COMMONWEALTH OF KENTUCKY
DEPARTMENT OF HIGHWAYS
FRANKFORT

HENRY WARD
COMMISSIONER OF HIGHWAYS

April 6, 1961

ADDRESS REPLY TO
DEPARTMENT OF HIGHWAYS
MATERIALS RESEARCH LABORATORY
132 GRAHAM AVENUE
LEXINGTON 29, KENTUCKY

D.1.7.
P.4.1.

MEMO TO: A. O. Neiser
Assistant State Highway Engineer

The Research Division has been in the process of developing methods of evaluating pavement riding quality for the past few years. As early as 1955, efforts were directed toward the recording of accelerations imparted to a passenger riding in a vehicle. Prior to that time, the studies in Kentucky involved more or less precise methods of measuring surface irregularities. A roller straight edge was equipped with a deviometer attachment that magnified the actual displacement seven times. A portable aluminum truss cross-section template was constructed and used for cross-section evaluation.

The present equipment is described in detail in "Triaxial Acceleration Analysis Applied to the Evaluation of Pavement Riding Evaluation", 1955 Reports of the Highway Materials Research Laboratory. The last report to the Research Committee on this project was in 1956.

A Roughness Index Method of rating pavements has been developed since the last report and is discussed in the attached "Analysis of Pavement Roughness", by R. L. Rizenbergs. A series of measurements were made in 1957 on flexible pavements being evaluated for a structural pavement design study. These pavements have since been re-evaluated and a series of additional projects included. Efforts are being made to make roughness index measurements of most new pavements constructed.

The report lists deterioration in Roughness Index values for successive years. A 2-lane section of the Danville-Stanford road (US 150) near Danville had an increase in roughness of 39% during a 3-year period. It is interesting to note that during this time, the

4-lane section just east of the original project was under construction and that the road was closed to through traffic for most of the 3-year period.

Roughness Index measurements were made on the Curtiss-Wright Coal-Modified Coal-Tar Test Roads. It appeared that this method correlated with the other types of evaluation used on that project.

It looks as if it will be possible to use the Roughness Index System for performance studies in pavement design evaluation. It may also be practical to use the Roughness Index to evaluate construction procedures or even to specify tolerable standards for construction.

Respectfully submitted,

W. B. Drake

W. B. Drake
Director of Research

WBD:dl
Encs.
cc: Research Committee Members
Bureau of Public Roads (3)

Commonwealth of Kentucky
Department of Highways

ANALYSIS OF PAVEMENT ROUGHNESS

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March, 1961

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I. INTRODUCTION

In earlier progress reports (1) (2)* dealing with the development of triaxial acceleration analysis as applied to the evaluation of pavement riding qualities, of which this report is a continuation, riding comfort or discomfort was emphasized. The accelerations monitored then were evaluated in terms of g's per sec., or "jerk" which is considered by some authorities to be a more significant index of comfort (see note below). The earlier methods of analysis have been reviewed, and acceleration is considered here to be the most practical parameter to use as a measure of pavement roughness. Most of the equipment and instrumentation has been retained, and the recording of triaxial accelerations has been continued. However, only accelerations in the vertical direction are considered in the present method of analysis.

In the summer of 1957, some 265 miles of bituminous concrete pavements were recorded and analyzed as part of a study on flexible pavement design (3). Since then, some 1000 additional miles of bituminous and portland cement concrete pavements have been tested. These

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Note: Analyses in terms of "jerk" are being continued. Significant relationship between average g's and "jerk" units are presented in Appendix II.

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* The number in parentheses refer to the list of references at the end of the report.

include some older pavements, newly constructed pavements, and Interstate sections thus far completed. Some of the roads have been re-tested periodically. These roads represent a cross section of Kentucky pavements and give an indication of the status of pavement roughness from the standpoint of workmanship on new pavements, rate of deterioration, and the effects of re-surfacing.

II. INSTRUMENTATION

The instruments used for detecting and recording accelerations were installed in a 1957 Ford 4-door sedan which is used specifically as a test vehicle for roughness and skid-resistance measurements. Vertical, transverse, and longitudinal, resistive-type, Statham accelerometers were strapped to the chest of a passenger occupying the seat beside the driver. A bubble-type level was affixed to the mounting base of the accelerometers in order to facilitate balancing.

A Consolidated Engineering Corporation bridge balancer provided a regulated input voltage for the accelerometers and a means of balancing the accelerometer circuits. Changes in the resistance of bridge elements in the accelerometers, and therefore the changes in voltage, are proportional to acceleration. Changes in voltage were monitored by a C.E. recording oscillograph. Mirrors mounted on the galvonometer armatures in the recorder amplify the movement of the armatures and reflect the light beam to a light-sensitive, moving film. Once the film is developed in the laboratory, it provides a permanent record of accelerations as experienced by the passenger.

III. PROCEDURES

Method of Recording Roughness

The test passenger was seated erectly, but relaxed, in the front seat with his arms resting in his lap. The accelerometers were strapped to his chest and leveled. Preferably a passenger weighing 150-170 lbs. was selected, otherwise, extra weights were placed on the seat between the legs of lighter passengers.

Sufficient starting distance was allowed in order to permit the vehicle to attain a normal testing speed of 51.5 mph. This speed is clearly indicated by a calibrated marker on the speedometer dial. An attempt was made to drive the vehicle in the normal wheel tracks. If passing was necessary to maintain the test speed, it was properly marked by an event marker on the film. Also, any other feature of the pavement or road that needed to be identified or omitted from chart analysis was marked for identification.

Method of Determining Roughness Indexes

Visual inspection of the charts affords a cursory appraisal of the roughness in a pavement and also serves to locate localized roughness or to indicate the variations in roughness within a section of road. It is more desirable, however, to reduce the recorded data to one or more satistical parameters which would be meaningful indexes of the magnitudes and distributions of roughness. For instance, the mere summation of accelerations x time (total area under the recorded trace) provides a basis for sampling the chart and for deriving an integrated, total roughness per mile of road.

The accelerations experienced by the test passenger appear on a chart 5 inches in width and of a length equal to 17.5 inches per mile of road tested. Only accelerations in the vertical direction were used to derive roughness indexes. Accelerations in the longitudinal and transverse directions were omitted -- mainly due to instability of the trace in respect to the reference lines. It was assumed, therefore, that vertical accelerations alone could adequately portray the roughness of pavements, and that horizontal accelerations would add to the magnitude of the roughness index without changing the relative ratings.

Each 1/4-in. length of chart represented an elapsed time of one second, and each 2 inches of amplitude represented 1 g. of vertical acceleration. To find the average accelerations a compensating polar planimeter was used to sum the areas under the curves. A convenient 2.5-in. length of chart, equivalent to 750 ft. of pavement length, was selected for a single summation.

The areas in square inches for an entire project or section thereof, were resolved into ft./sec.^{2} x sec., or g.-sec. The g. x sec. divided by the length of the measured chart (in seconds) gives average g's.

g.-sec. = 1/2 area, or in.^{2} /2; where scale modulus = 2 in./g.

L (length of chart in inches) = 1/4 in./sec.

Then,

Avg. g's = 1/2 Area ÷ 1/4 in./sec.

And

Roughness Index = Avg. g's x 10^4

As found above, average g's pertain to any length of the road analyzed and is multiplied by 10^4 to obtain an index of roughness in whole numbers. Of course, large variations in the acceleration trace may occur from one location to another, but these are averaged into the over-all value describing the pavement. However, as mentioned before, this value does not reflect the frequency distribution or concentration of the roughness. Appendix I contains plots of the distribution of the roughness values, per 750-ft. section of roadway, for the roads which are of particular interest in this study.

Normally the entire length of the chart was analyzed to obtain an over-all roughness index -- particularly those which appeared to be very rough and those which exhibited appreciable localized roughness. It was found that pavements ten miles and greater in length and having very low over-all roughness values could be analyzed on the basis of alternate 2.5-in. sections and be reasonably assured of checking the over-all value within ± 1%. In fact, it was found that very few new pavements could be reliably analyzed on the basis of each third 2.5-in. section of chart. The reliability of the roughness index, from the standpoint of reproducibility appears to be within ± 2%. The error in reproducibility may be slightly higher for very rough pavements where the values depend to some extent on how closely the vehicle can be driven in the wheel tracks previously run.

IV. RESULTS AND ANALYSES

The 265 miles of bituminous pavements recorded and analyzed in 1957 were rerun during the summers of 1959 and 1960. Most, if not all, bituminous pavements constructed since 1957 were tested for initial roughness and have been tested periodically thereafter. The approximate locations of all of the bituminous pavements studied are shown in Fig. 1; roughness indexes and other pertinent information concerning those roads are presented in Table 1.

Portland cement concrete pavements recorded in 1958 and '59 consisted mostly of new construction; however, in 1960, in addition to new construction, some 20 pavements constructed prior to 1956 were also tested and analyzed. Figure 2 is a map showing the approximate locations of all of the PCC pavements analyzed; and Table 2 presents the roughness indexes and other data applicable to these roads.

A general, summary analysis of all of the data is presented in Table 3.

Rating of Roads: According to Rougness Indexes

The roughnesses of PCC and bituminous pavements are considered in parallel plots in Fig. 3. The data was subdivided into identical quartiles (containing equal number of projects) which are indicated by the "word" classifications given at the bottom of Fig. 3. An overlap

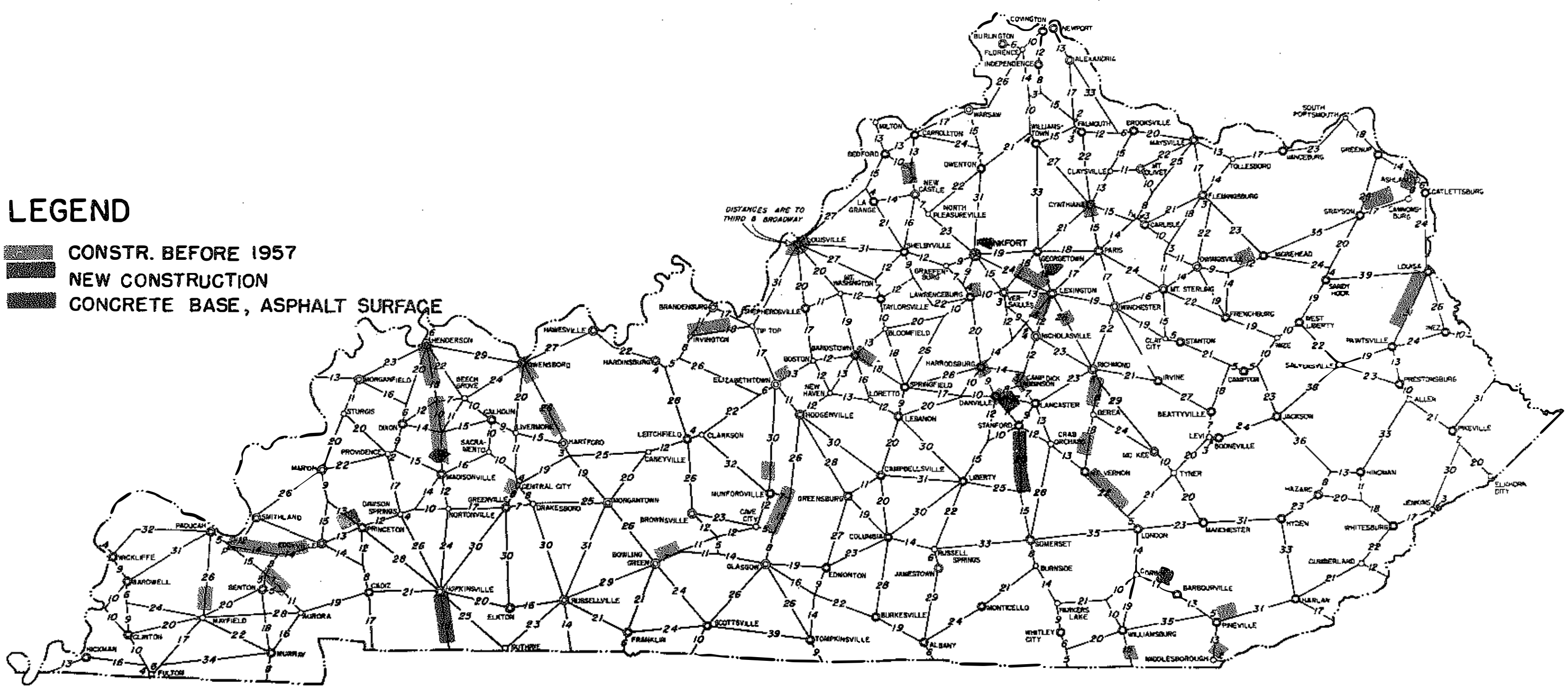


Fig. 1. Map Showing Locations and Approximate Length of Bituminous Concrete Pavements Studied.

TABLE I

BITUMINOUS CONCRETE PAVEMENTS

	ROUTE No.	PROJECT No. and Acc. yr.	BETWEEN	COUNTY	No. of MILES	ROUGHNESS INDEX 1957	1959	1960	% CHANGE. per 3 yrs.	COMMENTS
				US Routes						
1.	US 23 NB	77 A(23) 1948	Paintsville-Louisa	Johnson	22.9	600	654	723	19	
2.	US 25 NB	FI 29(9) 1951	London-Mt. Vernon	Laurel	2.3	734	740	411		Resurfaced '59 -44 %
3.	US 25 NB	FI 517(6) 1951	London-Mt. Vernon	Laurel	5.3	785	441	474		Resurfaced '59 -44 %
4.	US 25 NB	FI 517(7) 1951	London-Mt. Vernon	Rockcastle	4.7	803	552	530		Resurfaced '58 -31%
5.	US 25 SB	FI 70(6) 1954	London-Mt. Vernon	Rockcastle	3.0	933	924	926	0	
6.	US 25 SB	FI 88(6) 1950	Berea-Mt. Vernon	Rockcastle	6.0	843	624	609		Resurfaced '58 -30 %
7.	US 25 SB	FI 299(6) 1951-52	Richmond-Berea	Madison	7.9	558	749	774	32	Strip Patch
8.	US 25 SB	FI 124(4) 1946	Lexington-Clays Ferry	Fayette-Madison	1.3	663	894	760	14	
9.	US 25 SB	FI 23(16) 1948	Williamsburg-Tenn. Line	Whitley	3.2	744	787	692		
10.	US 25 NB	U 322(7)	Middlesboro By-pass	Bell	2.0	1035	1113	985		
11.	US 25 SB	UI 538(5)	Lexington Relief Rt.	Fayette	0.9		763	802	0	
12.	US 27 NB	S 366(2) F 525(2,3,4,5) 1948	Lancaster-Nicholasville	Garrard	12.7	669	787	758	13	Resurfaced '56
13.	US 27 SB	F 544(4,5) 1949	Lexington-Nicholasville	Fayette-Jessamine	8.1	622	720	634	2	Resurfaced '54
14.	US 27 SB	F 189(5,6) 1952	Cynthiana-Paris	Harrison	5.3	674	689	666	0	
15.	US 31 SB W	FI 104(12) 1953	Munfordville-E'town	Hart	3.0	560	611	645	14	
16.	US 31 SB W	FI 113(5) FI 16(2) 1955	Bowling Green-E'town	Warren	5.5	597	678	710	17	
17.	US 31 NB E	F 28(5) F 7(5) 1950	Glasgow-Hodgenville	Barren-Hart	12.1	493	515	554	11	
18.	US 41 SB	F 526(9) 1950	Henderson-Madisonville	Henderson	9.0	1101	764	839		
19.	US 41 SB	F 526(12) 1953	Madisonville-Henderson	Henderson-Webster	7.6	609	645	803	27	
20.	US 41 SB	F 526(13) 1953	Madisonville-Henderson	Webster	4.8	727	795	817	12	
21.	US 41 SB	F 526(10) 1951	Madisonville-Henderson	Webster	4.7	658	575	682		Patching -13%
22.	US 41 SB	F 526(6) 1948	Madisonville-Henderson	Hopkins	4.8	684	604	606		Resurfaced '57 -13%
23.	US 41 SB	F 526(7) 1950	Madisonville-Henderson	Hopkins	5.4	706	518	621		Resurfaced '58 -31%
24.	US 45 SB	F 146(19) 1956	Mayfield-Wingo	Graves	7.2	498	519	526	5	
25.	US 60 WB	FI 3(8) 1950	Morehead-Owingsville	Rowan	3.3	666	858	883	31	
26.	US 60 WB	F 1(4) & FI 8(4) 1950 FI 8(6) 1952	Ashland-Grayson	Boyd	7.9	694	811	836	20	
27.	US 60 WB	FI 4(4,6) 1952 & 1953	Ashland-Grayson	Carter	8.9	702	751	755	7	
28.	US 60 WB	F 523(3) 1953	Irvington-Grahampton	Breckenridge-Meade	11.0	550	563	570	3	
29.	US 60 WB	1950	Watterson Expressway	Jefferson	8.0	529	475	554	5	
30.	US 62 WB	F 530(8) 1955	Gilbertsville-Paducah	Marshall-McCracken	13.7	378	378	403	5	

TABLE 1 (Continued)

	ROUTE No.	PROJECT No. and Acc. yr.	BETWEEN	COUNTY	No. of MILES	ROUGHNESS INDEX 1957	1959	1960	% CHANGE per 3 yrs.	COMMENTS
31.	US 62 WB	F 40(6) 1953	Greenville-Central City	Muhlenberg	5.3	706	680	783	10	
32.	US 62 WB	F 208(4) 1953	Versailles-Lawrenceburg	Anderson	2.0	502	560	672	28	
33.	US 62 WB	F 530(6) 1953	Kuttawa-Kentucky Dam	Livingston-Lyon	8.9	478	538	483	1	
34.	US 62		E'town-Bardstown	Hardin	2.5			700		
35.	US 68 WB	F 163(9) 1951	Paducah-Cadiz	Marshall	8.0	452	403	513	13	
36.	US 119 SB	F 21(5) & F 151(7) 1956	Pineville-Harlan	Bell	5.4	542	589	603	10	
37.	US 127 NB	F 294(2) 1954	Danville-Harrodsburg	Mercer	3.0	642	739	721	12	
38.	US 150 WB	F 244(4) 1952	Danville-Stanford	Boyle	1.8	594	752	888	39	
39.	US 150 EB	F 222(4) 1952	Bardstown-Springfield	Nelson	6.4	600	651	686	13	
40.	US 231 SB	F 125(18)	Owensboro-Hartford	Daviess	5.0	658	674	786	19	
41.	US 231 SB	F 125(19) 1950	Owensboro-Hartford	Daviess-Ohio	11.3	715	800	844	16	
42.	US 421 SB	F 326(22) 1951	Frankfort-Lexington	Franklin-Woodford	8.0	514	548	596	14	
43.	US 421 SB	SO 552(2), S 552(1) & F 536(3) 1955	Carrollton-New Castle	Henry	6.5	744	838	870	17	
			Miscellaneous Pavements							
	US 41		Hopkinsville-Nashville	Christian	13.5			286		Constr. '56 4 lanes, 1/3 rule PCC base & BC surface
	US 640 & Ky. 278 WB		Princeton-Kuttawa	Lyon	5.4			312		Constr. '59
			State Routes							
1.	Ky. 54 EB	S 462 (4)	Fordsville-Leitchfield	Grayson	10.7	698	771	808	15	
2.	Ky. 69 SB	S 473 (2)	Fordsville-Hartford	Ohio	11.1	806	557	697		Resurfaced '57 -37%
3.	Ky. 69 SB	SP 92-224	Hartford-Centertown	Ohio	6.7	665	551	658		Resurfaced '59 -19%
4.	Ky. 80 EB	SP 100-235 (6)	Russell Springs-Somerset	Pulaski	5.3	654	703	707	8	
5.	Ky. 90 EB	S 10 (5)	Monticello-Burkesville	Clinton	4.4	650	725	715	9	
6.	Ky. 90 EB		Monticello-Burkesville	Clinton	2.7	511	578	622	20	
7.	Ky. 90 EB	F 116 (10)	Burkesville-Glasgow	Cumberland	3.0	566	680	663	16	
8.	Ky. 229 NB	S 150 (4)	Barbourville-London	Laurel	5.4	949	502	534		Resurfaced '58 -62%
			New Construction							
1.	US 25 E		Barbourville-Corbin	Knox	4.5			294		2 lanes, all Constr. '60
2.	US 25 SB		Lexington Relief Route	Fayette	3.4		379	431	22	Constr. '59
3.	US 25		Lexington Relief Route	Fayette	1.5			423		4 lanes Constr. '59
4.	US 27 SB		Stanford-Somerset	Lincoln-Pulaski	16.0		377	444	15	Constr. '59
5.	US 127		Frankfort-Thornhill By-pass	Franklin	1.2			368		4 lanes, all Constr. '59
6.	US 150 WB		Stanford-Danville	Lincoln	5.8			448		Constr. '59
7.	US 41-41A		Madisonville By-pass	Hopkins	1.5			463		2 lanes Constr. '60

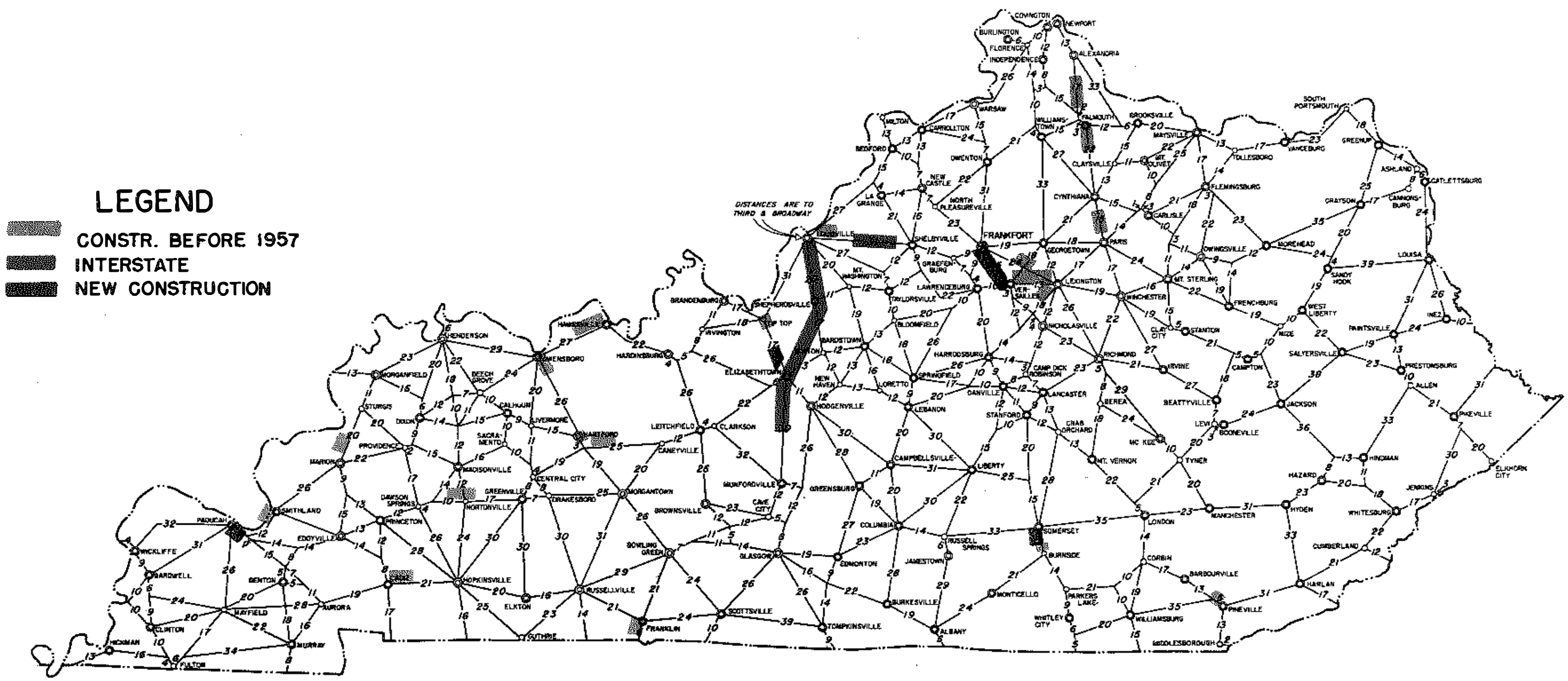


Fig. 2. Map Showing Location and Approximate Length of Portland Cement Concrete Pavements Investigated.

TABLE 2

PORTLAND CEMENT CONCRETE PAVEMENTS

	ROUTE No.	BETWEEN	COUNTY	No. of MILES	ROUGHNESS INDEX 1957	1959	1960	% CHANGE per 3 yrs.	COMMENTS
				Interstate					
	I 64	Louisville-Shelbyville	Jefferson	12.0			258		Constr. '60
	I 65	Kentucky Turnpike	Jefferson-Bullitt	36.0			358		4 lanes, ½ dist. 1/3 rule, Constr. '56
	I 65	E'town-Upton	Hardin	12.5			351		4 lanes, 1/3 rule Constr. '59
				US Routes					
1.	US 27	Cynthiana-Paris	Bourbon	6.7			537		
2.	US 27 SB	Falmouth-Cynthiana	Harrison-Bourbon	6.6			532		
3.	US 27 SB	Alexandria-Falmouth	Pendleton	6.7			598		
4.	US 27 SB	Somerset-Burnside	Pulaski	1.0			558		
5.	US 31W SB	Louisville-E'town	Bullitt	2.4			438		
6.	US 31W SB	Franklin-Tenn. Line	Simpson	5.5			540		
7.	US 60 WB	Smithland-Paducah	Livingston	5.2			445		
8.	US 60 WB	Hawesville-Owensboro	Hancock	8.5			611		
9.	US 60 WB	Sturgis-Marion	Crittenden	5.2			550		
10.	US 60 WB	Shelbyville-Louisville	Jefferson	3.5			370		
11.	US 60	Lexington-Versailles	Fayette-Woodford	9.3			391		4 lanes, 1/3 rule
12.	US 62 WB	Leitchfield-Beaver Dam	Ohio	5.2			586		
13.	US 62 WB	Greenville-Nortonville	Hopkins	5.1			721		
14.	US 68 EB	Harrodsburg-Lexington	Fayette	2.7			536		
15.	US 68 EB	Cadiz-Hopkinsville	Trigg	4.6			463		
16.	US 68 EB	Cadiz-Hopkinsville	Trigg	3.8			505		
17.	US 231	Owensboro-Hartford	Daviess	6.0			522		2 lanes, all 626 ('58)
18.	US 231	Hartford-Beaver Dam	Ohio	2.4			386		
19.	US 421 SB	Frankfort-Lexington	Franklin	4.5			576		
20.	US 25E NB	Pineville-Barbourville	Bell	2.8			731		
				New Construction					
1.	US 27 SB	Somerset-Cumberland Br.	Pulaski	5.5			371		4 lanes, ¾ rule Constr. '59
2.	US 31W NB	E'town-Louisville	Hardin	4.7			428		2 lanes, ½ rule Constr. '60
3.	US 60	Frankfort-Versailles	Franklin-Woodford	9.5			367		4 lanes, 1/3 rule Constr. '59
4.	US 60	Versailles By-pass	Woodford	1.3			410		4 lanes, all Constr. '60
5.	US 62 WB	Paducah By-pass	McCracken	3.0			345		Constr. '60

TABLE 3

SUMMARY OF DATA

PAVEMENT CATEGORIES	MEDIAN ROUGHNESS INDEX (1960)
All Pavements Combined	560
Recently Constructed Bituminous Concrete Pavements	412 387 (Avg. Initially)
Recently Constructed PCC Pavements	390 323 (Avg. Interstate)
Bituminous Concrete Constructed Before 1957	688
PCC Construction Before 1956	536

OTHER STATISTICS

Bituminous Concrete Deterioration (1957 to 1960):	Median of 13.3% per 3 yrs. or 4.4% per 1 yr.
Improvement of Resurfaced Bituminous Concrete Pavements:	Avg. of 34% on a total of 28.5 mi.
Number of Miles Recorded:	1957 - 265 mi. of BC 1958 - 12 mi. of PCC 1959 - 374 mi. (291 mi. of BC 83 mi. of PCC) 1960 - 508 mi. (312 mi. of BC 183 mi. of PCC 13 mi. of PCC Base and BC surfacing)
Average length of a Project Tested: (Constructed before 1957)	6.5 mi., Bituminous Concrete 4.7 mi., PCC

was allotted to each quartile in order to provide some tolerance at the margins of classification categories and in order to avoid sharp distinctions between pavements having nearly the same roughness indexes. The median roughness index of 560 was computed from all of the data available. It is, therefore, the median roughness index of all of the roads studied, and it was computed without any distinction as to the types or ages of the pavements. There are as many roads having roughness indexes greater than 560 as there are roads having indexes less than this value. Accordingly, the median was selected as the mid-point for the "word" classification. Hence, the first quartile to the left and right of the median were designated "good" and "fair" respectively. Thus, the outer quartiles, in the same respective order, were designated as "excellent", and "poor".

It is probably only by chance that none of the older PCC pavements fell within the "poor" classification. However, there are indications that older portland cement concrete pavements develop a pattern of roughness which is rather different from that of older bituminous concrete pavements. These differences seem to be related to the uniform frequency of joints in the concrete pavements -- which are apparently high in acceleration amplitude but short in duration and which do not contribute in due proportion to the roughness indexes based on average g's only. Accelerations of this type contribute in a greater proportion to "jerk" values; and it seems very probable, from this

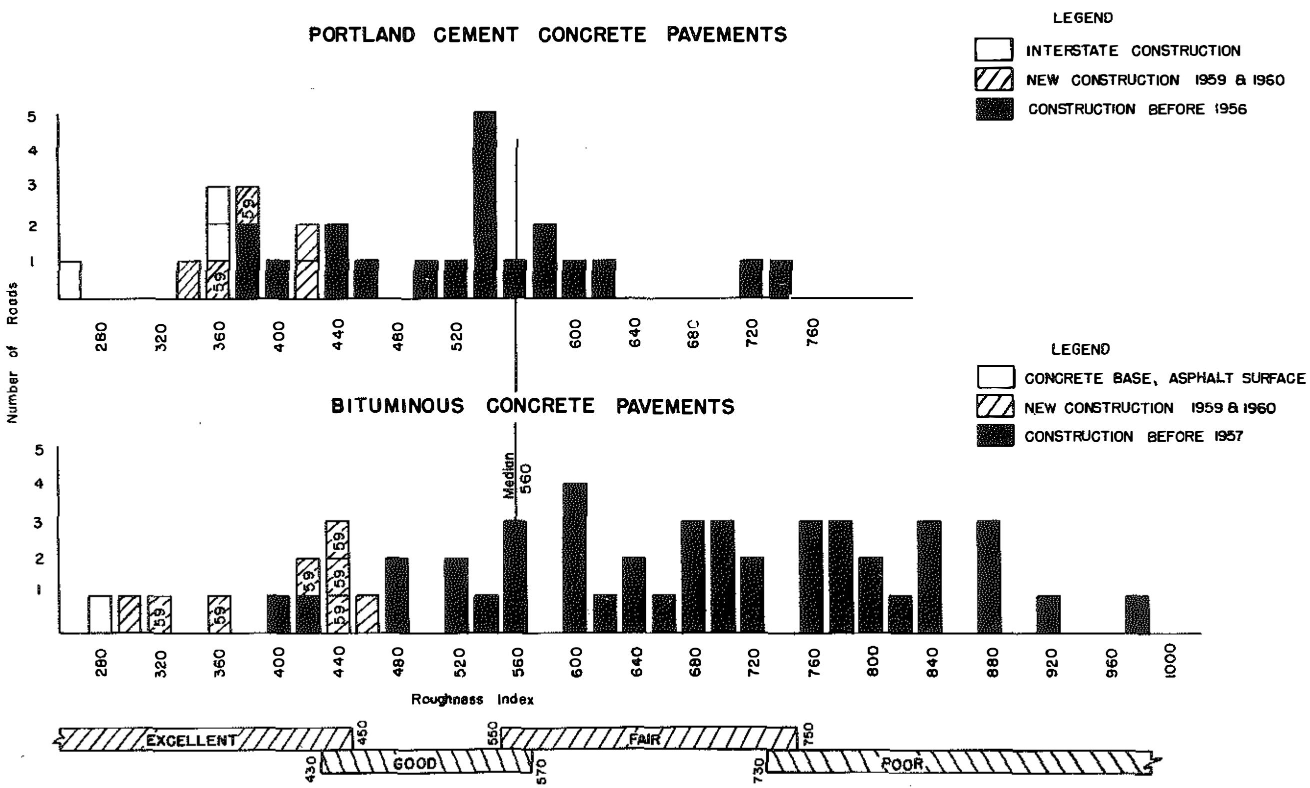


Fig. 3. Roughness Distribution of Portland Cement Concrete and Bituminous Concrete Pavements and Their Respective Classification According to 1960 Records.

standpoint that both average g's and "jerk" values are needed in order to evaluate roughness more completely.

Again referring to Fig. 3, several older pavements as well as very new ones fall within the "excellent" category. Likewise, several bituminous pavements constructed in 1959 were well within the "excellent" category when initially tested. When they were tested again in 1960, some of them rated as marginal, i.e. between "excellent" and "good".

Effect of Vehicle Speed on Roughness Index

There is no practical formula available by which the response of the car or a passenger therein may be related directly to pavement profile. There is an implied relationship, however, even if it is only in the sense that the "cause" must equal the "effect". Here, the "effects" are merely the accelerations imparted to a passenger's torso.

The response of a vehicle to roughness in the pavement profile depends, in a general way, upon the magnitude of the roughness, the interval or spacing of the irregularities on the road, and the frequency or rate at which they are encountered. For instance, there is a tendency for wheels to hop or bounce if the frequency of encountering irregularities is in the order of about 5 or more per second. At 60 mph. or 88 ft. per sec., this is equivalent to an interval of 8.8 ft. Irregularities which occur at frequencies close to the natural frequency of the body suspension system (1.5 cps), tend to cause the body of the car to bounce at its maximum amplitude. At 60 mph., this is equivalent to an interval of 58.6 feet.

From this point of view, it is easily surmised that roughness indexes based upon dynamic responses will vary with the speed of the test vehicle. Differences in roughness indexes determined at different speeds on a particular road may portray the nature of the roughness. For instance, if the roughness indexes increase in direct proportion to speed, it might be inferred that the interval of irregularities in the pavement would be uniform and constant; whereas, a disproportionate increase in the roughness index with respect to an increase in speed might suggest that longer-interval irregularities have become significant.

Figure 4 graphically illustrates the effect of speed on the roughness indexes for five sections of road. While it is recognized that such differences exist and that this aspect of the problem will require much further study, the present basis of evaluating roughness and the indexes reported herein were derived at one test speed only, i.e. 51.5 mph.

Roughness of Bridges and Railroad Crossings

In the normal course of roughness testing of pavements, all bridges, and railroad crossings were marked on the charts but were not included in the pavement roughness evaluations. However, since the accelerations experienced at these points were recorded and were

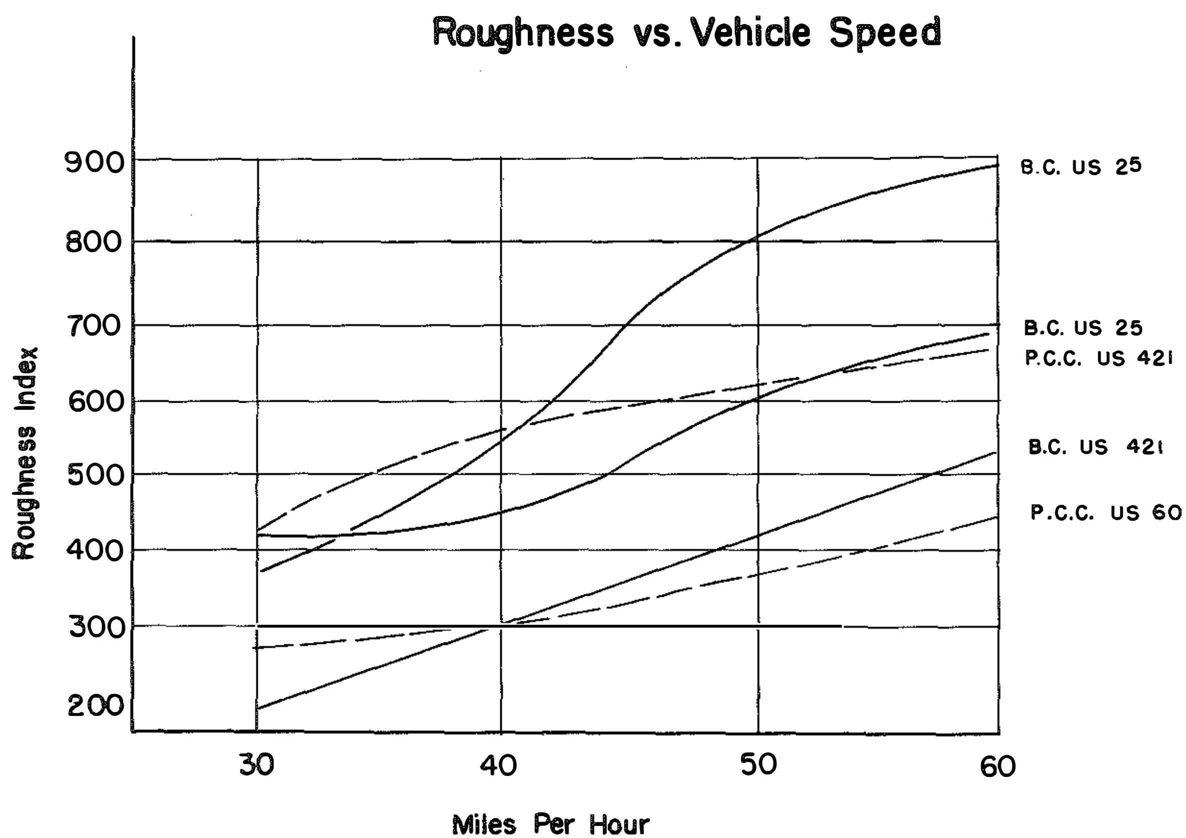


Fig. 4. Graph of Roughness Index of Various Pavements vs. Vehicle Speed.

so marked, it is of interest to examine the roughness at these places also. Oftentimes, bridge approaches and railroad crossings are recognizable on the chart because of the fact that they are points of roughness. Additionally, it seems reasonable to expect that bridge decks should be at least as smooth as an average pavement, and it is of interest to examine the charts from this point of view, also.

It was not practical, because of the short duration of these effects and the rather limited length of chart, to analyze these roughnesses in terms of the roughness index (computation of average g's). Therefore, only the maximum accelerations for 85 bridges in various categories and seven crossings are given in Table 4. Data for several specific locations (constructed since 1956) are given in Table 5.

TABLE 4

SUMMARY DATA ON BRIDGES & RAILROAD CROSSINGS

TYPE OF PAVEMENT	NO. OF BRIDGES	NO. OF LANES TESTED	BRIDGE MAXIMUM ACCELERATION IN G'S	BRIDGE APPROACHES (IN G'S) START	BRIDGE APPROACHES (IN G'S) END	R.R. CROSSINGS NO. TESTED	R.R. CROSSINGS MAXIMUM ACCELERATION IN G'S
Bituminous Concrete Pavements, Constructed Before 1957	41	41	0.20	0.21	0.175	2	0.275
Newly Constructed Bituminous pavements on US & Ky. Routes	4	6	0.187	0.192	0.112	3	0.158
PCC Pavements Constructed Before 1956	26	26	0.278	0.145	0.167		
Newly Constructed PCC	1	4	0.200	0.108	0.175	2	0.225
Interstate PCC	10	22	0.200	0.125	0.140		
PCC Base & Bituminous Surface	3	12	0.175	0.125	0.103		

TABLE 5

RECENTLY CONSTRUCTED BRIDGES & RAILROAD CROSSINGS

ROUTE	TYPE OF PAVEMENT	BETWEEN	COUNTY	LANE TESTED	BRIDGE APPROACHES START (IN G'S)	BRIDGE APPROACHES END (IN G'S)	MAXIMUM ACCELERATION IN G'S BRIDGE DECK	MAXIMUM ACCELERATION IN G'S R.R. CROSSING
I 64	PCC	Louisville-Shelbyville	Jefferson	Westbound Outer Station 1088+00	0.10	0.15	0.10	
				Westbound Inner Station 1088+00	0.10	0.10	0.10	
				Eastbound Outer Station 635+00	0.10	0.15	0.20	
				Eastbound Outer Station 702+00	0.15	0.05	0.15	
				Eastbound Inner Station 635+00	0.05	0.10	0.15	
				Eastbound Inner Station 702+00	0.15	0.20	0.15	
I 65	PCC	Elizabethtown Upton	Hardin	Southbound Outer	0.05 0.05	0.10 0.05	0.15 0.15	
				Southbound Inner	0.05 0.05	0.15 0.15	0.15 0.20	
				Northbound Outer	0.15 0.05	0.10 0.20	0.30 0.20	
				Northbound Inner	0.05 0.10	0.15 0.10	0.15 0.15	
I 65	PCC	Kentucky Turnpike	Jefferson Bullit	Southbound Inner and then Outer Staggered	0.25 0.25 0.20 0.20 0.10 0.05	0.20 0.15 0.20 0.35 0.10 0.10	0.35 0.25 0.35 0.35 0.10 0.30	
				Northbound Outer and then Inner Staggered	0.15 0.15 0.10 0.45	0.10 0.15 0.15 0.25	0.40 0.10 0.25 0.30	
US 60	PCC	Versailles-Frankfort	Franklin Woodford	Westbound Outer	0.20	0.20	0.15	
				" Inner	0.10	0.15	0.20	
				Eastbound Inner	0.10	0.20	0.20	
US 60	PCC	Versailles By-pass	Woodford	Westbound Outer				0.30 0.20
				" Inner				0.25 0.20
				Eastbound Outer				0.10 0.25
				" Inner				0.20 0.30
US 25 E	B.C.	Corbin-Barbourville	Knox	Northbound	0.15 0.20	0.15 0.10	0.20 0.15	0.10 0.20
				Southbound No. 2	0.15	0.10	0.15	0.50 0.15
US 25	B.C.	Lexington By-pass	Fayette	Northbound Outer	0.30	0.15	0.20	
				" Inner	0.10	0.05	0.30	
				Southbound Outer	0.10	0.20	0.20	
				" Inner	0.20	0.10	0.20	
US 127	B.O.	Thornhill By-pass	Franklin	Northbound Outer				0.10
				" Inner				0.15
				Southbound Outer				0.20
				" Inner				0.15
US 41 41A	B.C.	Madisonville By-pass	Hopkins	Eastbound	0.25	0.15	0.15	
				Westbound	0.10	0.20	0.10	
US 41	PCC Base Bit. Surf.	Hopkinsville-Nashville	Christian	Northbound Outer	0.15 0.15 0.30	0.10 0.10 0.10	0.10 0.20 0.25	
				Northbound Inner	0.10 0.25 0.10	0.20 0.10 0.10	0.20 0.20 0.10	
				Southbound Outer	0.30 0.10 0.10	0.20 0.05 0.20	0.30 0.10 0.20	
				Southbound Inner	0.15 0.05 0.10	0.10 0.10 0.10	0.15 0.15 0.20	

V. SUMMARY AND DISCUSSION OF RESULTS

The foregoing data represent only a partial assessment of the roughness of roads in Kentucky. Hence, an analysis of the data in terms of norms of performance would be somewhat premature. Within the data presented, however, significant comparisons may be made. It is of interest to examine new construction and more particularly new construction which represents the highest type of design and inspection, i.e., Interstate and Primary roads. Certainly, it is reasonable to expect these roads to be smoother and more comfortable to ride upon than roads in less expensive categories; and, the data thus far seem to confirm this.

For instance, the PCC on I-64, beginning at the English Station road in Jefferson County, and proceeding 12 miles eastwardly, is the smoothest pavement tested thus far (Roughness Index: 258). However, the second smoothest pavement, US 41, extending 13.5 miles south of Hopkinsville, consists of bituminous concrete overlaying PCC (constructed 1956, Roughness Index: 286). Third, in the order of increasing roughness, is the 4.5-mi. section of US 25-E, Corbin-Barbourville road, paved in 1960, (B.C. Roughness Index: 294). The Princeton-Kuttawa road, US 640, 5.4 mi., paved in 1959, easily qualifies for fourth place (Roughness Index: 312). Then in further succession:

5th - Paducah By-Pass, US 62, PCC, 3.0 mi., 1960,
Roughness Index: 345

6th - I-65, Elizabethtown-Upton, PCC, 12.5 mi., 1959, Roughness Index: 351.

7th - Kentucky Turnpike, PCC, 1956, Roughness Index; 358

8th - US 60, Versailles-Frankfort road, PCC, 9.5 mi., 1959, Roughness Index: 367.

9th - Thornhill By-pass, US 127, 1.5 mi., bituminous concrete, 1959, Roughness Index: 368.

10th - US 60, Middletown- St. Matthews, 3.5-mi. section, Roughness Index: 370.

11th - US 27, Somerset-Burnside road, PCC, 5.5 mi., 1959, Roughness Index: 371.

The Stanford-Somerset road, US 27, 16 mi., bituminous concrete, paved in 1959, had a roughness index of 377 when tested initially in 1959; but, when tested a year later, its roughness had increased to 444. Similarly, a 3.4-mi. section of the Lexington Relief Route which was completed in 1959 had a roughness index then of 379, whereas a year later it rose to 431.

Most of the roads tested in one or more successive years showed some increase in roughness except, of course, in cases where they had been resurfaced between test periods. The highest 3-year increase in roughness was 39% (Danville-Stanford road, 2-lane section). However, the average yearly increase for all roads was 4.3%.

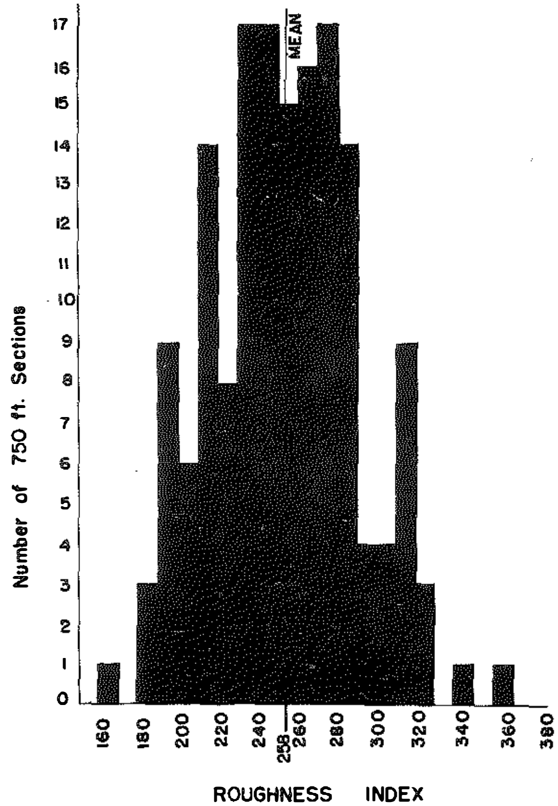
Resurfacing of 5.4 mi. of the London-Barbourville road, Ky. 229, reduced its roughness index from 949 to 502 which is 62% change from mean value. However, the average decrease for all roads resurfaced was 34%.

Although, it is evident that other comparisons may be made from the data, the Lexington-Versailles road invites particular attention. Even though it was constructed about 1940, its present roughness index is only 391. The Versailles By-pass, constructed in 1960, has a roughness index of 410, and the two new PCC lanes on US 31-W, Elizabethtown-Louisville, has a roughness index of 428.

APPENDIX I

I 64

LOUISVILLE - SHELBYVILLE



Length: 12.0 miles

Type: PCC

Year Constucted: 1960

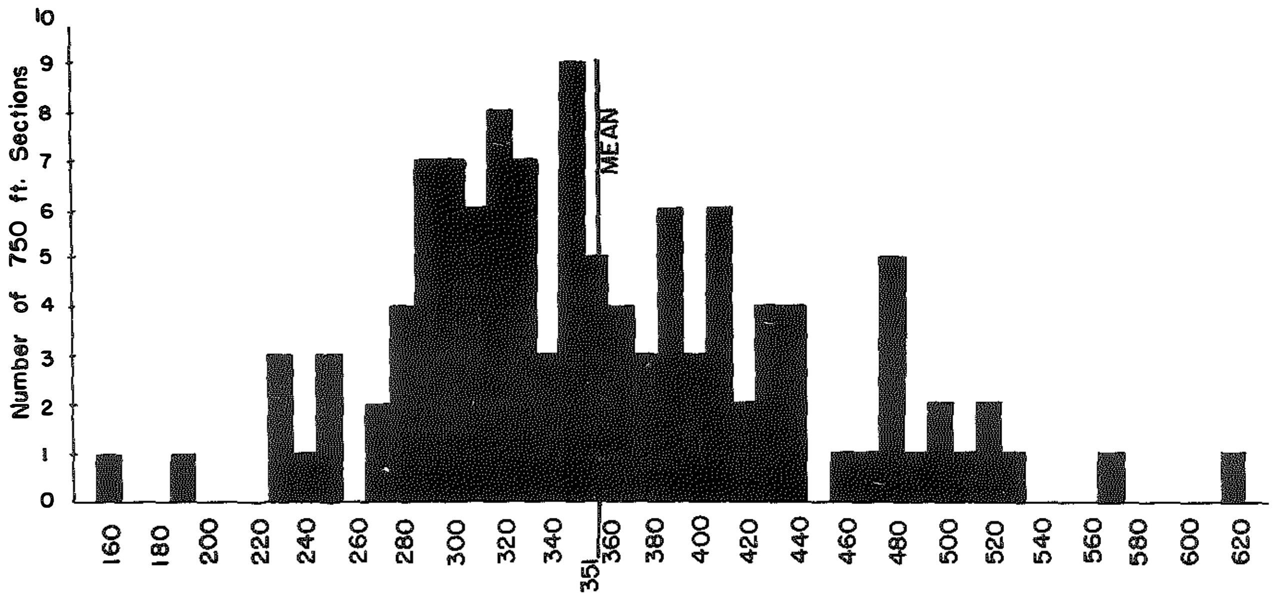
Date: September, 1960

NOTE: 7.5 miles eastbound

4.5 miles westbound

⅓ rule

I 65
ELIZABETHTOWN - UPTON



Length: 12.0 miles

Date: July & August 1960

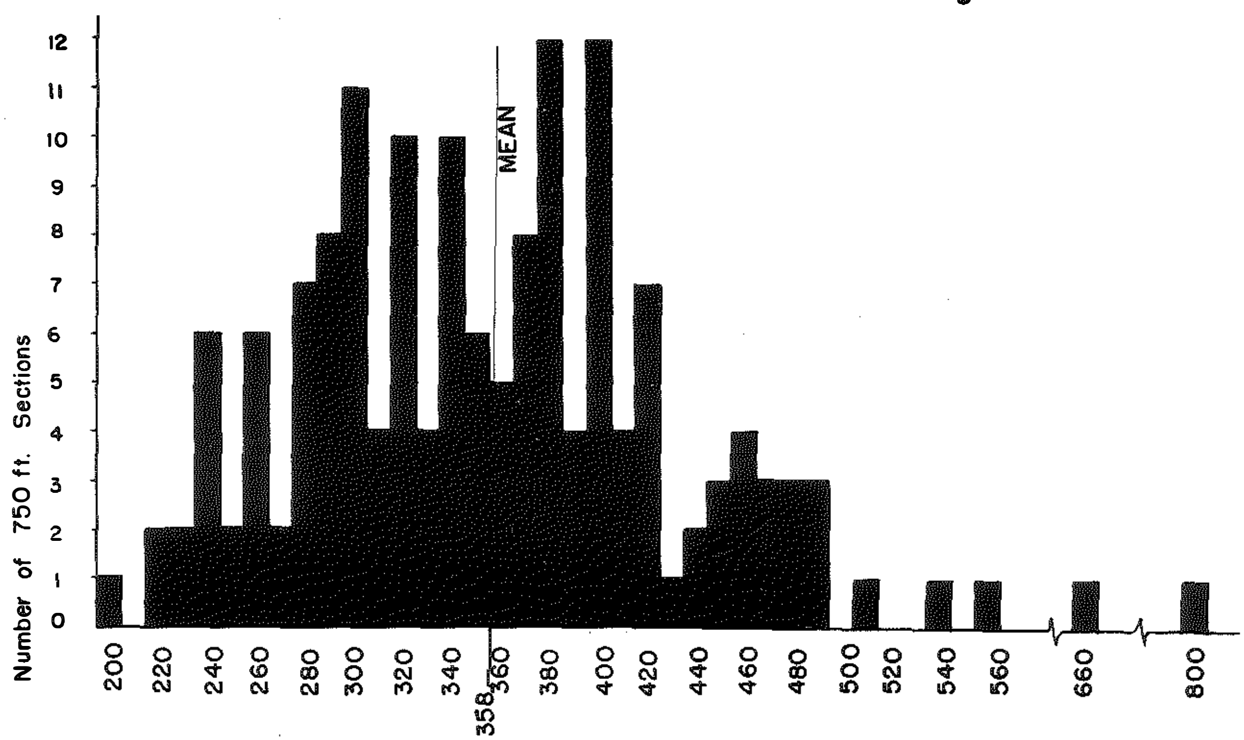
Roughness Index by lanes

outer (N.B.) = 389
outer (S.B.) = 332
Inner (N.B.) = 356
inner (S.B.) = 330

Type: PCC

Year Constructed: 1959

KENTUCKY TURNPIKE **1/3 rule**



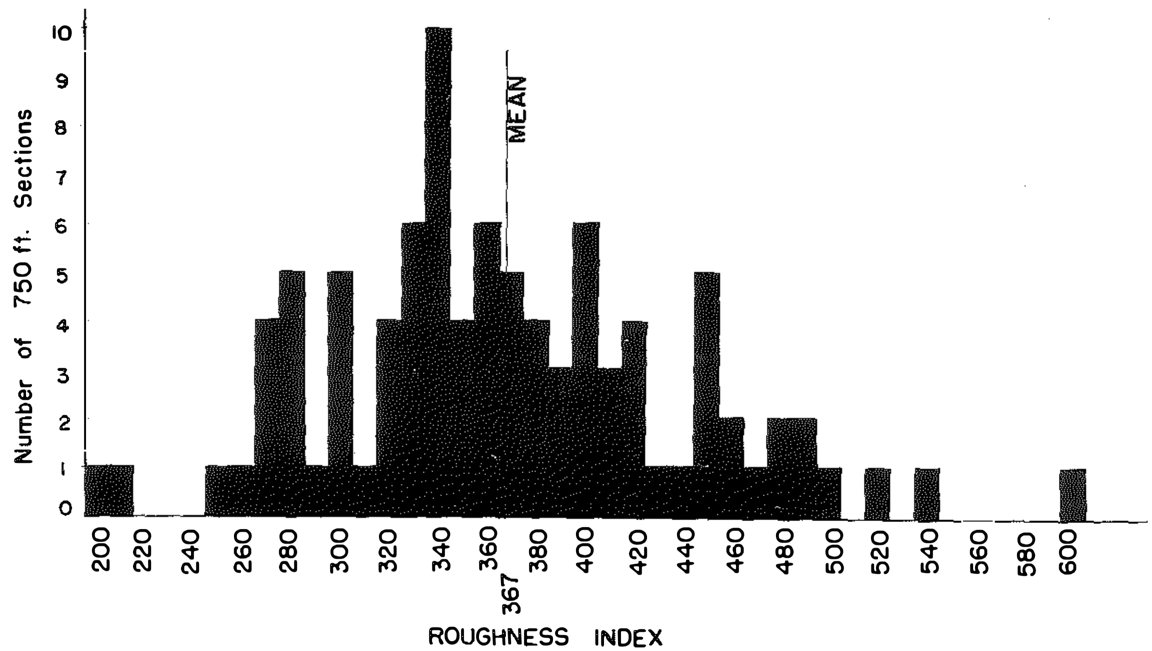
LENGTH: 36 miles DATE: September 1960 TYPE: PCC

Year Constructed: 1956

NOTE: 66 miles of pavement recorded

US 60
VERAILLES - FRANKFORT

1/3 rule



Length: 12.0 miles

Date: June & September 1960

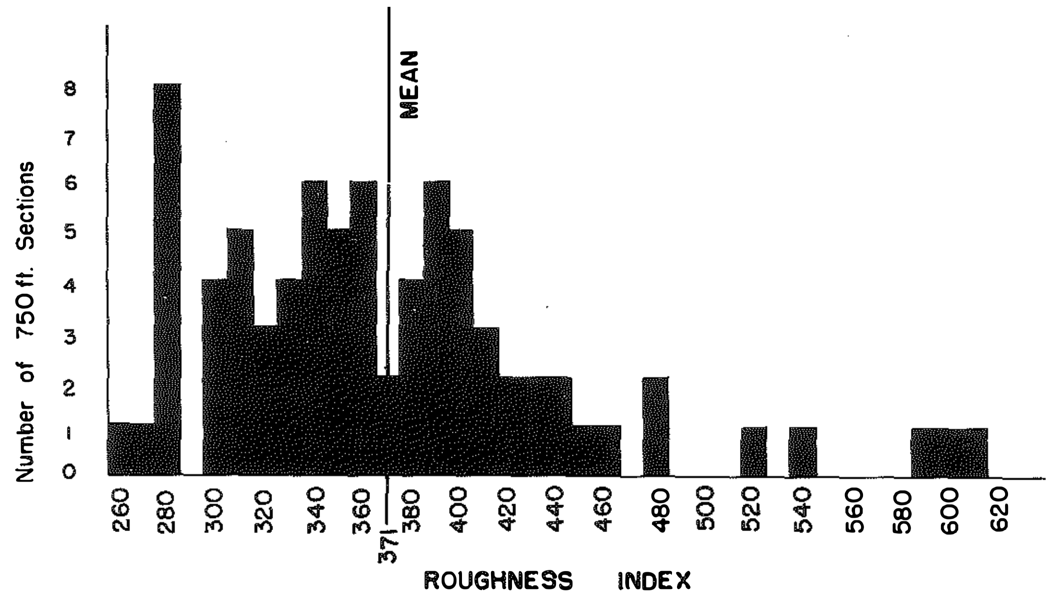
Year Constructed: 1959

Type: PCC

US 27

½ rule

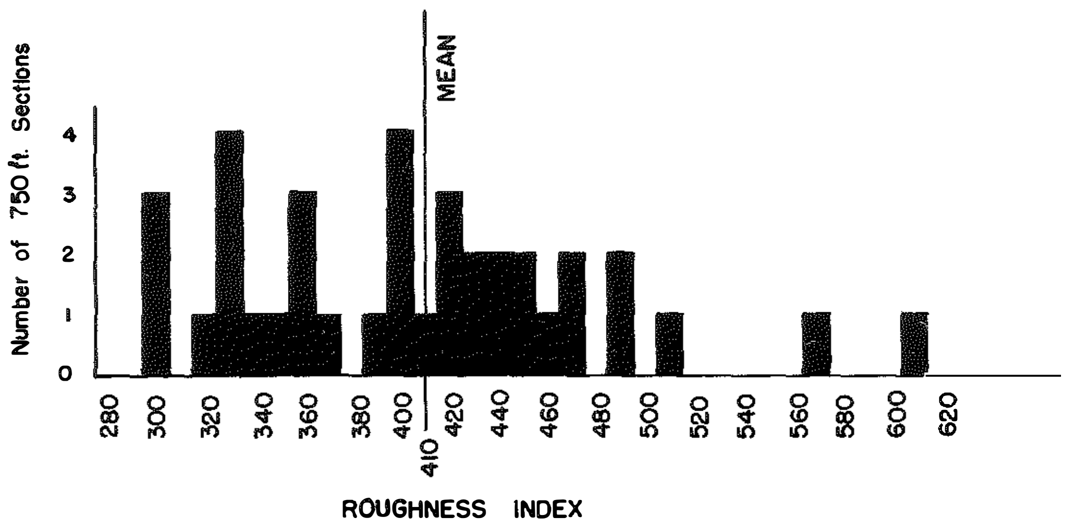
SOMERSET - BURNSIDE



Length: 5.5 miles   Date: July 1960   Type: PCC
Year Constructed: 1959

US 60

VERSAILLES BY-PASS



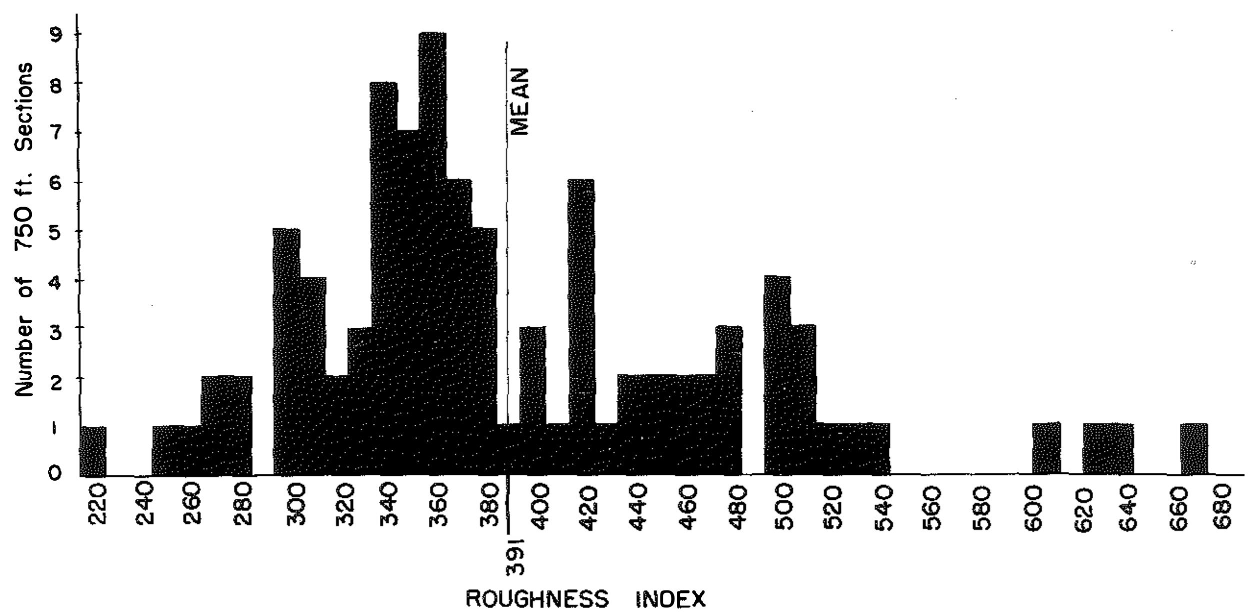
Length: 1.3 miles Date: June 1960 Type: PCC Year Constructed: 1960

Roughness Index by lanes:

inner (W. B.) 407	outer (W. B.) 380
inner (E. B.) 435	outer (E. B.) 420

US 60
LEXINGTON - VERSAILLES

⅓ rule



Length: 12 miles

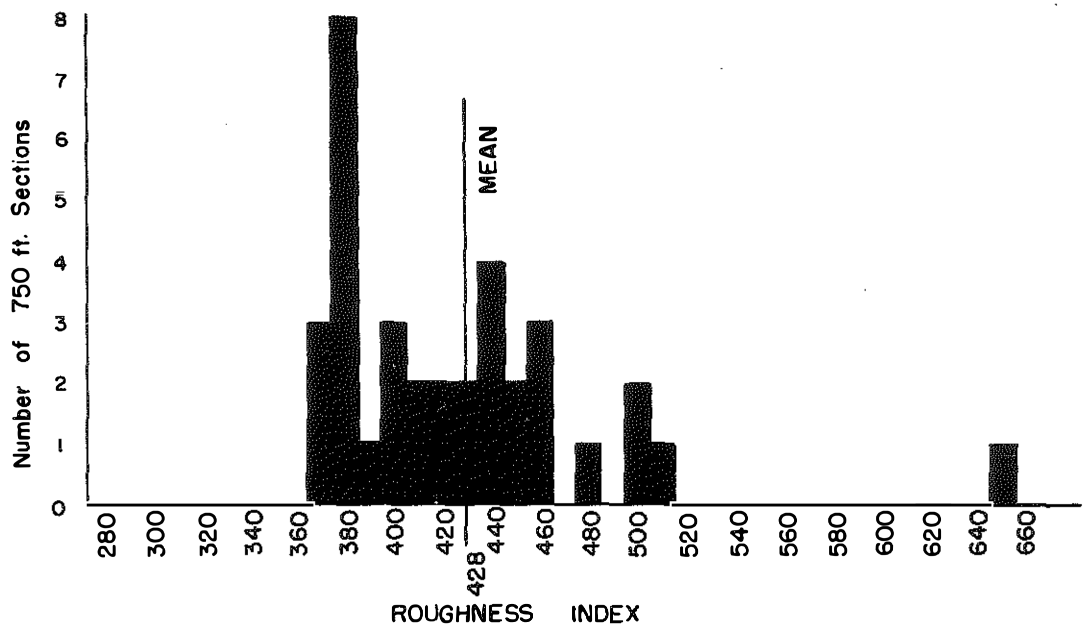
Date: June & September 1960

Type: PCC

Year Constructed: 1940

US 31W

ELIZABETHTOWN - LOUISVILLE



Type: PCC

Date: December 1960

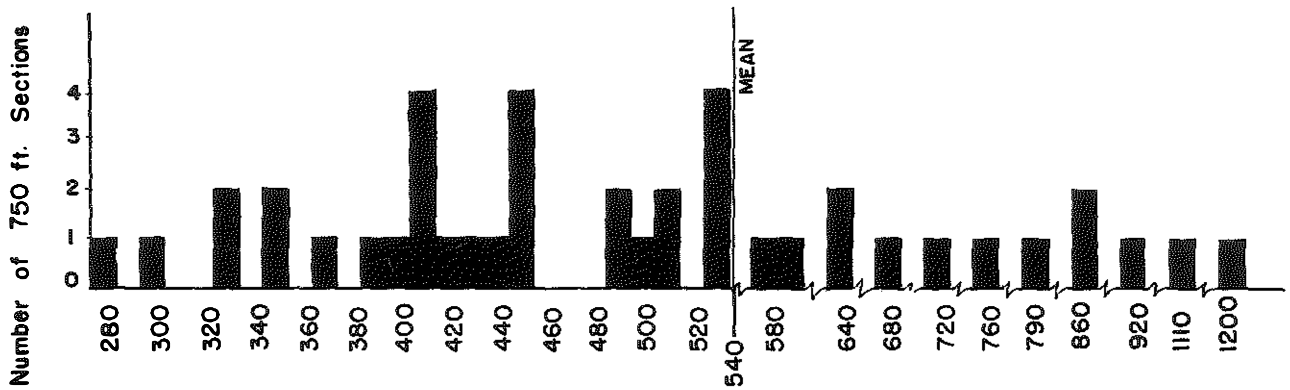
Length: 4.7 miles

Year Constructed: 1960

US 31-W

½ rule

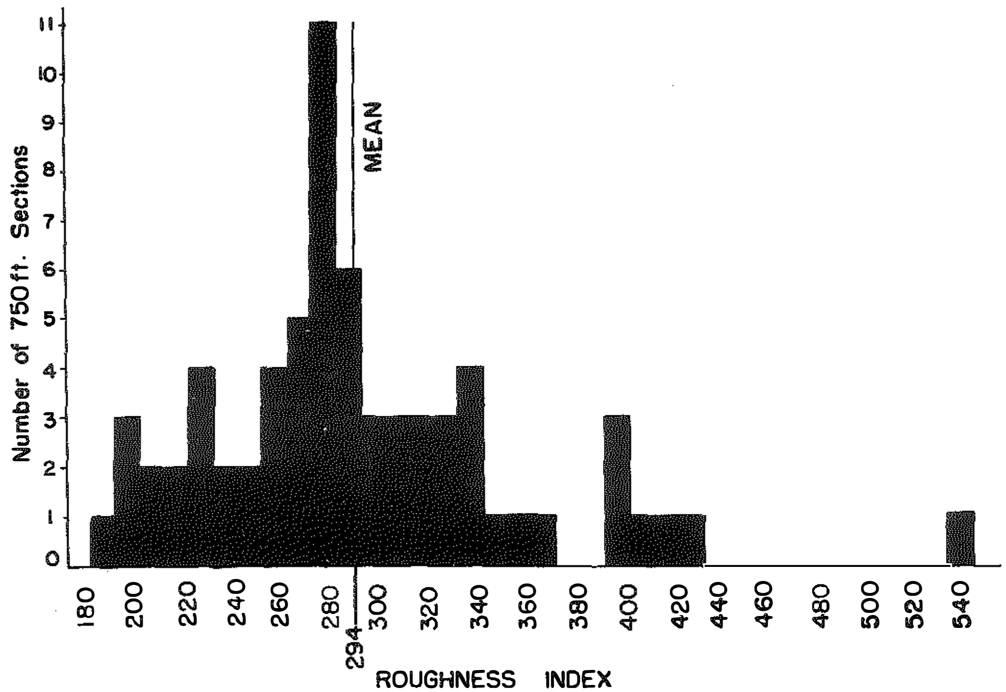
FRANKLIN - TENN. LINE



Length: 2.8 miles   Date: August 1960   Type: PCC

Year Constructed: 1949

US 25-E
BARBOURVILLE - CORBIN



Year Constructed: 1960

Length: 4.7 miles

Date: September 1960

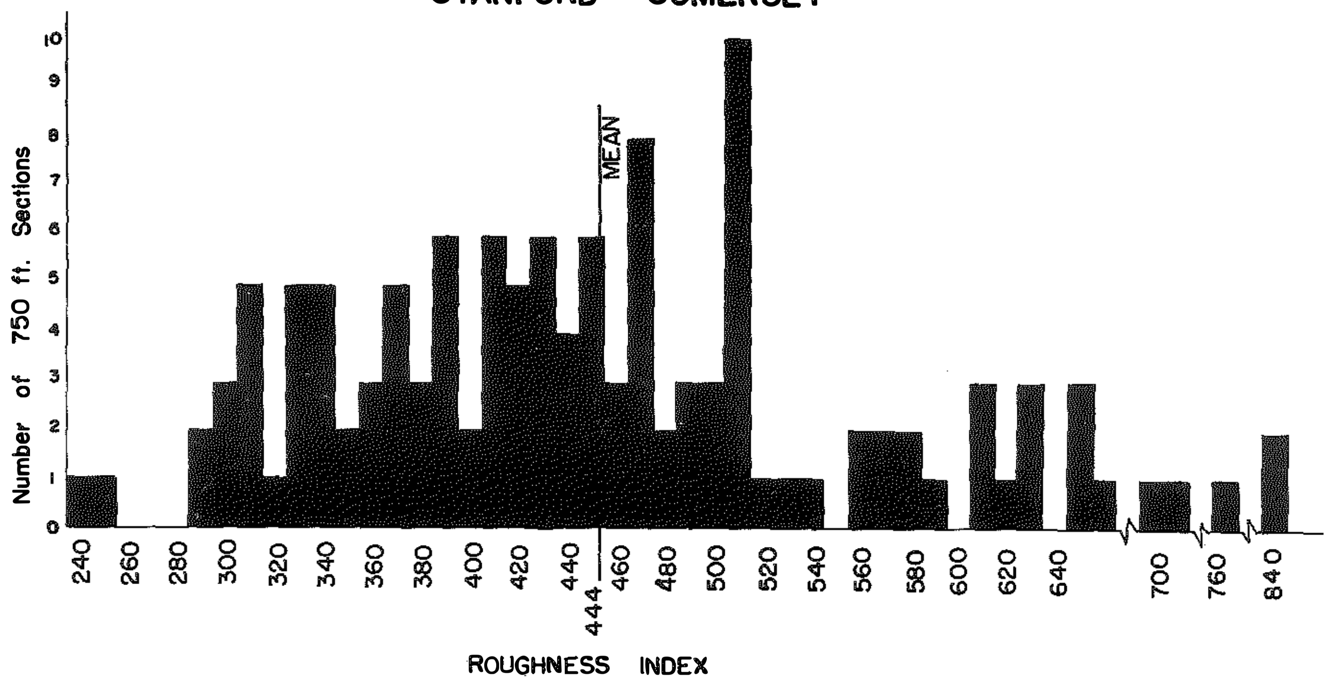
Type: Bituminous Concrete

Roughness Index by lanes:

Southbound - 308

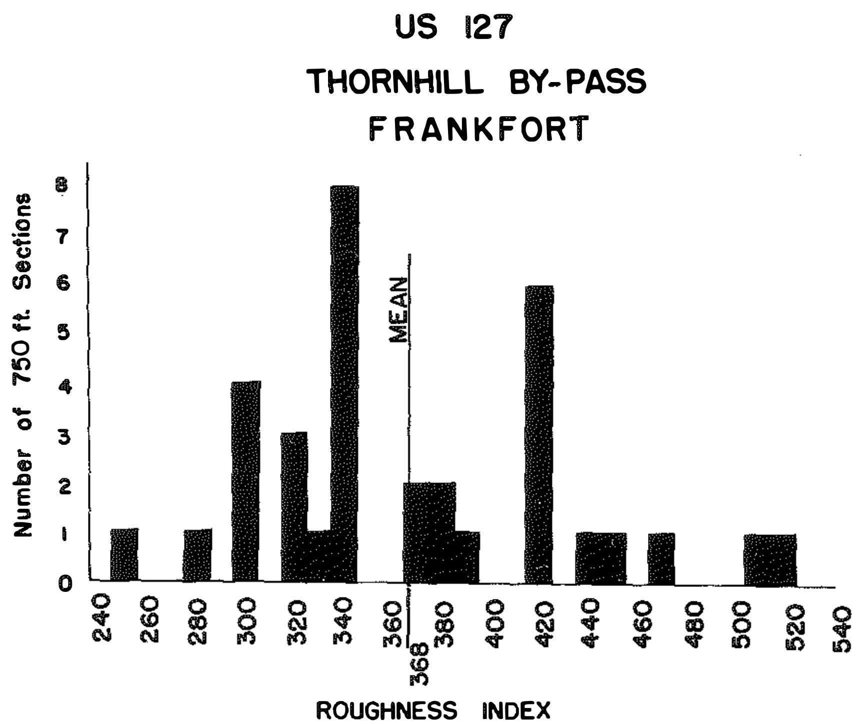
Northbound - 282

US 27
STANFORD - SOMERSET



Length: 17.6 miles
Date: July 1960
Type: Bituminous Concrete

Year Constructed: 1959
NOTE: Southbound lane only

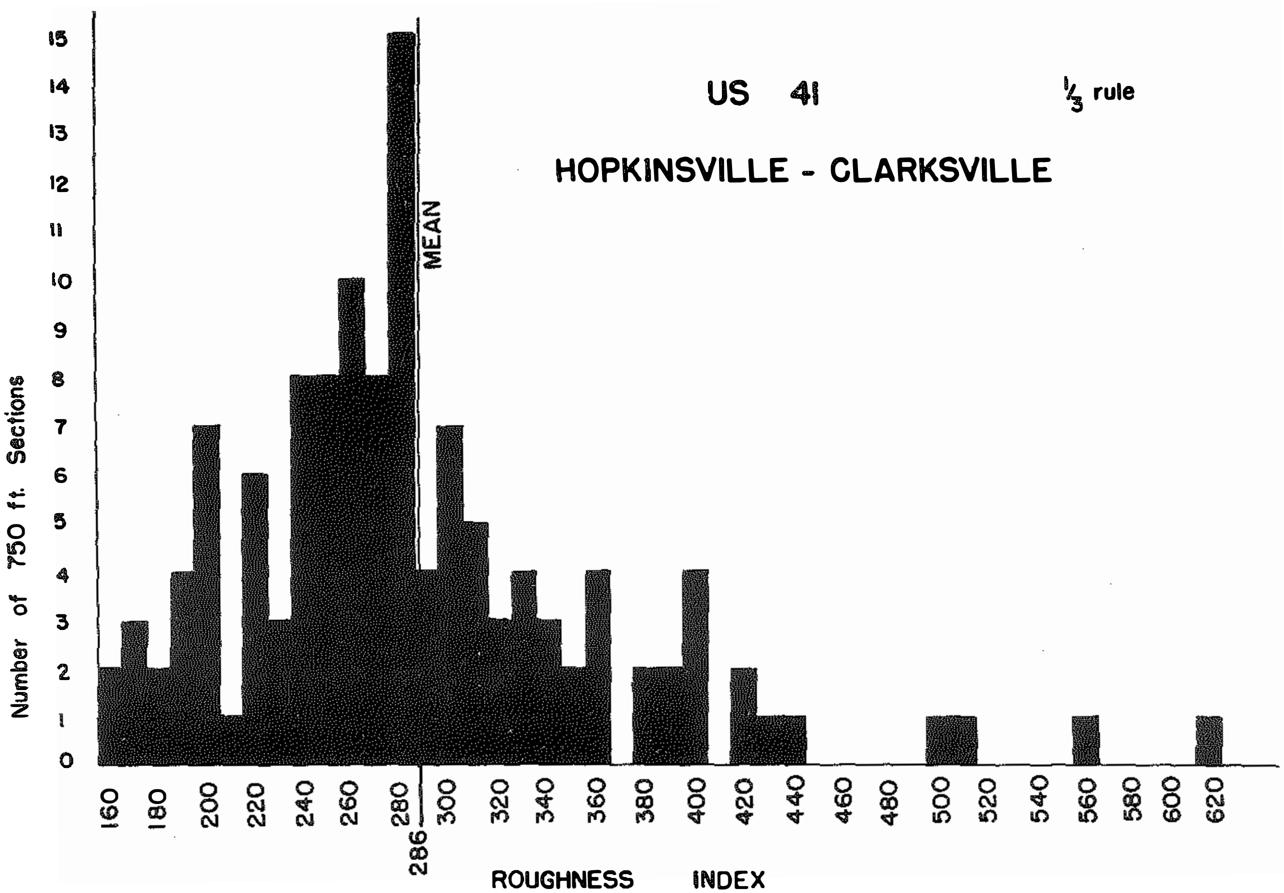


Length: 1.2 miles Date: June, 1960 Type: Bituminous Concrete

Year Constructed: 1959

Roughness Index by Lanes:

inner (S.B.) = 323
inner (N.B.) = 347
outer (S.B.) = 415
outer (N.B.) = 401



Length: 13 miles

Date: August, 1960

Type: PCC Base & Bituminous Concrete Surfacing

Year Constructed: 1956

APPENDIX II

ANALYSIS OF RIDING QUALITY

In order to express roughness in terms of "jerk" (rate of change of acceleration), which is thought to be more significant index of riding quality, it is necessary to know the "effective" amplitudes of the accelerations and their frequencies. A study of the records from various types of pavements was made to determine the relationships between acceleration amplitudes and their corresponding frequencies. Individual acceleration amplitudes of 0.05 g's or greater were measured in 0.05 g. increments, and these were plotted versus their corresponding frequencies. As illustrated in Fig. 5, amplitudes of increasing magnitude tend to occur at characteristically lower frequencies. In fact, the highest amplitudes approach the natural frequency of the car-body suspension system (1.5 cps.), and the higher frequencies (lowest amplitudes) tend to approach the wheel-hop frequency (about 5 cps.). The solid curve was derived from records taken on bituminous pavements and new concrete pavements. The dashed curve represents only older concrete pavements. This difference may be attributable to the fact that earlier pavements had closer joint intervals and to the fact that the joints were formed rather than sawed. Theoretically, a pavement with 25-ft. joint spacings would tend to induce vibrations at a rate of 3.5 per second at 60 mph.

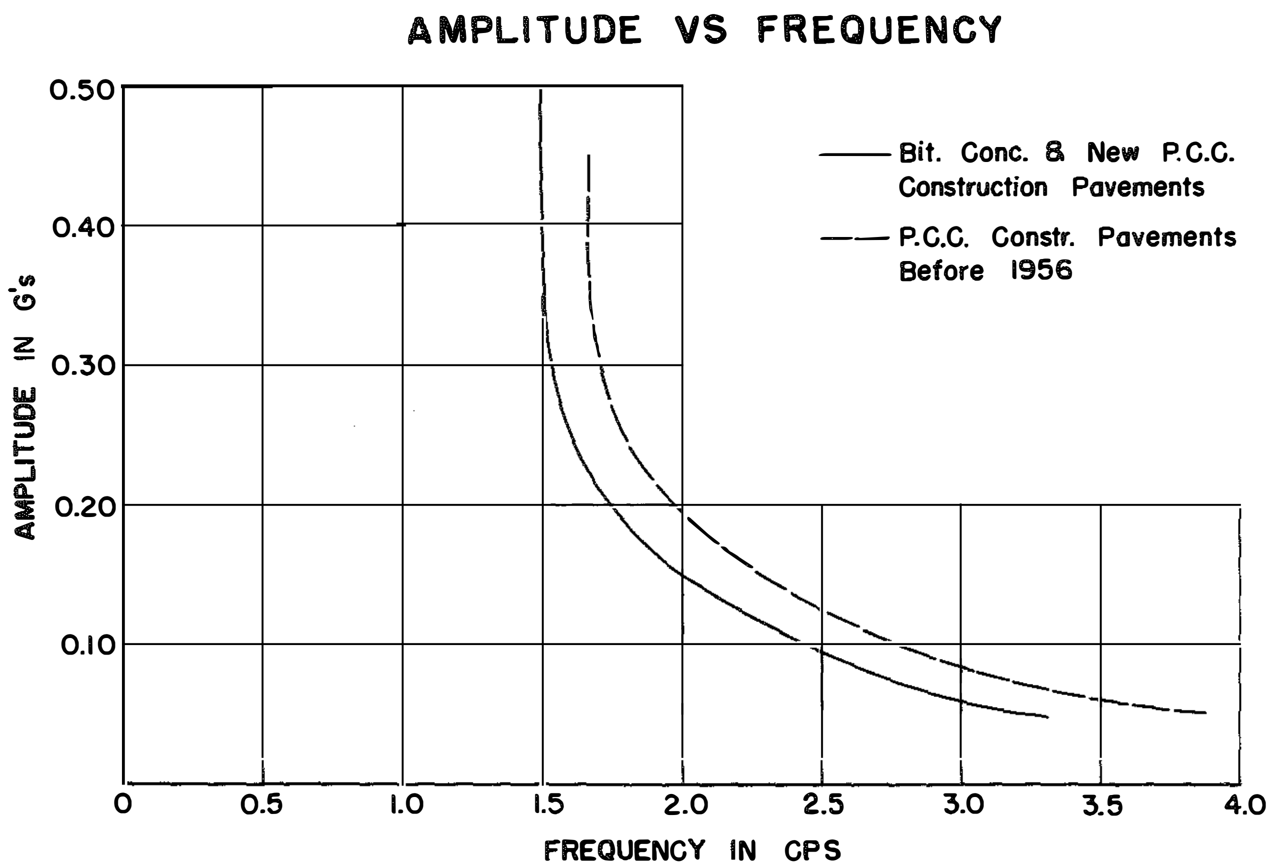


Fig. 5. Graph of Acceleration Amplitudes of Portland Cement Concrete and Bituminous Concrete Pavements vs. Frequency of these Amplitudes.

Although it was not stated so above, it is implied that if the median acceleration amplitude is determined by analysis of the record from a road, the corresponding median or "effective" frequency may be estimated from the curve in Fig. 5. Using the median amplitude and the interpolated frequency, a corresponding "jerk" value may be calculated, as follows:

Median Amplitude (in g's) x 2 x Frequency (in cps.)

= "jerk" (in g's per sec.).

In order to express the roughness of a road in terms of average g's (as in the roughness index) and also in terms of "jerk", it would be necessary to analyze the record by summing the areas under the acceleration curve and by determining the median amplitude. However, it was found from analyses of several roads that roughness index values correlated rather closely with "effective" frequency, as computed from corresponding "jerk" values (see Fig. 6). Consequently, average g's must be related to the median value of g (median amplitude) through the frequency parameter. In any case, according to Fig. 6, a roughness index may be used to interpolate an "effective" frequency from which, in turn, a corresponding "effective" amplitude may be interpolated from Fig. 5. Hence, it is possible to calculate a "jerk" value corresponding to roughness indexes. This has been done, and the equivalent values have been entered in Fig. 6, for more direct interpolations.

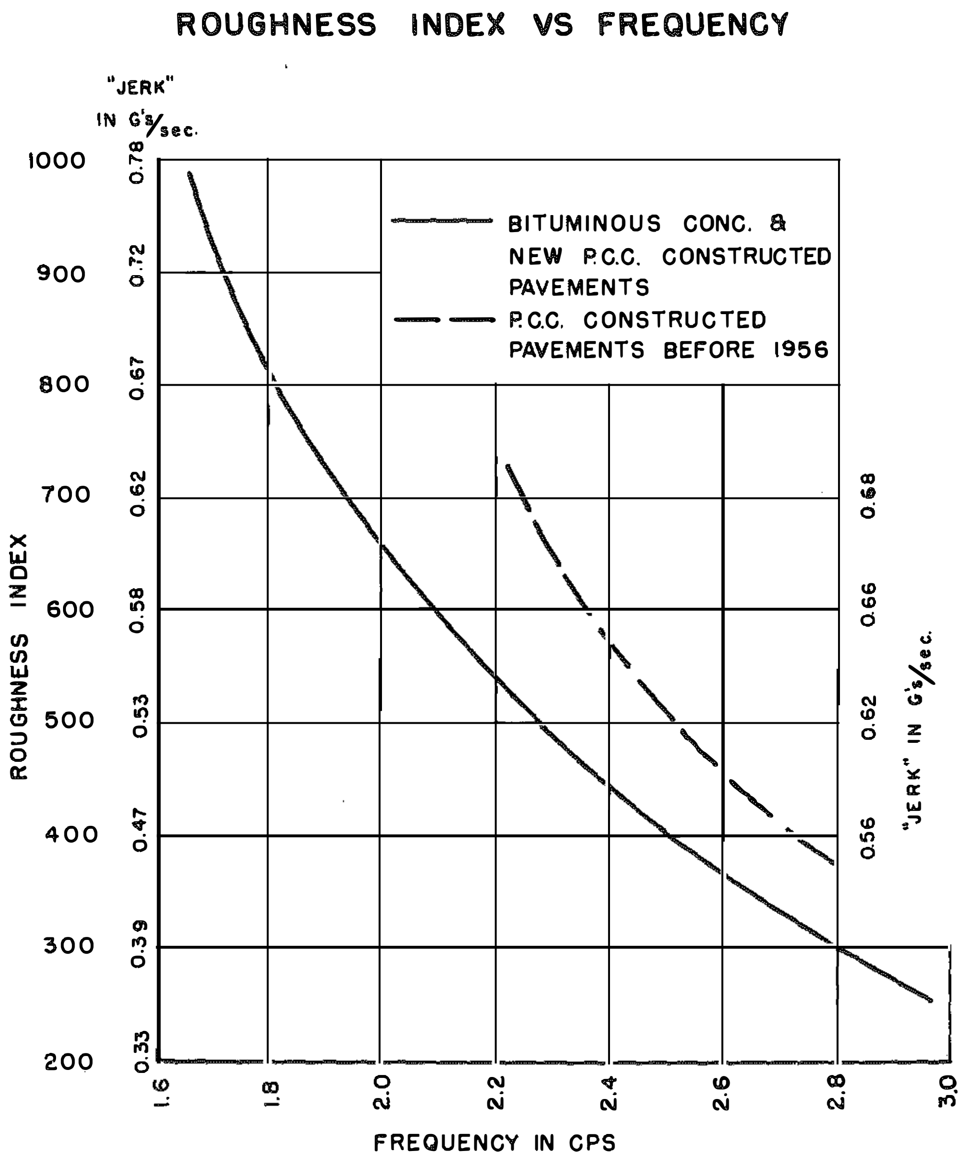


Fig. 6. Roughness Indexes Plotted against its Corresponding "Effective" Frequency of Bituminous Concrete and New Portland Cement Concrete Pavements. This Curve provides Means by Which to Convert Roughness Index Directly to Average "Jerk".

Riding quality is adjudged from the standpoint of human perception and discomfort thresholds to translational motion. For instance, a person in a closed elevator can not sense velocity; he can sense changes in velocity (acceleration); and, according to the concept of "jerk", he can sense rate of change in acceleration moreso under some conditions than he can sense acceleration. Hence, others (4)(5) have attempted to establish both perception thresholds and discomfort thresholds. Obviously, a passenger in a car can not be discomforted or fatigued by something which he can not even sense (see note below).

Note: There are more interesting aspects to this problem -- some of which involve motion sickness and fatigue. For instance, animals such as dogs and cats are susceptible to motion sickness; and a person who is completely immobolized and isolated becomes discomforted and fatigued. Also a person walking - which is certainly a normal and oftentimes enjoyable activity - experiences some fairly high accelerations and "jerks"; yet it seems ridiculous to think of walking as being uncomfortable. It is undeniable, of course, that a ride in a jolt-wagon over a rocky road would be unpleasant. In the most extreme concept of discomfort, it has been stated from studies of collisions that 40 g's if sustained for only a few milliseconds will cause "irreversible injury" (death).

According to McConnell (4), the approximate perception thresholds to translational motion are as follows:

Direction	Acceleration	"Jerk"
Vertical	± 0.125 g's	± 0.025 g's/sec.
Lateral	± 0.019 g's	± 0.009 g's/sec.
Longitudinal	± 0.030 g's	± 0.016 g's/sec.

According to the records analyzed thus far, the average vertical accelerations for the individual roads studied ranged between 0.023 g's and 0.099 g's; and, according to McConnell's criterion, the average accelerations experienced on all roads would be imperceptible. However, the very smoothest roads exhibited some amplitudes (about 15%) which were higher than 0.125 g's (the perception threshold); whereas, the roughest roads exhibited as many as 66% of the amplitudes above the perception threshold.

The average "jerk" values of the pavements in this study ranged from 0.395 g/sec. to 0.770 g/sec.; whereas, according to studies of comfort limits in the vertical direction, as introduced by R. N. Janeway (4), 1.27 g/sec. are regarded as being uncomfortable. Accelerations on bituminous concrete and newly constructed PCC pavements indicate that acceleration amplitudes above 0.42 g's will induce an average "jerk" of 1.27 g/sec. which may be considered uncomfortable. On older PCC pavements, accelerations of 0.37 g's combined with a higher frequency also yield an average "jerk" in excess of 1.27 g/sec. The roughest pavement encountered had 5.5% of all measured amplitudes above 0.42 g's. All of the pavements were rougher than the perception threshold of $\pm$ 0.025 g/sec. Even the smallest measured acceleration computed a rather high "jerk" value.

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2. Foy, W. S.; "Analysis of Pavement Riding Quality", Intra-departmental Report, Highway Materials Research Laboratory, Kentucky Department of Highways, November, 1956.

3. Drake, W. B. and Havens, J. H.; "Kentucky Flexible Pavement Design Studies", Bulletin No. 52, Engineering Experiment Station, University of Kentucky, June, 1959.

4. McConnell, W. A.; "Human Sensitivity to Motion as a Design Criterion for Highway Curves", Bulletin 149, Highway Research Board, Publication 483, 1957, pp. 34-56.

5. Janeway, R. N.; "Vehicle Vibration Limits to Fit the Passenger", Preprint of a paper presented at the meeting of the Society of Automotive Engineers, March, 1948 (Abstract, SAE Journal, August, 1948).