soil-aggregate mixture has a reasonably high silt and clay content for a depth of several inches.

Huang indicates that the formation of washboards might well be promoted by an excess of binder soil under wet weather conditions. Experience in New York suggests that, while potholing is a wet weather disease often encouraged by the action of binder soil, washboarding is largely a dry weather occurrence which is more likely to develop with too little than too much binder soil. It seems that washboarding is promoted by the liberation of granular material which may be displaced by moving traffic and that liberation during dry weather is likely to be hastened by a scarcity of cohesive binder soil.

Although it is understandable that angular aggregates are less likely to be displaced into corrugations or washboards than are rounded aggregates, it is not readily understandable why an excess of binder material would be a major cause of washboarding. It seems that washboarding is very seldom observed on earth (cohesive soil) roads and seldom on roads built with "packing" gravels if such materials have been treated with a palliative to reduce dusting and subsequent raveling. Bank-run materials used for gravel roads in central New York usually contain more than 10 percent minus No. 200 material and classic examples of washboarding are quite difficult to find.

Huang, in indicating that both pothole and washboard formation were associated with width of road surface, explains that wider surfaces were also associated with higher traffic volumes. Perhaps, too, higher vehicle speeds were associated with greater widths of road and had an effect on road performance, especially the washboarding.

CLOSURE, EUGENE Y. HUANG— The purpose of this paper was to present the results of a study aimed at determining some of the circumstances associated with the occurrence of potholes and washboards on soil-aggregate roads. Although associations between certain road circumstances and these formations are indicated by the chi-square test, there is indeed no evidence in the results that these associations are causal relationships. It must be noted, therefore, that any interpretation in the discussion of the results implying a cause-effect relationship between the associated variables was based upon the author's observation and knowledge of the roads investigated. Since the findings are limited to a certain extent to the types and conditions of the roads studied, the author appreciates the comments made by Mr. Spencer, which apparently came from his experience in this type of road construction, regarding a particular traffic action responsible for the start of many potholes and the phenomenon of washboards on roads in New York State.

With reference to Table 5, the author agrees that "there appears to be little if any difference between expected and observed frequencies" for roads with an average daily traffic exceeding 50 vehicles. However, the scope of the present investigation using a chi-square test was insufficient to indicate an independence between traffic and pothole formation. Consequently, a general statement was made that "road sections with a smaller volume of traffic appear to have less pothole problems than those with a larger volume of traffic." It would be interesting to extend the present investigation further in order to prove the definite relationship between traffic and pothole formation with daily traffic exceeding 50 vehicles.

Regarding the phenomenon of washboards and the type of material on which washboards form, many theories have been advanced. None of these theories have yet been adequately confirmed. The author agrees that a certain amount of "washboarding is promoted by the liberation of granular material which may be displaced by moving traffic and that liberation during dry weather is likely to be hastened by a scarcity of cohesive binder soil." Indeed many road engineers in tropical desert countries have reported the seriousness of these formations, particularly during dry seasons. However, the phenomenon of washboards on different types of materials has also been reported by engineers in other parts of the world. This nuisance is by no means peculiar to a certain kind or condition of material under a given climatic condition. Insofar as the author's observation is concerned, washboarding is ineluctable as long as the road material lacks a sufficient over-all mechanical stability to resist the kick-back or squeezing actions of moving wheels. Thus formations may occur on a material deficient in binder soil in dry weather, as well as on a material with excess binder under adverse moisture conditions such as that shown in Figure 2. The latter case appears similar to the washboard formations commonly observed on bituminous roads where a more or less soft surface material shapes itself into rhythmic undulations under the influence of traffic.

Spencer's suggestion concerning the possible association between vehicle speeds and widths of road and the effect of vehicle speed on road performance is helpful. Unfortunately, no observations are available from this investigation that could confirm this relationship.

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