ROAD ROUGHNESS MEASUREMENTS OF VIRGINIA PAVEMENTS

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SYNOPSIS

Road roughness measurements on five types of pavement included in 73 projects and totaling over 376 miles are reported. The purpose of the study was to obtain data on riding qualities of recently constructed pavements that could be used in evaluating design policies and construction practices.

A "Road Roughness Indicator" designed by the Public Roads Administration and constructed by the Virginia Department of Highways was used for these tests. This machine is a single wheel semi-trailer designed as a horizontal pendulum with the axle of the wheel placed at the center of percussion. An electric counter was used to record roughness measurements in inches per mile. A similar counter recorded revolutions of the trailer wheel. Tests were made at the speed of 20 mph. in the direction of traffic. The trailer wheel was run in the center of the traffic lane being tested. Roughness measurements were recorded for each one-half mile and at the end of the project.

Tests were conducted principally on high-type pavements on primary roads. Portland cement concrete, bituminous concrete, water-bound macadam, traffic-bound macadam and penetration macadam surfaces were tested. Projects tested varied from 0.94 to 23 miles in length. Test sections were selected to permit an evaluation of the riding qualities of the different design characteristics of the five types of surface. Tests were conducted on two, three, and four-lane pavements with traffic counts (24-hr. basis) ranging from 94 to 6566 vehicles.

Road roughness measurements ranged from a maximum of 272 for water-bound macadam to a minimum of 62 for bituminous concrete with an average of 156 in. per mi. for all projects tested. The average for each type ranged as follows: bituminous concrete 86, portland cement concrete 112, water-bound macadam 193 and penetration macadam 200 in. per mi.

There was very little difference in the riding qualities of belt-finished and broom-finished portland cement concrete or in bituminous concrete surfaces having a wide range in texture. However, in the macadam surfaces the testure of the surface treatment influenced the riding qualities of the pavement considerably. Mixed-in-place surface treatment provided a much better riding surface than plain surface treatment.

The Road Roughness Indicator was found to be a quick, dependable method of measuring riding qualities of pavement surfaces. Many check tests proved that reproducible results can be obtained with the device. The following possible uses for the machine are suggested: (1) for research studies of pavement design and performance; (2) for fostering a competitive spirit between engineers and between contractors; (3) for acceptance of new projects; (4) for determination of resurfacing and reconstruction needs; and (5) for use in conjunction with studies of motor vehicle operation.

From the time when man first began to travel from one place to another, "road roughness" has been a factor in the safety and comfort of the traveler. Guillies, rocks and fallen trees were obstacles to be overcome by the man traveling on foot before primitive roads were in use. With the coming of the wheeled vehicle, the wheels cut ruts and produced chuck holes which became mudholes during wet weather. Carts and wagons required much better roads than either the man on foot or on horseback. Likewise, with the coming of the automobile, with its greater speeds, smoother roads were needed. The development of the automobile from the early rugged models such as the Model-T Ford to the present design with the accompanying increase in weight and speed and a decrease in axle clearance made it necessary to change standards of design to meet the new conditions.

Since comfort and safety depend on a smooth riding surface, engineers have made a concerted effort to obtain smoother pavements and have made considerable progress. Equipment manufacturers have spent large amounts of time and money developing equipment to eliminate some of the irregularities incident to hand construction methods.

For many years roughness of a surface was measured by eye or with a straightedge. Visual measurements could not be recorded and were subject to the variation in opinions of different observers. Measurements with a straightedge were satisfactory for short sections, but were slow and not adapted to use for a relatively rapid survey of a considerable mileage of pavement. It was because of the need for a method of measuring and recording the roughness of a surface in a reasonable length of time that various machines have been developed for this purpose. One of the pioneers in the development of these machines was the U. S. Bureau of Public Roads, now the Public Roads Administration.

One of the earliest machines developed for this purpose was the "Profilometer" developed about 1923, by the U. S. Bureau of Public Roads and Illinois Division of Highways (*1*)[1] for use in the Bates Test Road. Several modifications of this machine have been constructed and used. While this machine was satisfactory for short sections it could not be operated rapidly over a large mileage of road. The results which were recorded on a graph were rather voluminous making their interpretation rather slow and complicated.

A second machine, developed in 1926 by the U. S. Bureau of Public Roads, the "Relative Roughness Determinator" (*2*) was a radical change from the profilometer. It consisted of a mechanical counter and mechanism to measure the spring deflections of an automobile. This machine could be used to measure rapidly the relative roughness of road surfaces in inches per mile. While this machine gave fairly good results, the variation in automobiles on which the machine was used made it difficult to compare pavements tested with different vehicles.

The "Dana Automatic Recording Roughometer" (*3*) was developed by the Engineering Experiment Station, State College of Washington, about 1932. A pantograph system attached to the front wheel of an automobile transmitted road roughness measurements to a record paper in the form of a graph. An automatic stamping device printed the mileage and the integrated roughness every half mile or oftener as required. This mechanism was also subject to the criticism that results obtained with different automobiles were difficult to compare.

The above machines were used by several states with varying degrees of success. While they were not entirely satisfactory, they were of great value in bringing to the attention of engineers and contractors the need for a machine to compare riding qualities of road surfaces.

DESCRIPTION OF EQUIPMENT AND TEST PROCEDURE

In an attempt to overcome the bad features of existing machines the Public Roads Administration constructed the "Road Roughness Indicator" which was described in a paper presented to the Highway Research Board (*4*) in 1940 and later published in *Public Roads* (*5*). This machine is a single wheel trailer which is towed by a car or light truck (Fig. 1). It operates as a horizontal pendulum in dynamic balance so that it is not materially affected by the towing vehicle. Spring deflections are accumulated by a double acting ball clutch (integrator) and transmitted electrically to a recorder carried in the towing vehicle. Wheel revolutions are recorded in the same manner so that distances can be measured accurately and when used with a stop watch the speed of the machine can be closely controlled. Damping pots were provided to control spring oscillation so that results would not be influenced by excessive oscillation of the spring-weight system of the trailer.

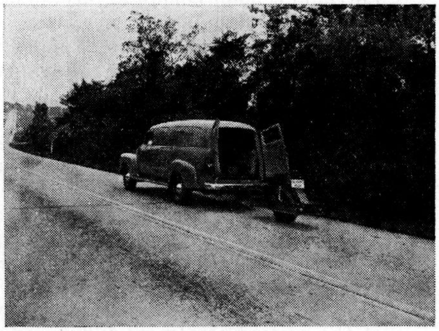

Figure 1. Road Roughness Indicator and Towing Vehicle Used in Road Roughness Tests

[1] Italicized figures in parenthesis refer to the list of references at the end of the paper.

After considerable experimental work the Public Roads Administration developed a procedure for operating the Road Roughness Indicator. Both air and dash-pot fluid temperatures are recorded at the beginning and end of a test. The fluid must be kept at the proper level, the tires must be maintained to a pressure of 30 ± 0.5 lb. and the towing vehicle operated at a constant speed of 20 mph. Variations in tire pressure, speed or fluid level in the dash-pots cause variations in results obtained.

The Road Roughness Indicator (Fig. 2) used in the tests described herein was built and each component carefully checked by the

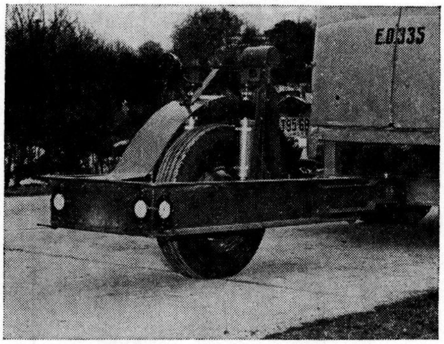

Figure 2. Close-up View of Road Roughness Indicator

TABLE 1
DETERMINATION OF NUMBER OF WHEEL REVOLUTIONS PER MILE

Run No.	1	2	3	4	5	6	Avg.
No. Wheel Revs.	740	739	740	740	740	740	740

Virginia Department of Highways from plans furnished by the Public Roads Administration. Loading deflection tests were made on each of the springs in the trailer assembly. The trailer was tested to determine the weight necessary to place the axle at the center of percussion. The integrator was calibrated over a wide range of amplitudes and the dash-pot fluid was tested to assure that its viscosity was within the range specified. While this machine was carefully constructed and checked, there is a possibility that measurements made with it will not check exactly with measurements made with another machine constructed from the same plans.

Before tests were started the speedometer of the towing vehicle was calibrated over a measured mile to determine its accuracy at 20 mph. The wheel of the trailer was then calibrated to determine the number of wheel revolutions in a measured mile (Table 1).

A further test to determine the accuracy of the machine consisted of repeat tests made over a 2-mile section of concrete pavement. Results of these tests and similar tests over a period of about one year are shown in Table 2.

All tests were run at 20 mph. in the direction of traffic with the trailer wheel in the center of the traffic lane. On three-lane roads only the outside lanes were tested except where a traffic officer was available to direct traffic during tests in the center lane. On other than three-lane roads, all lanes were tested with occasional repeat tests to check the accuracy of the integrator.

TABLE 2
CHECK TESTS ON STANDARD TWO-MILE SECTION

Date of Tests	No. of Tests	Roughness Measurements		
		Avg.	Max.	Min.
1947		*in. per mi.*		
Sep. 2	6	99.7	101.5	96.5
1948				
May 24	5	99.5	101.5	98.0
Jun. 1	1	100.5	100.5	100.5
Jul. 1	3	98.3	99.5	97.5
Jul. 7	2	99.0	99.0	99.0
Sep. 14	3	99.2	99.5	98.5
All Tests	20	99.3	101.5	96.5

DISCUSSION OF TEST DATA

For many years the Virginia Department of Highways has strived to obtain pavements with the best possible riding surfaces. Rigid specifications have been prescribed. Field engineers have given special attention to this item and have made a concerted effort to build into the pavement the qualities demanded by the traveling public. In line with this endeavor this series of tests was started to obtain factual data on the riding qualities of various types of pavements.

The measurements included in this report were started in May, 1948 and completed in September, 1948. Only two drivers were used on this work and all readings were recorded by the writer. For convenience of the reader, the projects tested are shown on a map by their location number (Fig. 3).

The majority of the projects reported are recently constructed projects on which information was desired by the Construction Engineer. Other projects were requested by the district engineers or were tested in order to supply information on types of pavement or pavement surfaces that had been in service for a much longer time. Some projects which had not been completed were included in order to obtain information on a particular type of surface.

Portland cement concrete, bituminous concrete, water-bound macadam, traffic-bound macadam and penetration macadam pavements were tested. Variations in the composition or finish of the above types are shown in the tabulation of data. In making this tabulation an attempt was made to study results of various factors, affecting riding qualities, such as differences in surface texture or the effect of traffic on the inside and outside lanes of multiple-lane roads.

It will be noted from Figure 5 that the projects tested are distributed over the entire State. Most of the concrete pavements are in the eastern part of the State where natural sand is abundant and the majority of the macadam surfaces are in the central or western part of the State where stone is more readily available.

The test data including the average 24-hr. traffic count has been tabulated for each type of pavement surface. The values for roughness measurements are shown in inches per mile for one-half mile intervals. In tabulating the maximum and minimum values, only those for one-half mile were used. Values for small fractions of a mile often appeared to be exaggerated as they were much higher or lower than the adjoining one-half mile. A summary of test results with maximum, minimum and average values for each type of surface tested was prepared to facilitate comparison of suraces by types.

The results of tests on 23 portland cement concrete pavement projects are shown in Table 3. The majority of these projects were constructed from 1942 to 1948 with transverse joints. One project with joints was constructed in 1935 and one project without joints in 1931. Traffic on these roads varies from 1022 vehicles per day to 6030 vehicles per day and averages 3184 for all concrete pavement tested.

Roughness measurements for belt-finished concrete averaged 113 with a maximum of 158 and a minimum of 88 in. per mi.[2] Broom-finished concrete (Fig. 4) averaged 109 with a maximum of 148 and a minimum of 82. While belt-finished concrete averaged slightly higher than broom-finished concrete, it will be noted that all of the older pavements were belt-finished and only the newer surfaces broom-finished. For all portland cement con-

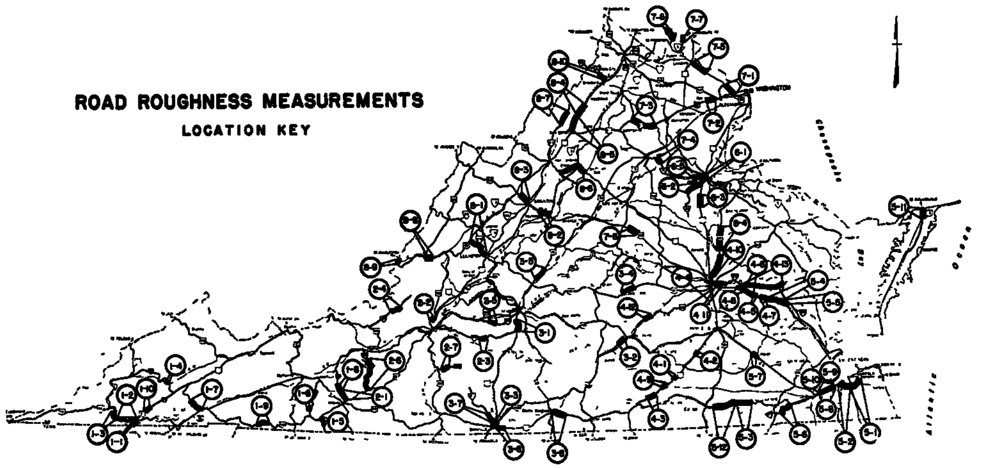

Figure 3

[2] All road roughness measurements are in inches per mile.

TABLE 3
ROAD ROUGHNESS TESTS
PORTLAND CEMENT CONCRETE SURFACES

Location No.	Rt.	Project	Designed Slab Length	Type of Finish	Date Comp.	Lanes Tested	Length Tested	Roughness Measurements			Avg [a] 24-Hr. Traffic Count	Remarks
								Avg	Max	Min		
			ft.				*mi*	*in. per mi.*				
4-1	1	420 CW3 455 AW2, B2	30	Belt	1947	2-O[b]	1.36	111	114	102	2279	Considerable settlement at bridge
						2-I[b]		114	124	106		Considerable settlement at bridge
4-2	1	420 BW2, B3	30	Belt	1947	2-O	1.32	106	110	100	2279	Considerable settlement at bridge
						2-I		111	118	110		Considerable settlement at bridge
4-3	1	467-AW3R, B1R, BW3R, B3	30	Belt	1947	2-O	2.73	122	132	106	2354	Three bridges
						2-I		129	136	120		Three bridges
5-1	13	1284 A1	30	Belt	1943	2-O	5.55	118	148	102	5152	Three bridges
						2-I		116	138	106		Three bridges
5-2	13	1284-A2	20	Belt	1943	2-O	1 71	130	140	124	5152	No tie bars or dowels
						2-I		118	128	112		No tie bars or dowels
3-1	29	134 AR2, B2, BR1	30	Belt	1948	2	4.78	104	110	98	2126	
4-4	33	1069 M1, AW1, CW1	30	Belt	1946	2-O	3.50	95	106	88	6030	One bridge inside lanes bit-conc
5-3	58	429 AR1, M1	30	Belt	1946	2	5.12	112	132	98	1022	Two bridges
5-4	60	1425 AW1, 157 AW1, BW1	30	Belt	1946	2-O	4 40	119	138	100	2802	One bridge
						2-I		126	146	104		One bridge
4-5	60	157-BR1, 257-R4	30	Belt	1947	2-O	2.50	95	98	92	3022	One bridge One RR grade cross.
						2-I		91	96	88		One bridge One RR grade cross.
4-6	60	257 R3	30	Belt	1946	2-O	4.98	102	114	94	3241	Two bridges
						2-I		103	116	92		Two bridges
5-5	168 Y	1425-A	30	Belt	1944	2	1.18	108	116	102	1177	Loose gravel on surface at int.
5-6	189	1001 AR1	20, 25, 30	Belt	1946	2	4 90	127	143	106	1667	Variable joint spacing
5-7	460	626 MW5, EW2, FW	30	Belt	1946	2-O	1 94	109	120	96	2927	Inside lanes are S T soil
5-8	460	657-E1	None	Belt	1931	2-I	6.90	131	158	106	5442	Considerable bit. patching
5-9	460	657-EW1, EW2	50	Belt	1935	1-O	6.90	119	130	96	5442	E.B Lane
5-10	460	657 EW4	30	Belt	1942	1-O	6.90	108	114	100	5442	W B. Lane
All Projects—Belt Finished Concrete							66.67	113	158	88		

TABLE 3—*Continued*

Location No.	Rt.	Project	Designed Slab Length	Type of Finish	Date Comp.	Lanes Tested	Length Tested	Roughness Measurements Avg.	Max.	Min	Avg.[a] 24-Hr Traffic Count	Remarks
			ft.				*mi.*	*in. per mi.*				
6-1	1 Atl.	1235-A, C3, 2, CIS	20, 25 30, 40	Broom	1945 1946	2-O	4.13	115	132	102	4305	Three bridges. Variable joint spacing
						2-I		108	118	94		Three bridges. Variable joint spacing
5-11	13	280-CW1, DW1	30	Broom	1948	2-O	3.36	109	132	98	3224	
						2-I		115	124	106		
5-12	58	429-CR1, M2, C1	30	Broom	1948	2	8.50	99	114	82	1022	Two bridges
4-7	60	FI-157-BW3	30	Broom	1948	2-O	3.17	107	120	98	2802	
						2-I		111	118	106		
4-8	60	FI-257-R1, 2, 395 R1, B2	30	Broom	1948	2-O	4.15	102	116	94	3241	
						2-I		106	124	98		Small amount of gravel on surface at one int.
3-2	360	285 A2, R1, 644 DR1	30	Broom	1947	2	4.63	119	148	100	1080	
All Projects—Broom Finished Concrete							27 94	109	148	82		
SUMMARY												
All Portland Cement Concrete							94.61	112	158	82		
Outside Lanes of Multiple-Lane Roads							58.60	110	148	88		
Inside Lanes of Multiple-Lane Roads							46.26	114	158	88		

[a] Average 24-hour traffic count for year ending June 30, 1948.
[b] O = Outside Lane.
I = Inside Lane.

Figure 4. Broom-Finished Portland Cement Concrete—Rt. Alt. 1, Location No. 6-1, Spotsylvania County—Average Road Roughness Measurements 111 in. per mi.

crete surfaces tested the average roughness measurement was 112. Outside lanes of multiple-lane roads averaged 110 and inside lanes 114.

Table 4 shows the results of tests on 23 bituminous concrete projects which total 163.34 miles. Three of these projects were constructed from 1940 to 1944 with the remainder constructed from 1946 to 1948. They are grouped according to the type of mix in the surface course. Type F-1 (sand asphalt) has the finest texture, Type I-3 a slightly coarser texture and Type H-2 the coarsest texture. The special mixes contain local sand or stone not meeting the grading requirements of the regular mixes. These surfaces were constructed on varied types of bases such as portland cement concrete, macadam, soil-cement and surface treated soils. The average 24-hr. traffic count for all bituminous concrete surfaces ranges from a maximum of 6566 to a minimum of 833 and averages 2766 vehicles.

The roughness measurements for Type F-1 surfaces (Fig. 5) averaged 89 with a maxi-

TABLE 4
ROAD ROUGHNESS TESTS
BITUMINOUS CONCRETE SURFACES

Location No.	Rt	Project or Schedule	Type Mix	Type of Base	Date Comp.	Lanes Tested	Length Tested	Roughness Measurements Avg.	Max.	Min.	Avg[a] 24-Hr Traffic Count	Remarks
							mi.	in. per mi.				
4-9	1	42-47	F-1	Concrete	1947	2	3.31	80	88	70	2961	O H. Bridge 1 base failure
4-10	2	43-47	F-1	S.T Soil	1947	2	10.00	77	86	70	2100	Five bridges
7-1	7	70-47	F-1	Macadam	1947	2-O[b]	2.79	110	126	86	6566	
						1-I[b]		107	116	100		3 Lane pavement
3-3	29 Alt	30-47	F-1	Macadam	1947	2-O	3.50	75	86	66	2388	Inside lane not tested
7-2	29-211	8	F-1	Old P M. on Conc.	1946	1-O	5.00	99	116	84	6537	W.B. Lanes not tested
						1-I		88	104	84		
4-11	33	S1069, M1, AW1, CW1	F-1	Macadam	1947	2-I	3.51	97	106	90	6030	One bridge Outside land conc.
6-2	51	12	F-1	Concrete	1946	2	6 40	95	104	88	833	Considerable roughness due to base movement
3-4	60	746-HS1, IS1	F-1	Soil-Cement	1947	2	7.80	72	78	64	1390	
4-12	360	45-47	F-1	Macadam	1947	2	3.50	76	84	72	2229	Two bridges
All Projects—F-1 Bituminous Concrete.							45.81	89	126	64	3448	
6-3	1	60-48	I-3	Concrete	1948	2-O	4.58	83	96	78	4643	
						2-I		82	87	76		
1-1	23	10-47	I-3	Macadam	1947	2-O	2.65	86	94	76	3433	One bridge 3 Lane pavement
8-1	60	81-47	I-3	Macadam	1947	2	10.50	87	112	74	1420	Two bridges
7-3	211	71-47	I-3	Macadam	1947	2	13 00	78	88	68	1440	
8-2	250	80-48	I-3	Macadam	1948	2-O	4.35	74	82	66	4427	3 Lane pavement
8-3	250	80-47	I-3	Macadam	1947	2	6 50	73	94	62	1639	Four bridges
All Projects—I-3 Bituminous Concrete...							41.58	80	112	62	2837	
6-4	2	14-44	H-2	S.T. Soil	1944	2	8 30	77	84	68	1988	One bridge
8-4	11	81-48	H-2	Macadam	1948	2-O	9.00	95	108	82	2881	3 Lane pavement
8-5	11	81-48	H-2	Macadam	1948	2-O	6.37	91	100	82	2395	3 Lane pavement One bridge
8-6	33	80-48	H-2	Macadam	1948	2	13.13	95	114	80	1337	One bridge—One RR grade crossing
1-2	58	10-47	H-2	Macadam	1947	2	8.74	92	104	78	2021	Four RR grade crossings
All Projects—H-2 Bituminous Concrete							45.44	90	114	68		

TABLE 4—*Continued*

Location No.	Rt.	Project or Schedule	Type Mix	Type of Base	Date Comp.	Lanes Tested	Length Tested	Roughness Measurements Avg.	Max.	Min.	Avg.[a] 24-Hr. Traffic Count	Remarks
							mi.	in. per mi.				
6-5	3	Fred. #1	Special	S.T. Grav.	1940	2	3.69	80	88	72	1991	Sand asphalt—local sand
4-13	33	44-97	Special	S.T. Soil	1947	2	23.00	87	112	66	1505	Sand asphalt—local sand
1-3	58	Bristol #2	Special	Macadam	1931	2	3.82	116	122	108	1454	Modified binder
All Projects—Special Design Bituminous Concrete.....					30.51	94	122	66				
SUMMARY												
All Bituminous Concrete Projects........							163.34	86	126	62		
Outside Lanes of Multiple-Lane Roads........							38.24	89	126	66		
Inside Lanes of Multiple-Lane Roads........							15.88	93	116	76		

[a] Average 24-hour traffic count for year ending June 30, 1948
[b] O = Outline Lane.
I = Inside Lane.

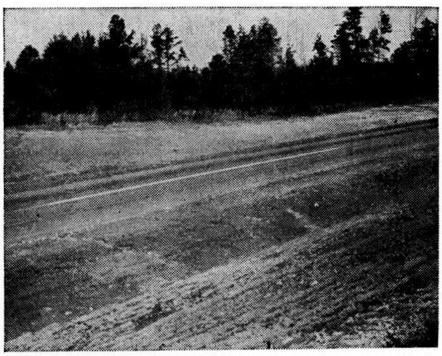

Figure 5. Type F-1 (sand asphalt) Bituminous Concrete Surface—Rt. 60, Location No. 3-4, Cumberland County—Average measurement for this project was 72 in. per mi.

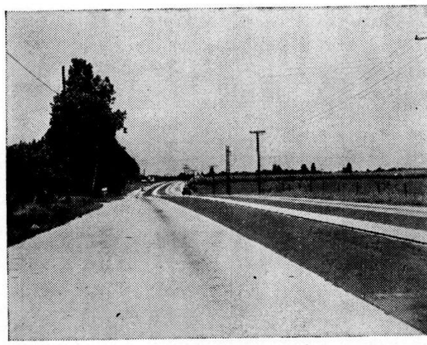

Figure 6. Dual-Type Surface on Rt. 33 in Henrico County—Outside lanes are portland cement concrete (Avg. roughness measurement 95 in. per mi.). Inside lanes are type F-1 bituminous concrete on a water-bound macadam base (Avg. roughness measurement 97 in. per mi.).

mum of 126 and a minimum of 64. An average of 80 with a maximum of 112 and a minimum of 62 was measured for the I-3 mixes. Type H-2 surfaces have an average of 90, maximum of 114 and minimum of 68. It is interesting to note that the smoothest of the H-2 surfaces (average 77) is the oldest and was constructed on a surface treated soil base. The fourth group, special mixes, averaged 94 with a maximum of 122 and a minimum of 66. Two of the three projects in this group were constructed in 1940 and 1941. The average of all bituminous concrete surfaces is 86. Outside lanes on multiple-lane pavements were again slightly lower than inside lanes with an average of 89 as compared to 93 for inside lanes. This may be partly accounted for by the fact that on most three-lane roads only the outside lanes were tested. It is significant that the I-3 surfaces were smoother than the finer textured F-1 surfaces. This may be due to the greater stability of the coarser I-3 mix and to the larger volume of traffic on the F-1 surfaces. Figure 6 shows a dual-type pavement with F-1 bituminous concrete on the inside lanes and portland cement concrete on the outside lanes.

TABLE 5
ROAD ROUGHNESS TESTS
WATER-BOUND MACADAM

Location No.	Rt	Project	Type of Surf Treat.	Date Comp	Lanes Tested	Length Tested	Roughness Measurements Avg.	Max	Min.	Avg[a] 24-Hr. Traffic Count	Remarks
						mi.	in. per mi.				
7-4	3	185-AR2, 755-A	Plain	1947	2	4.64	222	246	194	550	
7-5	7	S-514-ERI, FB3	Plain	1947	2	5.77	199	252	176	2102	One bridge
3-5	29	384-AS1, B1R, A2, B2	Plain	1947	2	8.98	227	258	186	1591	Two bridges
8-7	42	1169 - D2, B2, M1E	Plain	1948	2	4.60	225	270	180	188	Proj tested in two sections — One bridge
3-6	58	752-GR1, M2, B9	Plain	1947	2-O[b]	2.25	203	245	174	3630	One bridge
					2-I[b]		203	235	174		
8-8	60	S-189 F2, R2, B3, B2	Plain	1948	2-O	2 59	208	240	190	3209	One bridge
					2-I		213	222	202		
8-9	60	393-A1, 1384-GB5	Plain	1947	2	1 96	213	231	186	1306	One bridge
1-4	70	S-94-BR3	Plain	1948	2	2.24	245	268	226	922	
1-5	89	S-1275-M1, A2, B1, 2	Plain	1948	2	2.35	192	220	164	2958	Two bridges
1-6	94	S-665-H1, M3	Plain	1947	2	4 33	157	178	142	1077	
2-1	100	F-754-F	Plain	1947	2	6.95	202	226	172	743	One bridge
7-6	275	S-1377-F, B2	Plain	1947	2	4 15	200	272	160	178	One bridge
7-7	287	S-1171-D, B5	Plain	1947	2	1.66	211	246	190	782	One bridge
All Projects—Plain Surface Treatment						52.47	208	272	142		
2-2	11	S-640-CR2, B2, R	Mixed-in-Place	1947	2-O	0.94	137	152	126	4590	
					2-I		130	143	105		
1-7	19	S-518-AS1, B1, DS1	Mixed-in-Place	1948	2	5 68	138	160	106	1839	Four bridges
3-7	41	1023-D	Broom Drag	1948	2	2.99	192	239	164	1907	Project tested in two sections
3-8	58	587-AR1, B1R, AR2	Mixed-in-Place	1948	2	4 35	190	208	166	1664	Two bridges
1-8	100	754-DS1, E1S1, E2S1	Mixed-in-Place	1947	2	5 15	152	166	142	743	Two bridges
All Projects Mixed-in Place Surface Treatment . .						19.11	157	239	105		

SUMMARY

All Water-bound Macadam Surfaces . .	71.58	193	272	105		

[a] Average 24-hour traffic count for year ending June 30, 1948.
[b] O = Outside Lanes.
I = Inside Lanes.

The results of tests on 18 water-bound macadam projects, shown in Table 5, are grouped according to the type of surface treatment. These projects totaling 71.58 mi. were all constructed in 1947 and 1948. While many projects carry heavy traffic, the traffic is not nearly as heavy as that carried by either the portland cement or bituminous concrete surfaces. The average 24-hr. count varies from a maximum of 4590 to a minimum of 178 and averages 1666 vehicles.

For water-bound macadam projects with plain surface treatment, the roughness measurements average 208 with a maximum of 272 and a minimum of 142. The average for projects with mixed-in-place surface treatment is 157 with a maximum of 239 and a minimum of 105. The average for all macadam surfaces is 193. It will be noted that the average measurement for plain surface treatment is 66 percent higher than for the mixed-in-place surface treatment. This is a very wide difference which is quickly noted by the traveling public. It is due principally to the difference in methods of constructing the two types. Plain surface treatment has a much harsher texture than the mixed-in-place treatment. Also, the method of placing the mixed-in-place surface treatment tends to smooth out the high and fill in the low places while the plain treatment does not have this leveling effect. In a mixed-in-place surface treatment the aggregate is better coated and this thicker surface is not as susceptible to raveling under traffic as the plain surface treatment.

Five of the six traffic-bound macadam projects tested (Table 6) were parts of uncompleted projects, the sixth one having been completed in 1948. They are relatively short sections several of which were tested in two parts. All of these projects with a total length of 15.88 miles had a plain surface treatment which had been subjected to only light traffic. The average 24-hr. traffic count varies from a maximum of 781 to a minimum of 136 with an average of 408 vehicles.

TABLE 6
ROAD ROUGHNESS TESTS
TRAFFIC-BOUND MACADAM

Location No.	Rt.	Project	Type of Surf. Treat.	Date Comp.	Lanes Tested	Length Tested	Roughness Measurements			Avg[a] 24-Hr Traffic Count	Remarks
							Avg.	Max.	Min.		
						mi.	*in. per mi.*				
2-3	24	S-1460-A	Plain	Not[b] Comp.	2	1.75	166	180	156	136	Considerable loose stone on surface
2-4	42	S-1166-F	Plain	Not Comp.	2	1.59	227	246	210	150	Surface treatment was prime only
8-10	55	S-1219-E1 E2	Plain	Not Comp.	2	1.10	117	126	110	201	W. B. Macadam topped with 3 in. of 1-in. down crusher run
1-9	58	S-1409-A	Plain	Not Comp.	2	6.84	214	250	186	584	Considerable loose stone on surface
1-10	71	S-1196-C, D, E	Plain	Not Comp.	2	2.73	220	246	188	781	Project tested in two sections
2-5	297	S-1323-H5 H6, H3 Ext.	Plain	1948	2	1.87	206	224	192	593	Project tested in two sections
All Projects Traffic Bound Macadam						15.88	192	250	110	408	

[a] Average 24-hour traffic count for year ending June 30, 1948.
[b] Projects shown as not completed were under construction and only parts that had been surface treated were tested.

The roughness measurements for traffic-bound macadam surfaces averaged 192 with a maximum of 250 and a minimum of 110. These results are slightly lower than the 208 for water-bound macadam with a plain surface treatment. It is interesting to note that if one project averaging 117 (very low for this type of surface) were eliminated the remaining projects would average 207 just one point below the average for water-bound macadam with a plain surface treatment. However, the maximum and minimum are much lower for traffic-bound macadam than for water-bound macadam.

Three penetration macadam surfaces (Table 7) totaling 31.12 miles were tested. One project completed in 1946 carries 1190 vehicles per day while the remaining projects carry 129 and 94 vehicles respectively with an average 24-hr. traffic count of 471 for all projects. The 1946 project has a soil-cement base. The other projects are constructed on granular stabilized bases.

Roughness measurements on penetration macadam surfaces averaged 200 with a maximum of 258 and a minimum of 148. The oldest project which also carried the most traffic was the smoothest of the three. However, one of the remaining projects had nine bridges which contributed to its roughness and the other had just been sealed with the result that the surface texture was very harsh.

Penetration macadam with the highest average roughness has the third highest range (110 in. per mi.) which may be attributed to the method of construction. Traffic-bound macadam with a range of 140 was next to the highest and water-bound macadam the highest with a range from maximum to minimum of 167 in. per mi. However, if only water-bound macadam with plain surface treatment is considered, the range is 130 in. per mi. which is close to the range for traffic-bound macadam.

The roughness measurements of each type of surface are affected by many factors. Common to all types of surfaces are the effects of subgrade or base support, workmanship, age, amount of traffic, number of bridges and the amount and condition of patches. Workmanship determines whether a surface will be constructed to the standards specified in the design as necessary for a smooth riding

TABLE 7
ROAD ROUGHNESS TESTS
PENETRATION MACADAM SURFACE

Location No.	Rt.	Project	Type of Base	Date Comp.	Lanes Tested	Length Tested	Roughness Measurements			Avg.[a] 24-Hr. Traffic Count	Remarks
							Avg.	Max.	Min.		
						mi.	*in. per mi.*				
2-6	102	S-1270-AC	Stabilized Soil	1948	2	18.60	205	228	168	129	Nine bridges on project
7-8	250	FI-565 HS1 IS1	Soil-Cement	1946	2	7.39	171	200	148	1190	Some base failure
2-7	674	1320-P	Stabilized Soil	1948	2	5.13	223	258	196	94	Some loose stone on surface
All Projects						31.12	200	258	148	471	

[a] Average 24-hour traffic count for year ending June 30, 1948.

A summary of test data is shown in Table 8 and presented graphically in Figure 7. It will be noted that of the five pavement types tested, bituminous concrete is the smoothest with an average of 86 and portland cement concrete is slightly higher with an average of 112. The averages of all projects for each of the other types are rather close with an average of 193 for water-bound macadam, an average of 192 for traffic-bound macadam and an average of 200 in. per mi. for penetration macadam.

It is interesting to note the range between maximum and minimum of each of the surfaces types. Bituminous concrete which has the lowest average roughness also has the lowest range (64 in. per mi.) between maximum and minimum. The next lowest range (76 in. per mi.) is for portland cement concrete which has next to the lowest average roughness.

TABLE 8
ROAD ROUGHNESS TESTS
SUMMARY OF RESULTS

Type of Pavement	Length Tested	Roughness Measurements			Avg. of 24-Hr. Traffic Counts	No. of Projects Tested
		Avg.	Max.	Min.		
	mi.	*in. per mi.*				
Portland Cement Concrete	94.61	112	158	82	3184	23
Bituminous Concrete	163.34	86	126	62	2766	23
Water Bound Macadam	71.58	193	272	105	1666	18
Traffic Bound Macadam	15.88	192	250	110	408	6
Penetration Macadam	31.12	200	258	148	471	3
All Surfaces	376.53	156	272	62		73

surface. There is a progressive, although slow, distortion of a pavement surface with age. As a pavement gets older the effect of weather causes many defects to appear. The amount of traffic, plus the effect of continuous traffic causes a gradual settling or breaking of the surface. It was found that on multiple-lane roads the roughness of inside and outside lanes varied according to the type of surface, age and amount of traffic. Bridges may be rigid concrete structures that have very little influence on riding qualities or they may be flimsy truss spans with rough floors that cause much higher readings than would otherwise be obtained.

When testing pavement surfaces for riding qualities the problem of evaluating the road roughness measurements presents itself. Since there is little information available on this subject certain ranges of roughness were arbitrarily selected to describe the riding qualities of a surface as excellent, good, fair or rough as shown in Table 9.

It is realized that this classification is subject to debate and that the type of irregularity in the surface and the speed of the car have a very definite effect on the riding qualities of any pavement. However, these proposed standards are in line with the findings of Professor R. A. Moyer (*6*) who after con-

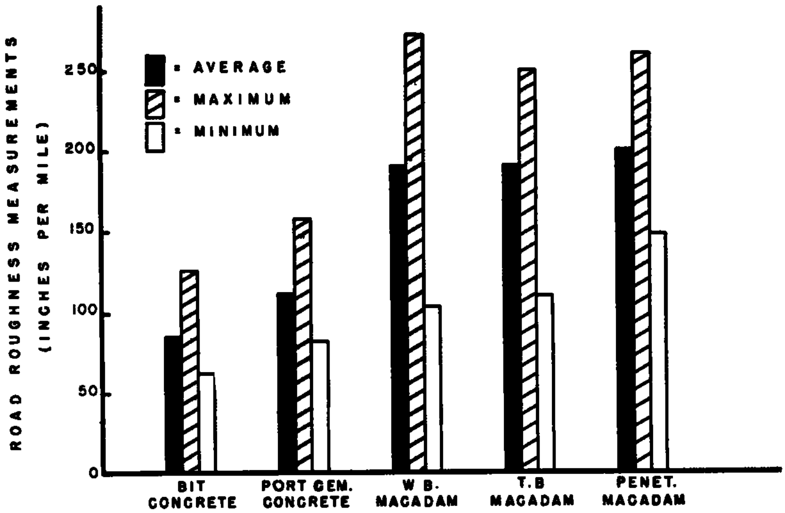

Figure 7. Road Roughness Measurements by Pavement Types

All surfaces have features, not necessarily common to other types, which affect their riding qualities. The roughness measurements of portland cement concrete pavement are influenced by the condition of transverse joints, cracking, scaling, spalling and faulting of slabs. Surface texture of bituminous concrete and the various types of macadam may influence the amount of roughness measured. A coarse textured surface tends to give a slightly higher reading especially where fairly coarse aggregate is used in plain surface treatments or seals. The bituminous concrete and penetration macadam surfaces are relatively thin courses which depend on a base course for support. Any failure of this base would have an adverse effect on the riding qualities of the surface.

TABLE 9
SUGGESTED STANDARDS FOR EVALUATING PAVEMENT SURFACES

Roughness Measurements (In. Per Mi.)	Riding Qualities
Below 100	Excellent
100–150	Good
150–200	Fair
Above 200	Rough

ducting extensive tests stated . . . "the drivers of the test cars and the writer have agreed that a roughness index of 100 inches per mile or less should be considered as a high standard of surface smoothness, that up to 160 inches per mile should be considered acceptable up to 65 mph., but that values in excess of 200 inches per mile indicated a degree of roughness which was definitely uncomfortable to the driver and observer in the test car at speeds of 35 mph. and higher."

Professor Moyer also found indications that... "with roughness values greater than 200 inches per mile ... the gasoline, oil and tire costs were definitely higher than on the surfaces with roughness values less than 160 inches per mile."

Table 10 shows the evaluation of surfaces by types. It will be noted that all of the portland cement and bituminous concrete surfaces are rated as excellent or good while the water-bound and traffic-bound macadams are rated good, fair or rough with the greatest mileage being in the last two classes. All penetration macadam is classed fair or rough. It should be remembered, however, that the majority of the traffic-bound macadam projects were mostly short sections of incompleted projects and that there were only three penetration macadam projects tested, the results of which were influenced by such features as numerous bridges, base failures, etc.

TABLE 10
EVALUATION OF PAVEMENT SURFACES

Riding Qualities	Mileage by Types					
	P. C. Conc.	Bit. Conc.	W. B. Mac.	T. B. Mac.	Pent. Mac.	All Types
Excellent	14.50	156.73				171.23
Good	80.11	6.61	6.62	1.10		94.44
Fair			24.94	1.75	7.39	34.08
Rough			40.02	13.03	23.73	76.78
Total	94.61	163.34	71.58	15.88	31.12	376.53

When considering the test results it must be borne in mind that these results were obtained with one machine and that they may not be exactly the same as would have been recorded by another machine of the same type. A small amount of checking this machine against another machine indicated that identical readings may not always be possible. However, although maximum and minimum values with the two machines were slightly different, the rating of consecutive sections fell in the same order with each machine.

COMPARISON OF FAULTING AND ROAD ROUGHNESS MEASUREMENTS

A recent performance survey on two adjoining portland cement concrete pavement projects gives a good comparison of the relation between road roughness measurements and faulting of slabs. The two projects selected for this survey are on U. S. Rt. 13, a four-lane divided highway, in Norfolk and Princess Anne Counties. They were constructed by the same contractor in 1943. Drainage is good and topography and soils are uniform throughout the sections surveyed. The average 24-hr. traffic count is 5152 vehicles for each project.

The project shown in Figure 3 at location No. 5-1 was constructed with contraction joints spaced at 30-ft. and expansion joints spaced at 90-ft. intervals. The longitudinal center joint was formed by placing a ribbon in the slab. Wire mesh reinforcing steel, tie bars and dowels were used in this pavement. The section of this project on which the survey was made did not contain any structures.

The adjoining project shown as location No. 5-2 was constructed with contraction joints spaced at 20-ft. and expansion joints at 120-ft. intervals. The longitudinal center joint in this pavement was also formed by placing a ribbon in the slab. Because of the war-time emergency no reinforcing steel, tie bars or dowels were used in this project.

Road roughness measurements were made with the Road Roughness Indicator described above. Faulting at joints was measured with the device shown in Figure 8, which was originated by the Joint Highway Research Project at Purdue University and constructed by employees of the Virginia Department of Highways. On transverse joints measurements were taken one foot from the outer edge and at the center of the slab. Measurements on longitudinal joints were made one foot on each side of the transverse joints.

On the project with reinforcing steel, tie bars and dowels, road roughness measurements average 112 with a maximum of 122 and a minimum of 102 in. per mi. Inside lanes averaged 111 and outside lanes 113 in. per mi. Measurements on the project without reinforcing steel, tie bars and dowels averaged 124 with a maximum of 140 and a minimum of 112 in. per mi. Inside lanes averaged 118 and outside lanes 130 in. per mi. The difference in roughness of these projects, 7 for inside lanes and 17 for outside lanes, shows the effect of increased traffic.

The average faulting at joints on the first project was $\frac{3}{32}$ in. for transverse joints and $\frac{2}{32}$ in. for longidutinal joints. For the second project (no reinforcing, tie bars or dowels) the faulting was $\frac{6}{32}$ in. at transverse joints and $\frac{4}{32}$ in. at longitudinal joints. Since faulting of transverse joints was measured on the outside lanes only, no comparison between lanes can be made.

A comparison between faulting at transverse joints and road roughness measurements is shown in Figure 9. It will be noted there is a very definite increase in road roughness as faulting at joints increases. However, the ratio of faulting to road roughness is not constant since the degree of road roughness is affected by many other factors.

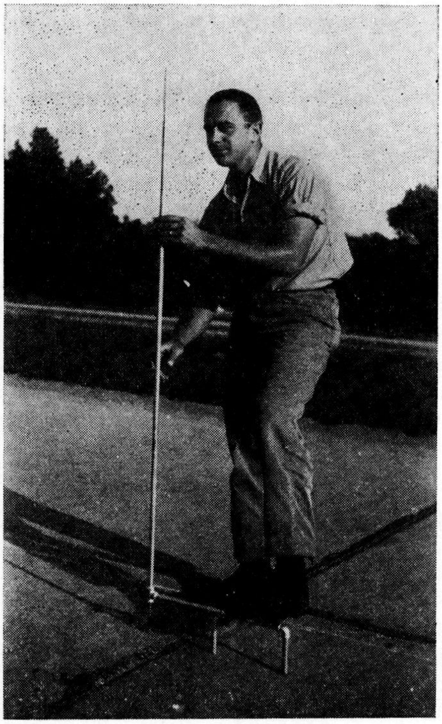

Figure 8. Measuring Faulting at Joints—The rod inside of the pipe is free to move and the zero point has been set with the bottom of the rod in a plane with the two fixed legs.

SUMMARY AND RESULTS

The more important results of the road roughness measurements on five types of pavement (73 projects) totaling over 376 miles are summarized as follows:

1. The Road Roughness Indicator is a convenient, satisfactory and rapid means of evaluating riding qualities of a pavement surface.

2. Test results can be recorded in a form convenient for study or comparison of two or more projects.

3. Repeat tests with the Road Roughness Indicator give results that check closely considering the effect of temperature and the inability of the driver to follow in exactly the same path on each run.

4. Riding qualities of all pavements and therefore road roughness measurements are affected by such factors as workmanship during construction, pavement age, amount and type of traffic, number of bridges and the number and condition of patches.

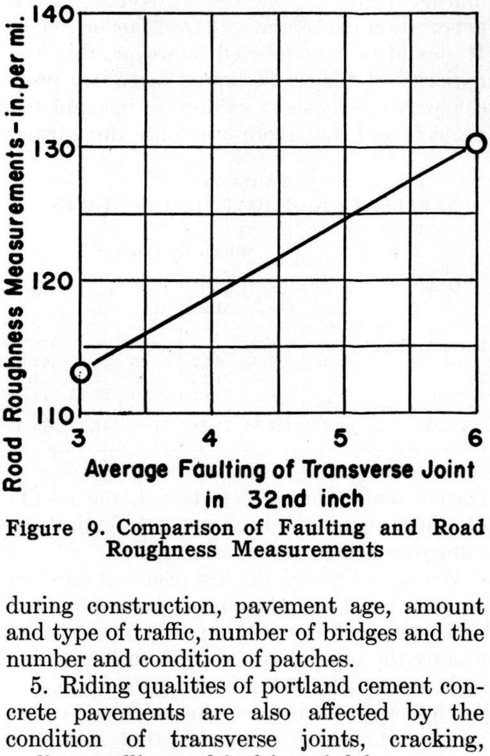

Figure 9. Comparison of Faulting and Road Roughness Measurements

5. Riding qualities of portland cement concrete pavements are also affected by the condition of transverse joints, cracking, scaling, spalling and faulting of slabs.

6. Riding qualities of any relatively thin surface course such as bituminous concrete and penetration macadam are influenced by the stability of the base.

7. Texture of bituminous surfaces has a considerable bearing on road roughness measurements. This is especially pronounced where a harsh texture results from the use of the coarse aggregates in plain surface treatment.

8. Bituminous concrete surfaces were found to have the best riding qualities of any type of surface tested. There was only a narrow range between the average for the four types (F-1, I-3, H-2, etc.) used in the surfaces tested.

9. Portland cement concrete surfaces were slightly rougher than bituminous concrete surfaces. Results indicate that under comparable conditions, there is very little difference between road roughness measurements of belt-finished concrete and broom-finished concrete.

10. The average roughness measurements for water-bound macadam were about the same as for traffic-bound macadam. However, due principally to the use of two types of surface treatment on water-bound macadam, the range between maximum and minimum was much greater than for traffic-bound macadam.

11. Macadam projects with mixed-in-place surface treatment were much smoother than those with plain surface treatment. The mixed-in-place treatment corrects small irregularities in the base and finishes to a finer texture than plain surface treatment.

12. Road roughness measurements on penetration macadam surfaces averaged higher than any of the other surfaces. However, the range from maximum to minimum was much less than for either the water-bound or traffic-bound macadam. Test results on the three penetration macadam surfaces were influenced by harsh surface texture, some base failures and numerous bridges.

13. Bituminous concrete and portland cement concrete, the smoothest surfaces, carry the heaviest traffic. However, these surfaces were designed for heavy traffic and constructed to the high standards of smoothness obtainable on surfaces of these types.

14. The comparative roughness of inside and outside lanes on multiple-lane pavement depends on the type of surface, the amount of traffic and the age of the various lanes. Where portland cement concrete pavement is widened, the newer outside lanes may be much smoother than the older inside lanes.

SUGGESTED USES FOR ROAD ROUGHNESS DATA

Road roughness measurements are very valuable in highway research work. They are an important part of a pavement condition survey. These measurements can be used to compare the riding qualities and performance of various types of pavement or to compare various sections of experimental projects. Some factors that might be studied are pavement design, subgrade soil type, construction methods, weather conditions including temperature, age of pavement and amount of traffic.

Publication of the road roughness measurements on each new project constructed would tend to create a competitive spirit between field engineers and between contractors that would result in smoother riding surfaces. If a contractor knows that his pavement will be tested, the psychological effect will undoubtedly result in a greater effort to obtain smooth pavement.

Another use for this information might be in acceptance of new projects from the contractor. This would require considerable work to develop specifications for each design or type of surface. A bonus could be paid for surfaces with good riding qualities and a penalty for surfaces with rough riding qualities.

Road roughness measurements have been used in Virginia to determine the advisability of resurfacing a considerable mileage of high type pavement. This information is especially valuable when the surface to be applied is one of the more expensive types. The same technique could be used where the need for reconstruction of a road is questionable.

It has been suggested that the road roughness indicator might be equipped with an automatic device that would mark the pavement when it passes over bumps or depressions of a certain magnitude. This feature could be of great value especially in maintenance work.

Professor Moyer found that the machine was of value in conjunction with studies of the economics of motor vehicle operation. Tire, gasoline, oil and maintenance costs, important factors in the operation of a motor vehicle, may be adversely affected by rough pavements.

The above suggested uses of road roughness measurements are believed to be all feasible with the present machine. However, further refinements in design will increase its value to the engineer.

ACKNOWLEDGMENTS

The writer wishes to express his appreciation for the help given by all of those who have assisted from time to time with this investigation. This work was initiated by Mr. T. F. Loughborough, Construction Engineer, and carried on under the general supervision of Mr. T. E. Shelburne, Diiector of Research.

Valuable assistance was rendered by Messrs. L. W. Teller and E. G. Wiles of the Public Roads Administration in calibrating and testing the "Road Roughness Indicator." Mr. A L. Anis of the Division of Tests and employees of the Equipment Division constructed, checked and maintained the equipment. Other employees of the Division of Tests and the District Materials Engineers assisted greatly in running the tests. Messrs. M. B. McReynolds and W. L. Flinn, Jr. drove the towing vehicle for all tests.

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DISCUSSION

L. W. Teller, *Public Roads Administration*—This excellent paper brings out very clearly the useful nature of the information that can be developed through a systematic use of the road roughness indicator. The reporting of data from a statewide survey as comprehensive as this one is a valuable addition to the literature.

There are a few brief comments that I would like to offer on this paper and on the method in general.

1. In our use of similar equipment over the past 8 years roughness index values have been determined for considerable mileages of pavements in various States of the Atlantic Seaboard, Middle West and in the eastern national parks. I believe that an examination of our data would support rather well the relations between index values and adjective ratings suggested by the author in his Table 9.

It is noted that he reports index values of 64, 66, 70 and 72 in. per mi. for certain bituminous pavements. These values certainly reflect exceptionally smooth surfaces. In our work we have found a number of new pavement surfaces of both portland cement concrete and bituminous types that showed index values within the range 70 to 80 in. per mi. It has also been our experience that many newly finished pavements of either type show index values greater than 100 in. per mi. These comparisons, as the author suggests, give valuable information on the effects of methods of construction and workmanship.

2. We have sometimes heard comments to the effect that data obtained with this relatively lightweight vehicle operating at a relatively low speed perhaps had little or no relation to the effect of surface roughness on the behavior of heavier vehicles operating at higher speeds. On this point the following may be of interest.

A number of years ago the Public Roads Administration made a study of the impact forces developed by the wheels of motor vehicles. During the course of the investigation one series of tests was made in which the impact forces resulting from conditions of natural road roughness were determined.

Seven concrete pavements and 7 bituminous pavements were selected and classified with a road roughness indicator. For each type the 7 pavements ranged from very smooth to very rough and the range was about the same for each type. A test vehicle weighing 24,000 lb., equipped with balloon tires, was driven over each section at constant speed and the frequency of impact reactions of various magnitudes was determined. Speeds up to 40 mph. were employed. When these impact data were analyzed, it was found that the impact reaction frequency curves for the 14 pavements arranged themselves, with one minor exception, in the same order as the surfaces had been rated on the basis of the roughness data. This indicates that the conditions of road surface roughness which affected the wheel of the roughness indicator and produced the index values affected in a similar way the wheels of the heavy vehicle that produced the impact reactions.

3. Referring to the author's list of suggested uses for roughness data, I would add that such data may be used also to provide factual evidence of the degree of improvement that has been effected by various patching, resurfacing and reconstruction operations.

4. Like many other measuring devices this equipment requires rather meticulous care to maintain it in the standard operating condition. Without such care the general level of the index values may be raised or lowered depending upon the cause. For example, the Road Research Laboratory in England, which has built and is using this equipment, became curious as to the cause of certain apparent discrepancies which appeared in their data. An investigation showed that certain of the tires which had been used were "out of round", that is, the radius was not constant. As a result of their study they arrived at a tolerance on the rolling radius below which this factor had a negligible effect on the roughness index. Tire eccentricity would, of course, increase index values for all surfaces and would introduce an effect which had nothing to do with road roughness. Other conditions such as friction in the spring suspension would tend to depress the level of the index values.

Since all users might not exercise equal care in maintaining and operating the equipment, I am inclined to question the practicability of the author's suggestion for making roughness index values the basis for contract acceptance, desirable as such a use might appear to be.

R. L. Sheppe, *Closure*—The writer wishes to thank Mr. Teller for his discussion which is a valuable addition to the report. His report of the correlation between road roughness and impact further emphasizes the value of the road roughness measurements.

Our experience confirms Mr. Teller's statement regarding the meticulous care that should be exercised in maintaining and operating the machine. We agree that this machine could be used satisfactorily for acceptance testing only if it were maintained and operated with the utmost care.