

Research Report
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PAVEMENT ROUGHNESS IN KENTUCKY

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16. Abstract Over two hundred pavement sections in Kentucky have been periodically measured for pavement roughness over a period of several years. This pavement service-life historical data can be used to assess quality of construction, pavement service-life, present and anticipated pavement condition. Road users perception of ride quality can be related to these measurements. Response-type road roughness measuring systems have been used to collect roughness measurements and correlation studies have been performed to relate measurements from current systems. Several factors influence pavement roughness. An early factor is construction workmanship. Other factors are traffic loading, environment, geology, and age.					
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INTRODUCTION

The intended purpose of any highway is to carry traffic and to serve the public. A good pavement is one that rides well, provides for efficient and safe movement of goods and services, and is pleasing to the eye of the driving public. It is therefore necessary to assess the quality of service being provided by a pavement.

An important function of the engineer involves evaluation of in-service pavements. It is necessary to establish the condition of pavements from the perspective of establishing design criteria and/or maintenance and resurfacing priorities. Pavement evaluation may be considered in two categories: condition surveys and evaluation surveys. Condition surveys are made to determine the condition of the pavement at a given point in time. For example, pavements may be categorized as rough versus smooth or adequate versus inadequate. Condition surveys are normally used to establish needs, priorities, or ratings. Pavement condition may be assessed in terms of four parameters: riding comfort, load-carrying capacity, safety, and aesthetics (1, 2).

Evaluation surveys deal with the determination of the structural adequacy of the pavement. These surveys generally deal with such factors as pavement thickness, pavement type, quality of paving materials, and volume and composition of the traffic stream. Evaluation surveys are generally required to establish input parameters into a pavement management and overlay design method for the formulation of rehabilitation, restoration, and reconstruction alternatives.

There are two kinds of roughness: (1) that which is constructed in the pavement and (2) that which develops in the pavement through use or abuse. Deterioration would occur from settlement of the embankment and heaving of the subgrade even if a pavement were not used. Some traffic and massaging is helpful in preserving a pavement. Overloading, however, is damaging and produces roughness. Roughness is one of the main justifications for resurfacing a pavement. A history of the development of roughness would describe the service-life of a pavement. Initial roughness alludes to the quality of workmanship in the construction. Roughness, traffic, and age are meaningful from the standpoint of how well the pavement performed or fulfilled its designed functions.

A pavement is too rough if a driver is unable to keep the vehicle under safe control while traveling at a reasonable speed or if a passenger is unable to sit comfortably in the seat or is needlessly tossed about and jolted. High-speed roadways demand a higher degree of perfection and smoothness than low-speed roads. Dips and waves in the profile not noticeable at low speeds may become hazardous at high speeds.

The road users' perceptions of pavement roughness are related to vehicle motion, expressed in terms of linear translational motion (Figure 1) and rotational motion (Figure 2). Both modes are involved in the real motion of a vehicle. The three principal directions of translational motion in a Cartesian coordinate system represent vectorial quantities.

The principal objectives in studies and investigations of road roughness have been to measure quality (smoothness) of construction and to establish eligibility and priority for overlay. Elaborate and sophisticated apparatus have been developed for measuring, recording, and analyzing actual profiles of pavements. Beginning with the most

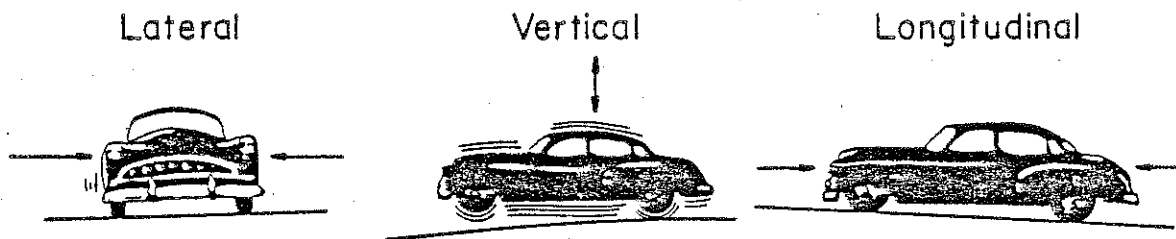


Figure 1. Linear Translational Motion Resolved into Components in the Three Principal Directions (Excluding Rotation).

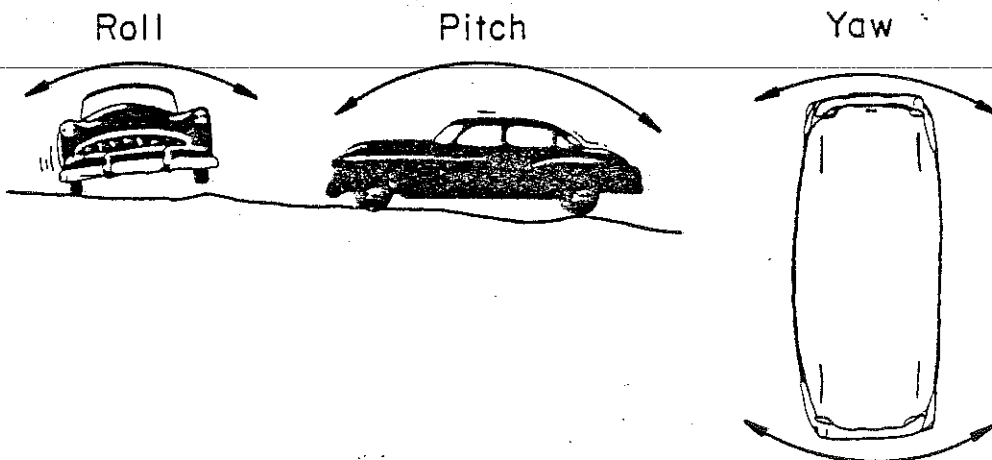


Figure 2. Rotational Motion about the Three Principal Axes.

elementary form of a straightedge, the rolling-type straightedge with recording equipment evolved. When a pavement deviates from construction tolerance specifications, "high spots" may be removed by grinding. Other devices such as the Bureau of Public Roads Roughometer measure the response of the sprung mass of the vehicle body and simulates one quarter of an automobile suspension system. Response-type devices measure the deflection of the suspension spring and eliminate the motion acceleration of the mass.

PAVEMENT ROUGHNESS MEASUREMENT

Measurements of pavement roughness have been used from two perspectives: determination of relative smoothness for motor vehicles and as a correlation factor indicating a failure of one or more component of the pavement structure. Roughness testing in Kentucky has been used to assess quality of construction and to assess pavement service-life histories and present serviceability indices relative to the road users' perceptions of ride quality.

Pavement roughness is normally divided into three components: transverse variations, longitudinal variations, and horizontal variations in pavement profile. Previous studies have shown that longitudinal variations in profile are probably the major contributors to pavement roughness (2). Transverse variations are considered the next major contributors with horizontal variations or the general curvature of the roadway as the least contributor to pavement roughness.

Pavement roughness may be measured using a number of devices. Some commonly used roughness measuring devices include the following:

1. US Bureau of Public Roads Roughometer (BPR),
2. CHLOE profilometer (CHLOE),
3. Rolling straightedge (RSE),
4. British Road Research Laboratory profilometer (RRL),
5. Surface Dynamics Profilometer (SDP),
6. Road Meter (e.g., PCA or Mays type) (RM), and
7. Precise leveling for profile determination (LEVEL).

These devices normally determine the deviation of the pavement profile from some established reference. More detailed descriptions of these testing devices and their applications are presented elsewhere (1 - 25).

In many situations, the term roughness index (RI) is used to describe the accumulation of displacements over a specified distance (2).

A strip chart from a recorder showing the profile of a mile of pavement is too long to evaluate visually or to compare with other charts. However, charts could be inspected visually to pinpoint localized roughness and to permit (1) location of the pavement in question, (2) measurement of the amplitude and wavelength of surface irregularities, and (3) judgments concerning possible remedial actions. The profile analog recorded on magnetic tape enables further evaluation in the laboratory.

PAVEMENT ROUGHNESS TESTING IN KENTUCKY

In Kentucky, pavement roughness has been measured by three response-type road roughness measuring systems:

- (1) Automatic Roughness Measuring System (ARMS),
- (2) Surface Dynamics Profilometer (SDP), and
- (3) Mays Meter, a road meter (RM) device.

ARMS uses an accelerometer to measure vertical movements of a passenger's torso. Roughness is computed as the sum of the area under the vertical acceleration trace. Roughness Index (RI) is the sum of the accelerations divided by elapsed time during the test. Roughness testing using this procedure was developed in Kentucky during the late 1950's and early 1960's.

A Surface Dynamics Profilometer, purchased by the Kentucky Department of Transportation in 1968, measures the actual pavement profile of one or two road tracks at speeds comparable to those of highway travel. Both the amplitude and wavelength of surface irregularities may be determined. In 1970, a Quarter-Car Simulator (Model 1088), a special purpose analog computer designed to process Surface Dynamics Profilometer data, was added. The Quarter-Car Simulator is an electrical analogy of a vehicle suspension and includes the tire, wheel mass, suspension springs, shock absorber, and vehicle mass. Two vehicle simulation models are available -- the Bureau of Public Roads Roughometer (BPR) and a 1969 Chevrolet Impala. The use of the SDP and Quarter-Car Simulator in Kentucky is described in detail elsewhere (17).

Surface Dynamics Profilometer pavement profiles processed through the Quarter-Car Simulator give output in g's per mile (Roughness Index) (16 - 18). An index was developed to range between 180 for a very smooth pavement to 1,000 for a very rough pavement. Roughness index is given in g's X 10⁴.

One approach thought to be the ultimate for processing and reducing roughness recordings was a power spectrum analysis. An analog magnetic tape representing a length of pavement is scanned continuously in playback until all events have been sorted and compiled. Power is a rate of expending energy, and the output chart portrays the energy levels associated with frequencies and numbers of events. A power spectrum analyzer was acquired; but unfortunately, the equipment could not be made to operate satisfactorily. Efforts were abandoned after a few years.

A Mays Ride Meter, to measure rear-axle-to-body excursions through a photocell sensing system was purchased in 1977. That system drives a stepping motor for pen and chart drive movements of a 6-inch wide paper tape recorder. The recording pen moves at a rate proportional to the movements of the differential and vehicle body. Roughness is proportional to the total undercarriage movement and is obtained by measuring the amount of chart movement per unit length traveled. Distance traveled is indicated on the chart by an event marker attachment to the speedometer drive (2).

Roughness indices as determined by the ARMS method were correlated with profile measurements obtained with SDP and evaluated using the Quarter-Car Simulator. Roughness indices obtained from the BPR roughometer simulation correlated well with the Kentucky automobile method of test (17).

Mays Ride Meter values have been correlated with the SDP and Quarter-Car Simulator. An indirect correlation therefore is available relating roughness as determined by the Kentucky ARMS method and roughness as measured by the Mays Ride Meter. The equations, correlation

coefficients, and procedures used in the collection of data and the development of the equations are presented in Appendix A.

HISTORICAL TRENDS IN PAVEMENT ROUGHNESS

Over two hundred pavement sections have been evaluated for pavement roughness on a periodic basis during the past twenty to twenty-five years. The times between testing have varied. Pavement sections have been grouped according to network classifications: Interstates, Parkways, US Routes, and Kentucky Routes. A more complete description of the data sample is presented in Tables 1 through 4.

Since several test vehicles have been used, the development of a pavement roughness service-life history requires "standardization" of data to some established reference. Initial roughness estimates were established using the Kentucky ARMS method. Later estimates of pavement roughness were determined using the SDP and Quarter-Car Simulator. Still later, estimates of pavement roughness were obtained using the Mays Meter. The Kentucky ARMS method was selected as the reference. Correlations are documented in Appendix A.

CLASSIFICATION OF DATA

Pavement types may be grouped into three general categories: flexible pavements (bituminous-asphaltic concrete), rigid pavements (portland cement concrete), and composite pavements (two or more distinctly different bound layers). Inspection of Kentucky roughness data indicated that measurements had been made in all categories. Flexible pavements were separated into two groups: asphaltic concrete pavements and asphaltic concrete pavements overlaid with another asphaltic concrete layer. All rigid pavements were grouped together. No attempt was made to separate pavements according to type of reinforcement or other features. The only composite pavements found in the data sample consisted of rigid pavements having an asphaltic concrete overlay. Those pavements were grouped together. The data were subdivided into four separate categories:

1. Asphalt Concrete Pavements,
2. Asphaltic Concrete Overlays on Asphaltic Concrete Pavements,
3. Portland Cement Concrete Pavements, and
4. Asphaltic Concrete Overlays on Portland Cement Concrete Pavements.

The data also will be subdivided according to network classifications:

1. Interstates,
2. Parkways,
3. US Routes, and
4. Kentucky Routes.

FACTORS CONTRIBUTING TO PAVEMENT ROUGHNESS

Pavement roughness is made up of both long wavelength, low frequency, high amplitude disturbances in the pavement surface and also disturbances of low amplitude, high frequency, short wavelengths. Long wavelength roughness is normally associated with consolidation and differential settlement of foundation materials (1). Geology and material characteristics of the foundation material may be very closely related to long wavelength roughness. Short wavelength roughness is

TABLE 1. DESCRIPTION OF ROUGHNESS DATA FOR INTERSTATE ROUTES
(Distributions are Presented in Appendix B)

PAVEMENT TYPE*	SECTIONS		ROUGHNESS INDEX				TOTAL MILES	SECTION LENGTHS (MILES)			
	PERCENT	NUMBER	MEAN	MIN	MAX	RANGE		MEAN	MIN	MAX	RANGE
1	72	481	390	195	785	590	3192.0	6.6	0.3	12.6	12.3
2	21	139	380	230	650	420	750.9	5.4	2.5	9.5	7.0
3	4	27	265	195	420	225	130.1	4.8	2.5	8.1	5.3
4	3	24	435	330	630	300	102.0	4.2	0.3	11.8	11.5
Totals	100	671	385	195	785	590	4175.0	5.3	1.4	10.5	9.1

Median Roughness Index -- 380

YEARS IN SERVICE	NUMBER OF SECTIONS	MEAN RI
0.0 - 2.4	171	330
2.5 - 7.4	229	380
7.5 - 12.4	116	420
12.5 - 17.4	87	420
17.5 - 22.4	63	440
22.5 - 27.4	5	605

*Pavement Types

- 1 -- Portland Cement Concrete
- 2 -- Asphaltic Concrete
- 3 -- Asphaltic Concrete over Asphaltic Concrete
- 4 -- Asphaltic Concrete over Portland Cement Concrete

TABLE 2. DESCRIPTION OF ROUGHNESS DATA FOR PARKWAY ROUTES
(Distributions are Presented in Appendix B)

PAVEMENT TYPE*	SECTIONS		ROUGHNESS INDEX				TOTAL MILES	SECTION LENGTHS (MILES)			
	PERCENT	NUMBER	MEAN	MIN	MAX	RANGE		MEAN	MIN	MAX	RANGE
1	54	285	370	200	600	400	1994.1	7.0	1.1	17.6	16.5
2	42	219	350	180	985	805	1558.6	7.1	0.6	15.8	15.2
3	4	21	335	250	420	170	111.0	5.3	0.8	16.5	15.7
4	0	0	-	-	-	-	-	-	-	-	-
Totals	100	525	360	180	985	805	3663.7	7.0	0.6	17.6	16.5
Median Roughness Index		- 355									
YEARS IN SERVICE	NUMBER OF SECTIONS		MEAN RI								
0.0 - 2.4	139		325								
2.5 - 7.4	198		360								
7.5 - 12.4	94		400								
12.5 - 17.4	66		380								
17.5 - 22.4	28		395								
22.5 - 27.4	-		-								

*Pavement Types

- 1 -- Portland Cement Concrete
- 2 -- Asphaltic Concrete
- 3 -- Asphaltic Concrete over Asphaltic Concrete
- 4 -- Asphaltic Concrete over Portland Cement Concrete

TABLE 3. DESCRIPTION OF ROUGHNESS DATA FOR KENTUCKY ROUTES
(Distributions are presented in Appendix B)

PAVEMENT TYPE*	SECTIONS		ROUGHNESS INDEX				TOTAL MILES	SECTION LENGTHS (MILES)			
	PERCENT	NUMBER	MEAN	MIN	MAX	RANGE		MEAN	MIN	MAX	RANGE
1	0	0	-	-	-	-	-	-	-	-	-
2	84	74	495	260	995	735	304.0	4.1	1.4	9.3	7.9
3	9	8	430	345	570	225	24.2	3.0	0.8	4.6	3.8
4	7	6	455	415	510	95	24.6	4.1	3.9	4.5	0.6
Totals	100	88	465	260	995	735	352.8	3.7	0.8	9.3	8.5

SYSTEM CLASSIFICATION**	PAVEMENT TYPE	SECTIONS			TOTAL MILES
		PERCENT	NUMBER	MEAN RI	
3	2	86	49	470	210.0
	3	7	4	395	12.1
	4	7	4	470	15.6
Totals		100	57	465	237.7
4	2	72	11	605	59.4
	3	14	2	565	5.4
	4	14	2	425	9.0
Totals		100	15	575	73.8
6	2	88	14	515	34.6
	3	12	2	355	6.8
	4	0	0	-	-
Totals		100	16	495	41.4

Median Roughness Index - 490

*Pavement Types

- 1 -- Portland Cement Concrete
- 2 -- Asphaltic Concrete
- 3 -- Asphaltic Concrete over Asphaltic Concrete
- 4 -- Asphaltic Concrete over Portland Cement Concrete

**System Classifications

- 3 -- State Primary
- 4 -- State Secondary
- 6 -- Urban

TABLE 4. DESCRIPTION OF ROUGHNESS DATA FOR US ROUTES
(Distributions are Presented in Appendix B)

PAVEMENT TYPE*	SECTIONS		ROUGHNESS INDEX				TOTAL MILES	SECTION LENGTHS (MILES)			
	PERCENT	NUMBER	MEAN	MIN	MAX	RANGE		MEAN	MIN	MAX	RANGE
1	34	168	480	285	775	490	857.0	2.0	1.0	8.6	7.6
2	29	148	460	250	830	580	592.1	1.0	2.2	6.4	4.2
3	30	149	470	215	840	625	665.8	2.4	0.3	10.9	10.6
4	7	37	430	165	715	550	162.8	2.1	0.6	6.7	6.1
Totals	100	502	465	165	840	680	2277.7	1.9	0.3	10.9	10.6

SYSTEM CLASSIFICATION*	PAVEMENT TYPE	SECTIONS			TOTAL MILES
		PERCENT	NUMBER	MEAN RI	
3	1	36	119	475	656.5
	2	39	130	470	537.1
	3	16	55	480	234.5
	4	9	30	425	136.0
Totals		100	334	470	1564.1
4	1	24	37	515	146.2
	2	12	18	385	55.0
	3	60	93	460	429.0
	4	4	7	445	26.7
Totals		100	155	465	656.9
6	1	92	12	420	54.3
	2	0	0	-	0.0
	3	8	1	330	2.3
	4	0	0	-	0.0
Totals		100	13	415	56.6

Median Roughness Index - 455

*Pavement Types

- 1 -- Portland Cement Concrete
- 2 -- Asphaltic Concrete
- 3 -- Asphaltic Concrete over Asphaltic Concrete
- 4 -- Asphaltic Concrete over Portland Cement Concrete

**System Classifications

- 3 -- State Primary
- 4 -- State Secondary
- 6 -- Urban

usually associated with some defect or abnormality in the pavement structure such as heaving, washboarding, potholes, pavement breakup, etc.

There are questions concerning the effects of the environment on pavement roughness. Certainly environmental factors combine with other factors that contribute to pavement roughness. Examples include roughness associated with consolidation of embankments or heaving of pavements due to frost in the subgrade or the breakup of pavement during spring thaw. There would be some change in pavement roughness due to these environmental factors even though no traffic used the pavement.

It has been well documented that pavement temperature has a significant effect on the strength or modulus of elasticity of asphaltic concrete. It also is known that temperature affects expansion and contraction and curling and warping of portland cement concrete pavements. The effect of pavement temperature on pavement roughness measurements is not yet known. However, curling and warping of concrete pavements could affect pavement roughness more than associated changes in modulus of elasticity of flexible pavements.

The primary purpose of a pavement is to support traffic. As a pavement supports more and more traffic, it becomes more fatigued. Fatigue is normally expressed as the accumulation of equivalent 18-kip axleloads (18-kip EAL's). The accumulation of 18-kip EAL's is a function of the volume of traffic using the facility, the distribution of vehicle classifications in the traffic stream, and the degree of damage relative to one 18-kip EAL for the various vehicle classifications. All factors have some effect on change in pavement roughness associated with increased pavement fatigue.

Generally speaking, as a pavement becomes older it becomes rougher. Increase in roughness may be the result of increased traffic and the associated fatigue, environmental considerations such as consolidation and heaving, or more likely a combination of the two factors. Long-term increases in roughness normally would be considered a result of a combination of fatigue and environmental factors; whereas, short-term increases could be either of the two. For example, a short-term increase in roughness could result from an acceleration in the accumulation of 18-kip EAL's or from pavement break up during spring thaw. It is difficult to separate environmental aspects from fatigue aspects of pavement roughness. In general, pavement roughness increases with time or fatigue (loadings).

ROUGHNESS AND SERVICE LIFE HISTORIES

Test sections for evaluation of historical trend roughness data have been grouped according to network classification: interstates, parkways, US routes, and Kentucky routes. Each category was further subdivided according to pavement type: asphaltic concrete, portland cement concrete, asphaltic concrete overlying an older asphaltic concrete pavement, and asphaltic concrete overlying an older portland cement concrete pavement. Each pavement section yields a history of Pavement Roughness Index (RI) versus time in service or versus accumulated fatigue (18-kip EAL's). The rate of change in pavement roughness is related to the initially constructed pavement roughness. Normally, pavement roughness increases very slowly during the first

months of service and in many cases even decreases. Figures 3 through 6 illustrate roughness index relationships for individual sections.

Roughness Index versus time in service relationships may be combined for appropriate network classifications and pavement types. Statistical mean relationships have been developed for each category (Figures 7 through 20). It is much more difficult to develop relationships relating Roughness Index and accumulated 18-kip EAL's because the relationships vary from section to section and road to road. Also, it is very difficult to separate increases in roughness due to environmental factors such as consolidation from increases in roughness due to traffic loadings and accumulated fatigue. For these reasons, mean relationships of Roughness Index versus accumulated 18-kip EAL's were not developed.

Linear regressions have been used to describe the relationships between pavement roughness index and time-in-service. There are questions regarding the validity of a linear model. Exponential and quadratic models have been tried on a limited basis, but these models did not explain a significantly greater portion of the variability in data. It is anticipated that there is a point in time where the relationship will cease to be linear and that roughness will increase at an accelerating rate as the pavement continues to deteriorate. Such an upturn has been observed on some isolated sections requiring resurfacing and rehabilitation much earlier than anticipated. An example is presented in Figure 21.

It may be seen from Figure 21 that a number of models may be used to describe relationships between pavement roughness history and service life for a single pavement section. Generally, more complex models may define more adequately these relationships for a single pavement section; however, use of complex models becomes more difficult when a number of pavement sections are combined. In some situations, use of more complex models may not result in any significant improvement in defining variability of data than do linear models. Therefore, linear models were used for analyses presented this report. Additional study is recommended to determine more appropriate models generally relating pavement roughness with service life.

Linear regressions of roughness data were used in development of cost estimates for pavement resurfacing, restoration, and rehabilitation of interstate highways (RRR program) in 1977 and again in 1980. Results of those analyses plus estimates of accumulated pavement fatigue were presented in 1977 and 1980 reports (26, 27).

Curve fitting and statistical analyses for this study were determined using the Statistical Analyses Systems (SAS) computer program. Analyses portions of that computer program provide for sophisticated data management capabilities. In some situations, portions of a data set were missing. If the missing variable was called for during a specific analysis, all observations for that particular data record will be excluded from that particular evaluation, but other portions of that data record will be available for other analyses. A "missing data" note will appear at the bottom of any plot where some portion of the data record was missing. In those situations, data records with missing variables were not included in the specific analysis but were maintained for other evaluations.

The "out of range" note refers to data where any portion of the data record was outside the limits of the specified plotting format. Thus, the explanation of a 40-year service life on the x-axis. These limits

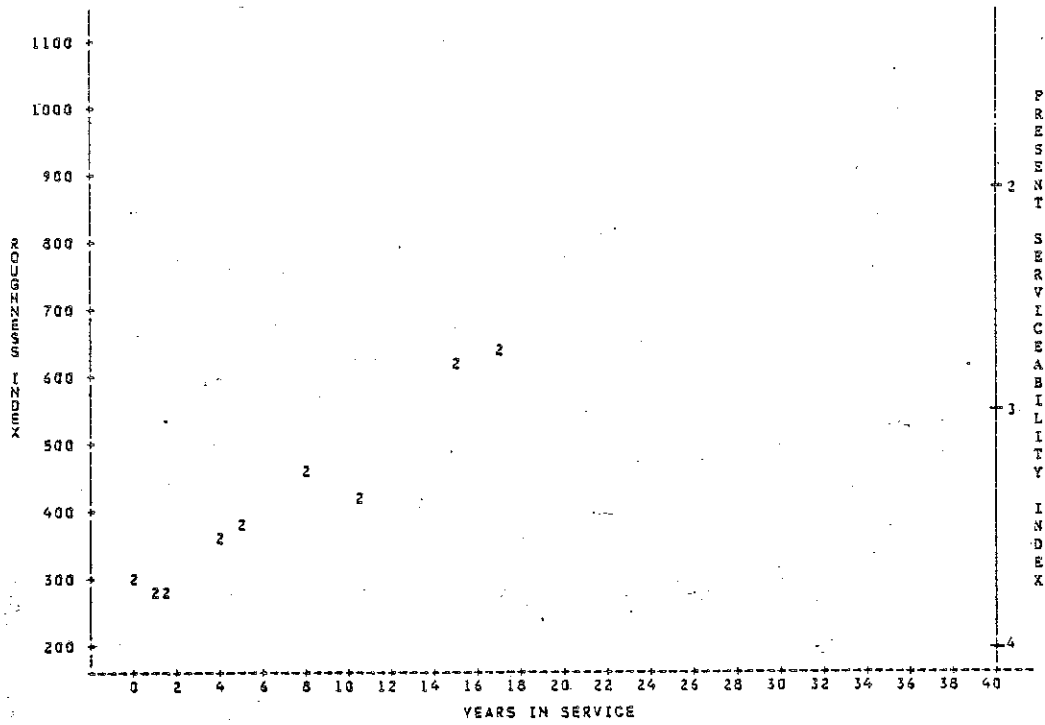


Figure 3. Roughness Index versus Months in Service for a Section of Interstate Pavement (I 64, MP 181.4 to 185.4).

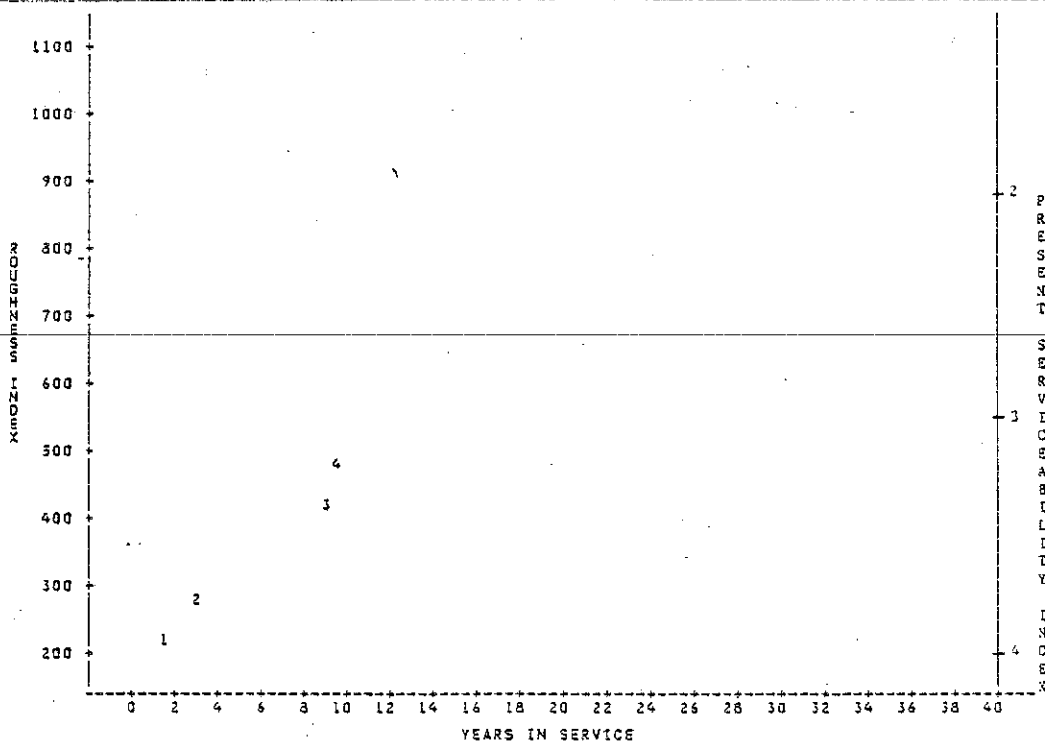


Figure 4. Roughness Index versus Years in Service for a US Primary Route (US 60 in Boyd County.)

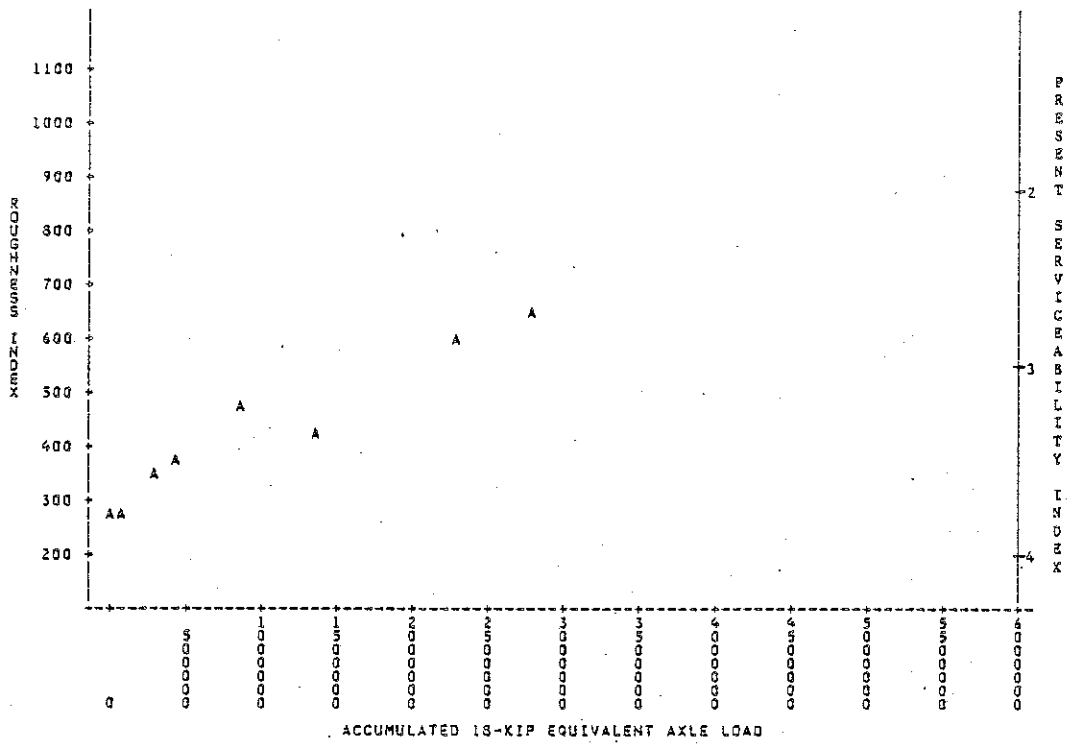
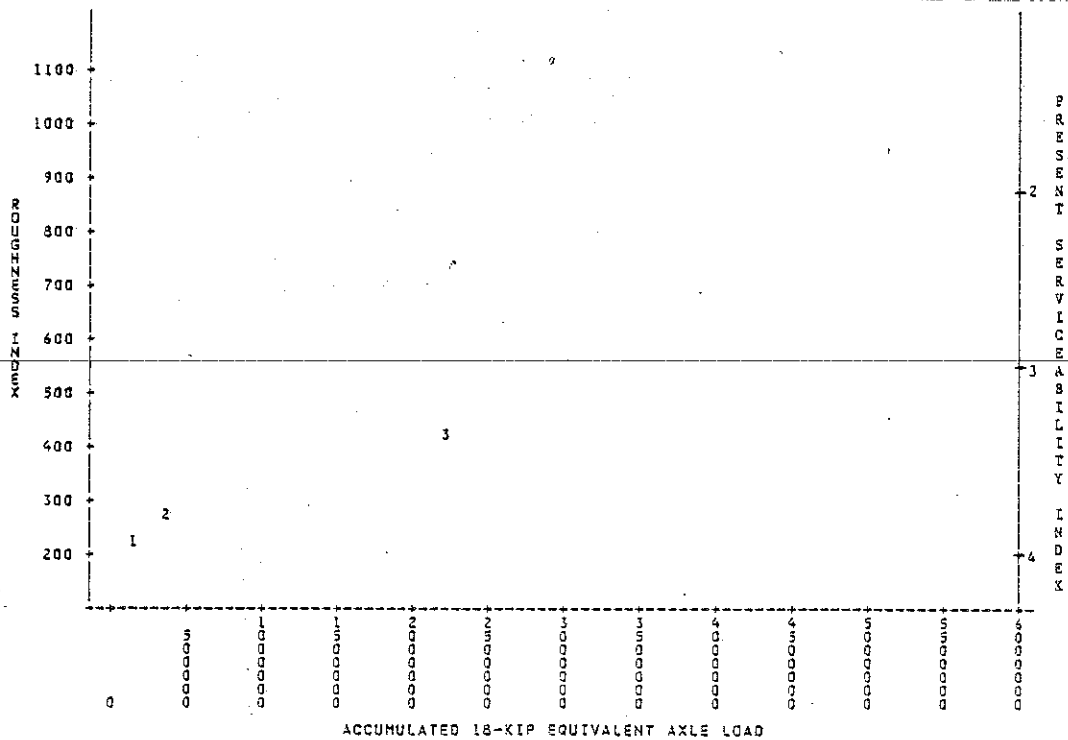
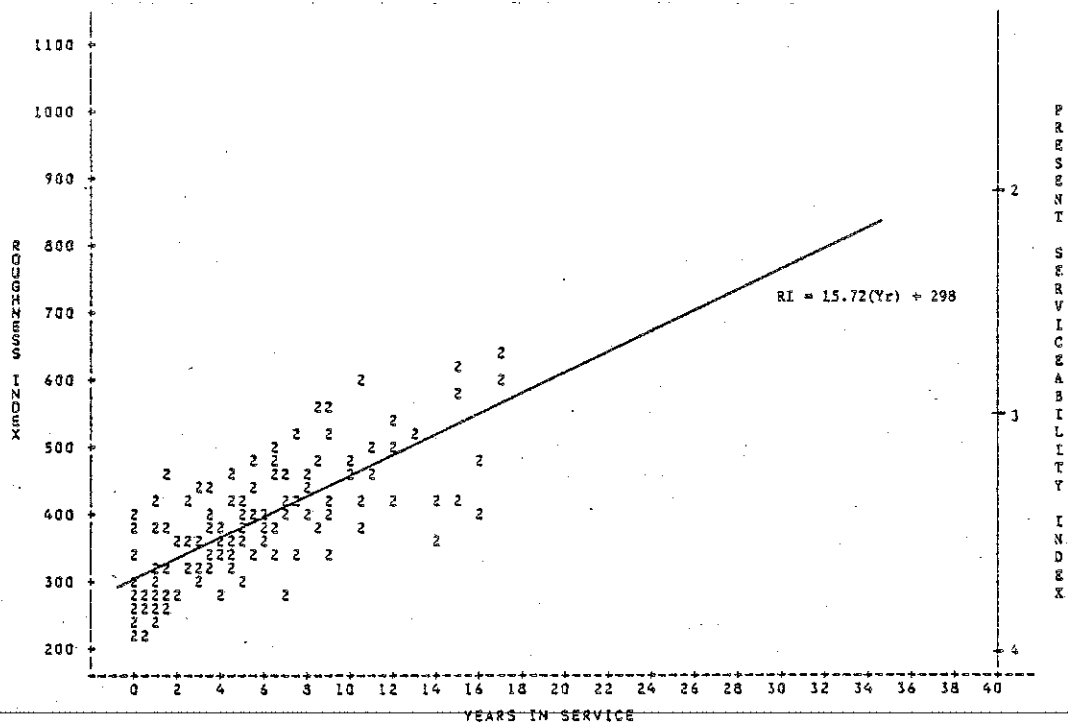


Figure 5. Roughness Index versus Accumulated 18-kip Equivalent Axleloads (I-64, MP 181.4 to 185.4).



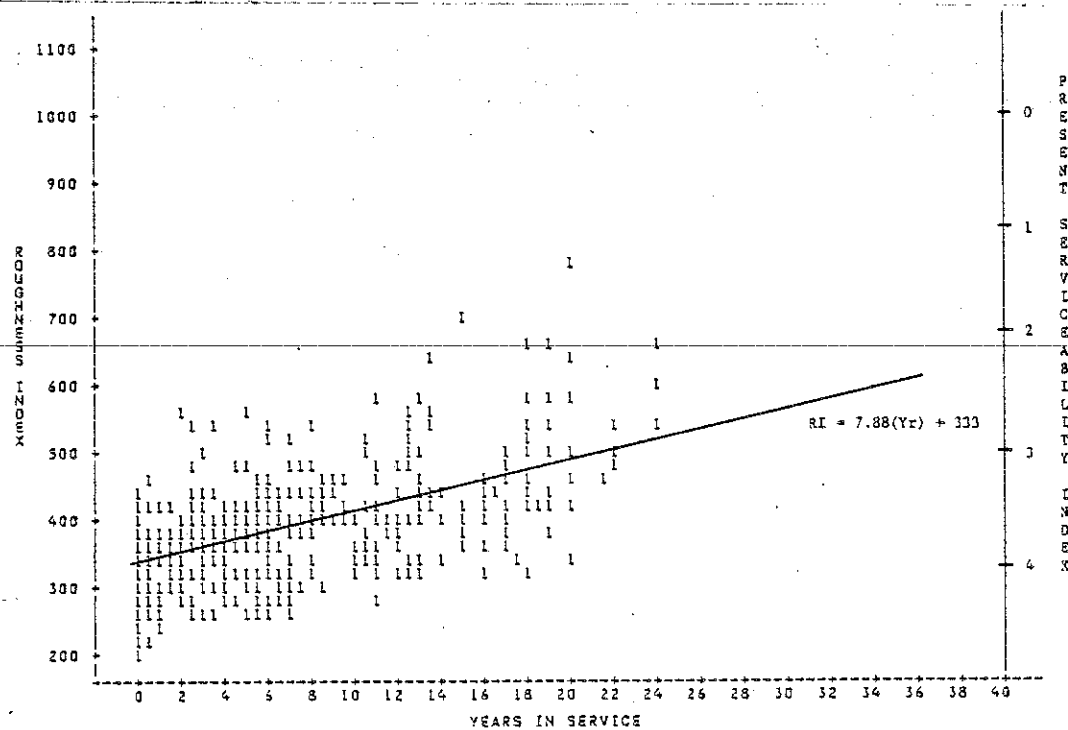
NOTE: 1 OBS HAD MISSING VALUES OR WERE OUT OF RANGE

Figure 6. Roughness Index versus Accumulated 18-kip Equivalent Axleloads (US 60, Boyd County).



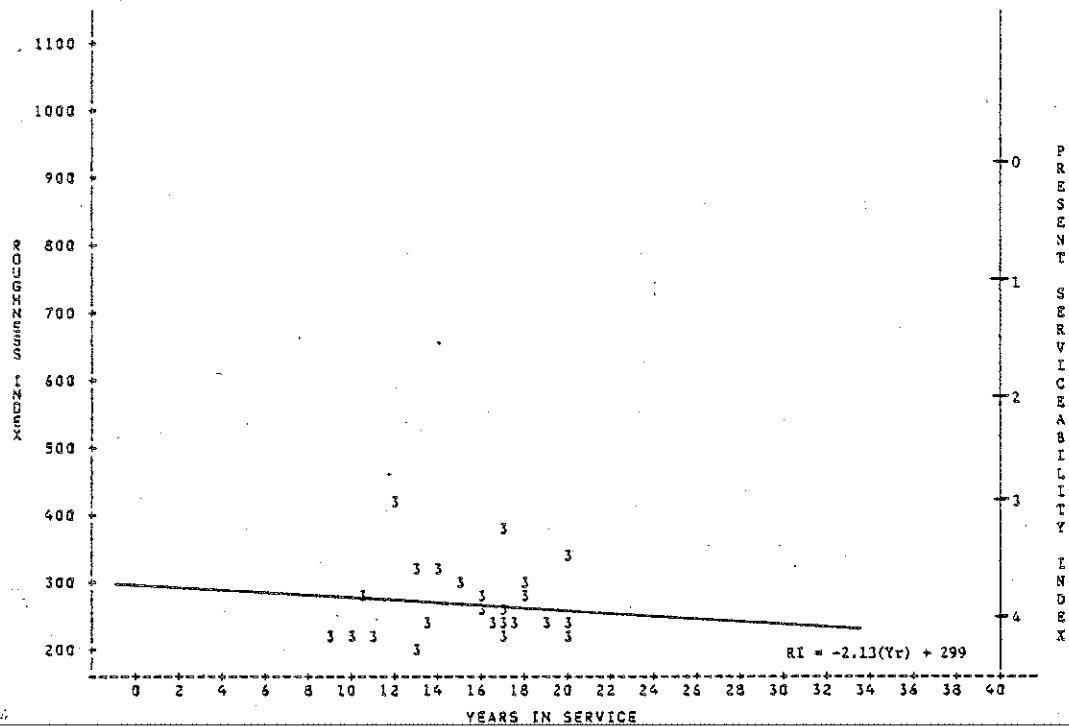
NOTE: 38 OBS HIDDEN

Figure 7. Roughness Index versus Years-In-Service: Interstates
— Asphaltic Concrete Pavements.



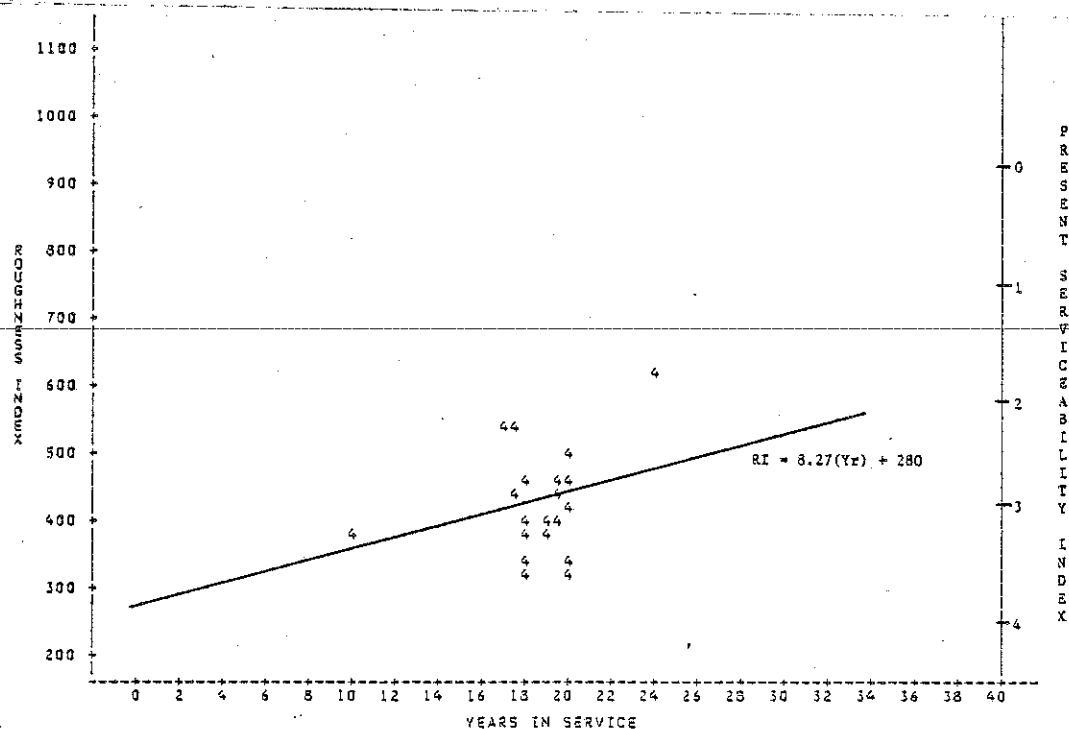
NOTE: 1 OBS HAD MISSING VALUES OR WERE OUT OF RANGE 218 OBS HIDDEN

Figure 8. Roughness Index versus Years-In-Service: Interstates
— Portland Cement Concrete Pavements.



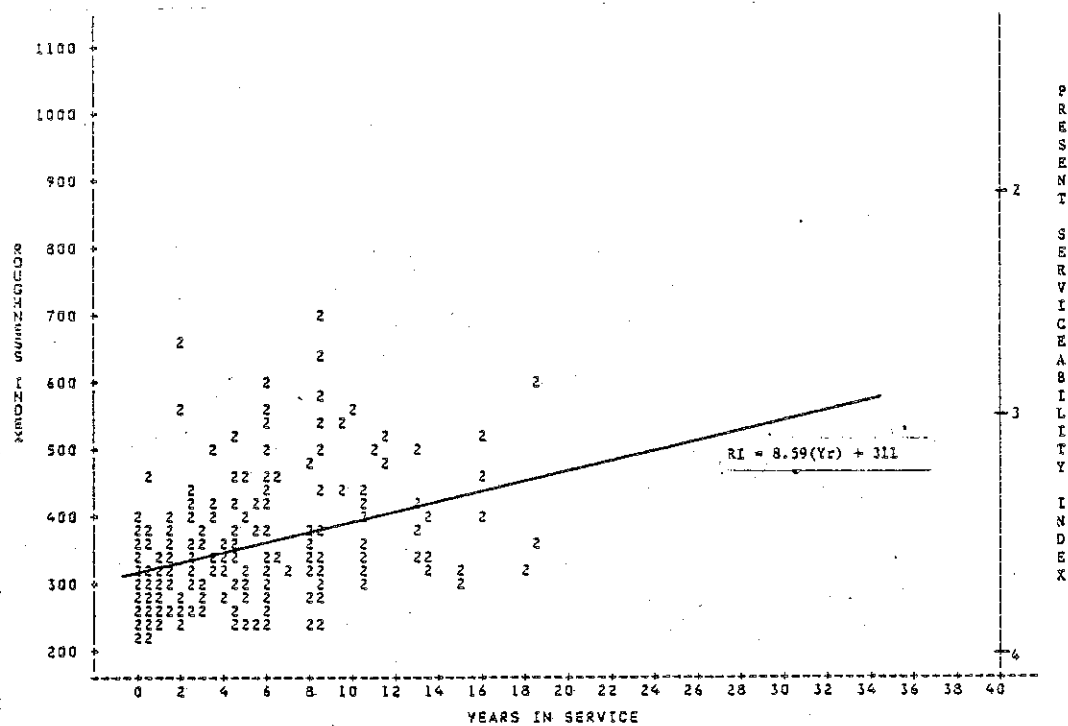
NOTE: 2 OBS HAD MISSING VALUES OR WERE OUT OF RANGE 1 OBS HIDDEN

Figure 9. Roughness Index versus Years-In-Service: Interstates -- Asphaltic Concrete Overlays on Asphaltic Concrete Pavement.



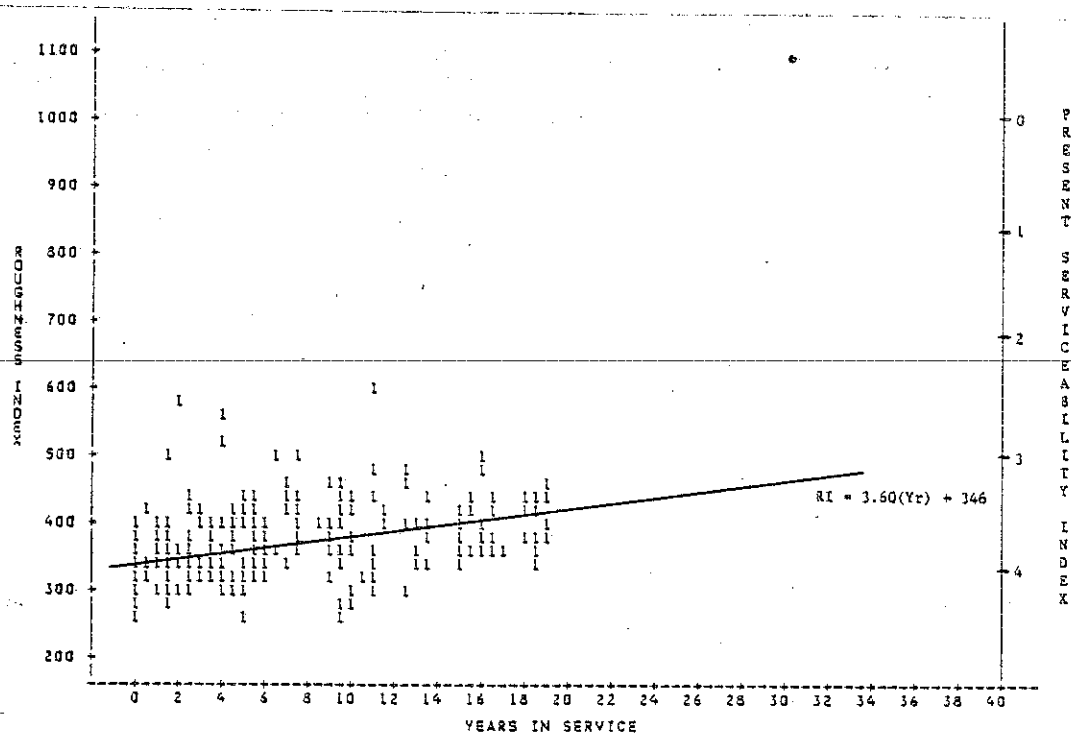
NOTE: 4 OBS HIDDEN

Figure 10. Roughness Index versus Years-In-Service: Interstates -- Asphaltic Concrete Overlays on Portland Cement Concrete Pavement.



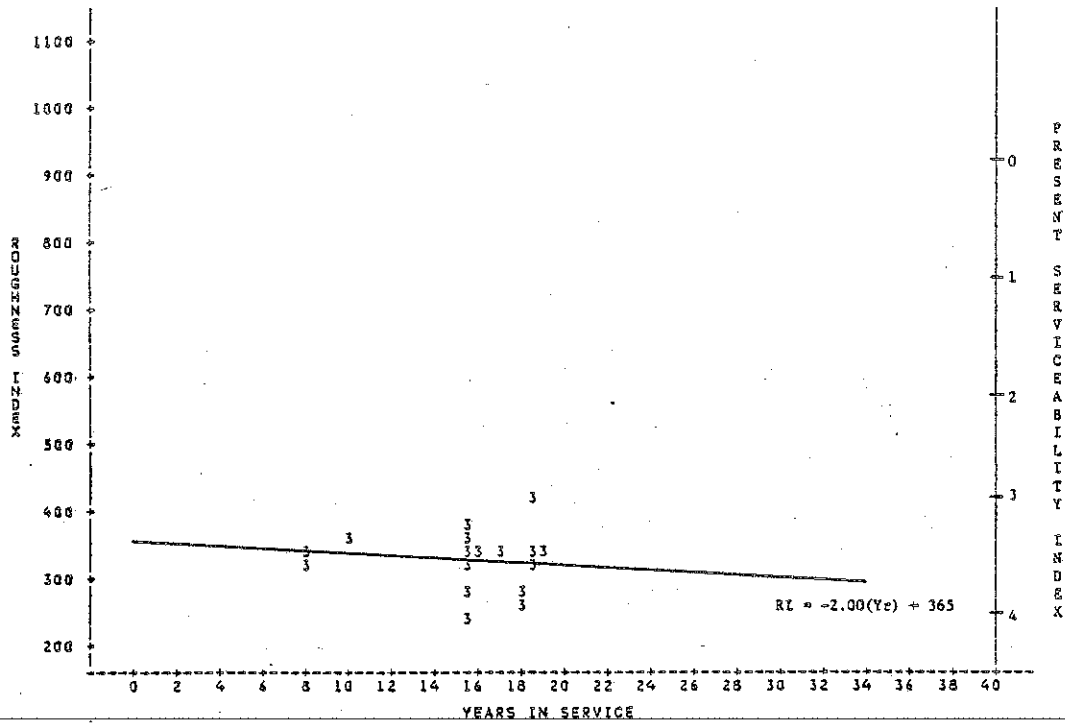
NOTE: 12 OBS HAD MISSING VALUES OR WERE OUT OF RANGE 66 OBS HIDDEN

Figure 11. Roughness Index versus Years-In-Service: Parkways
-- Asphaltic Concrete Pavements.



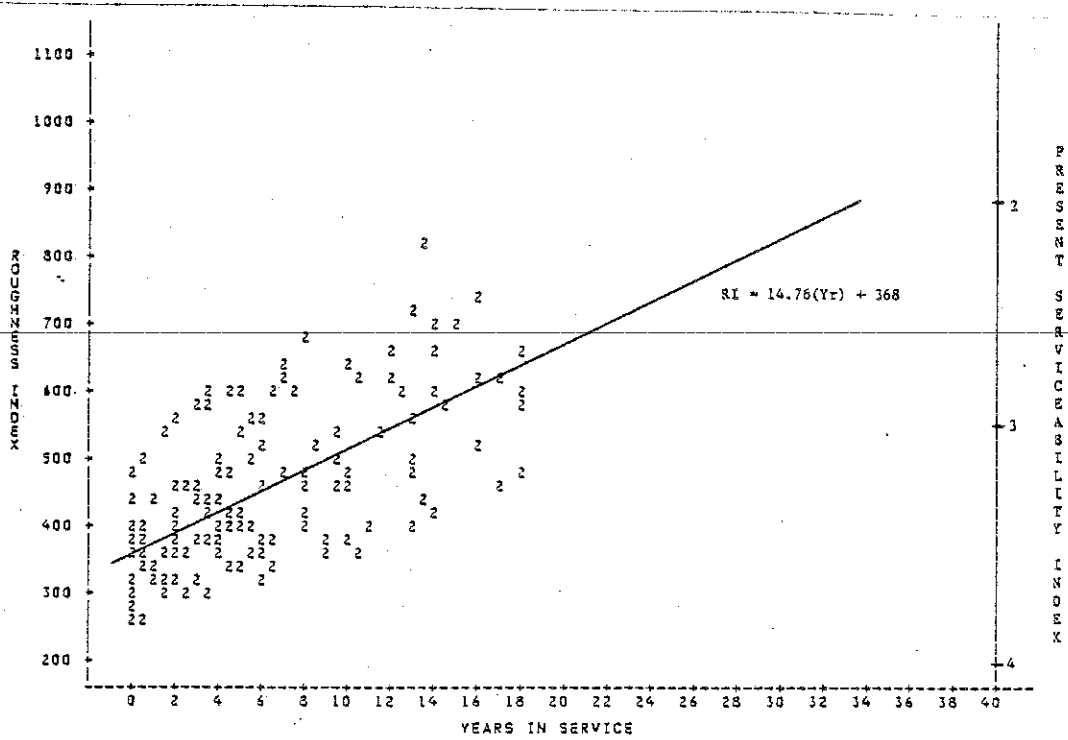
NOTE: 1 OBS HAD MISSING VALUES OR WERE OUT OF RANGE 125 OBS HIDDEN

Figure 12. Roughness Index versus Years-In-Service: Parkways
-- Portland Cement Concrete Pavements.



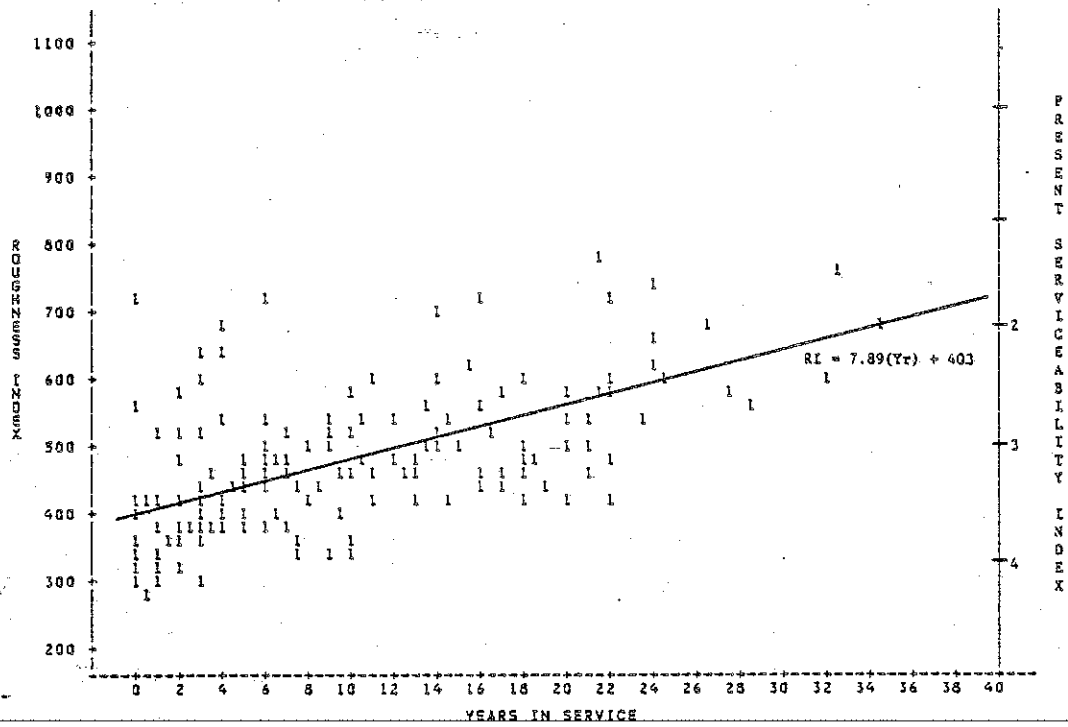
NOTE: 4 OBS HIDDEN

Figure 13. Roughness Index versus Years-In-Service: Parkways
 -- Asphaltic Concrete Overlays on Asphaltic Concrete Pavements.



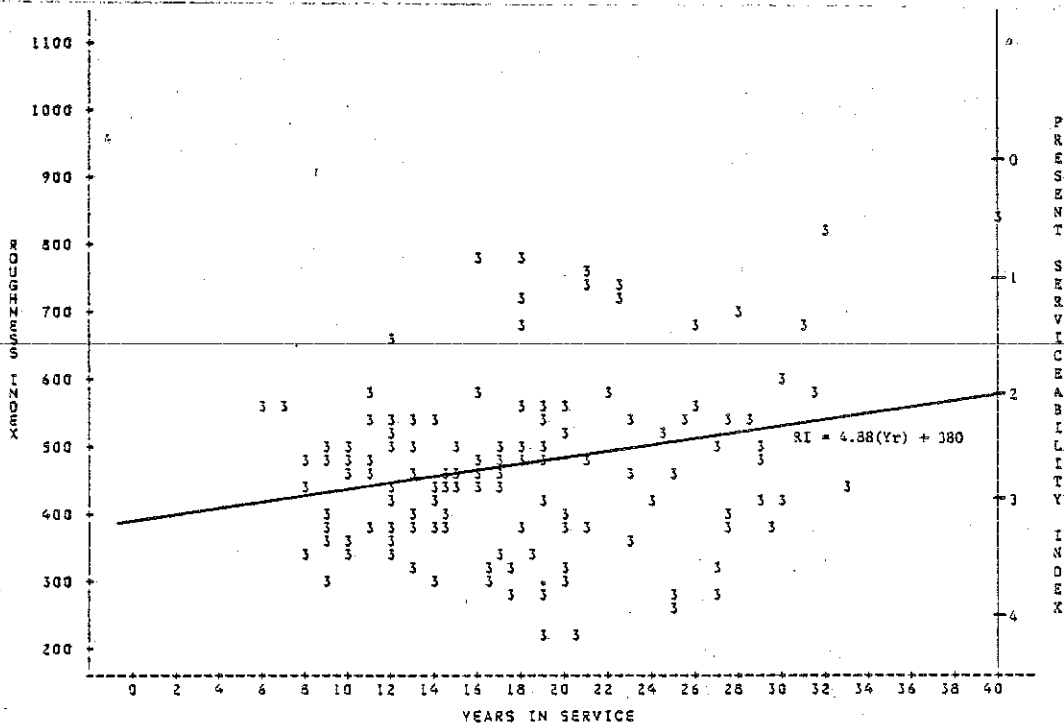
NOTE: 27 OBS HIDDEN

Figure 14. Roughness Index versus Years-In-Service: US Routes
 -- Asphaltic Concrete Pavements.



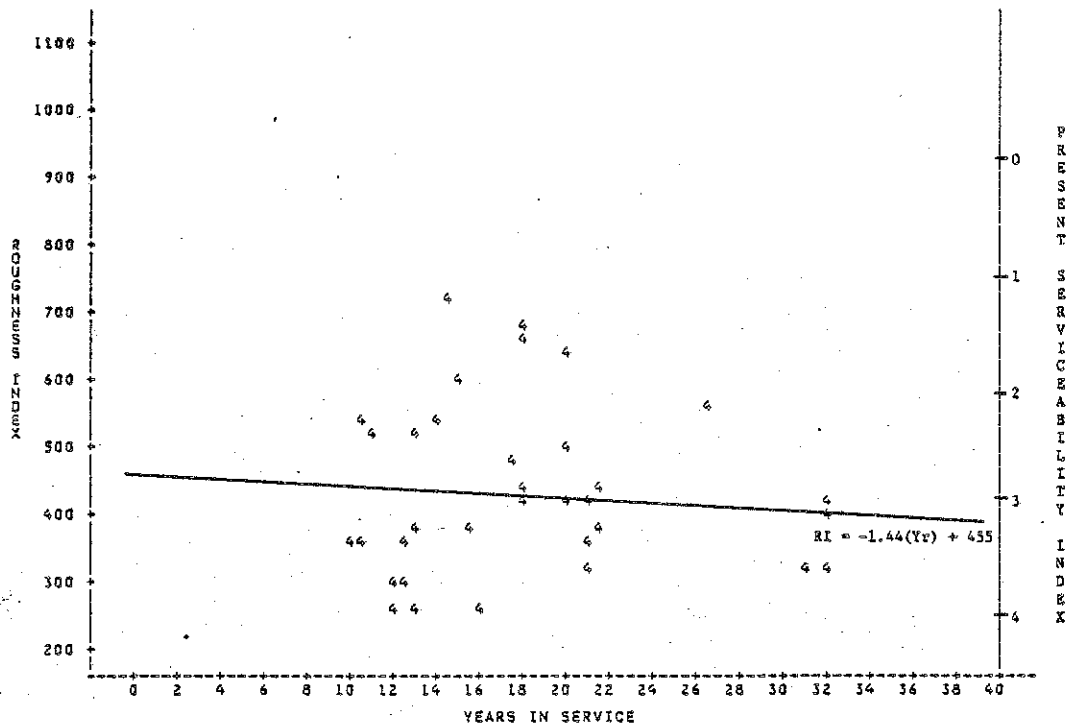
NOTE: 1 OBS HAD MISSING VALUES OR WERE OUT OF RANGE 19 OBS HIDDEN

Figure 15. Roughness Index versus Years-In-Service: US Routes
 --Portland Cement Concrete Pavements.



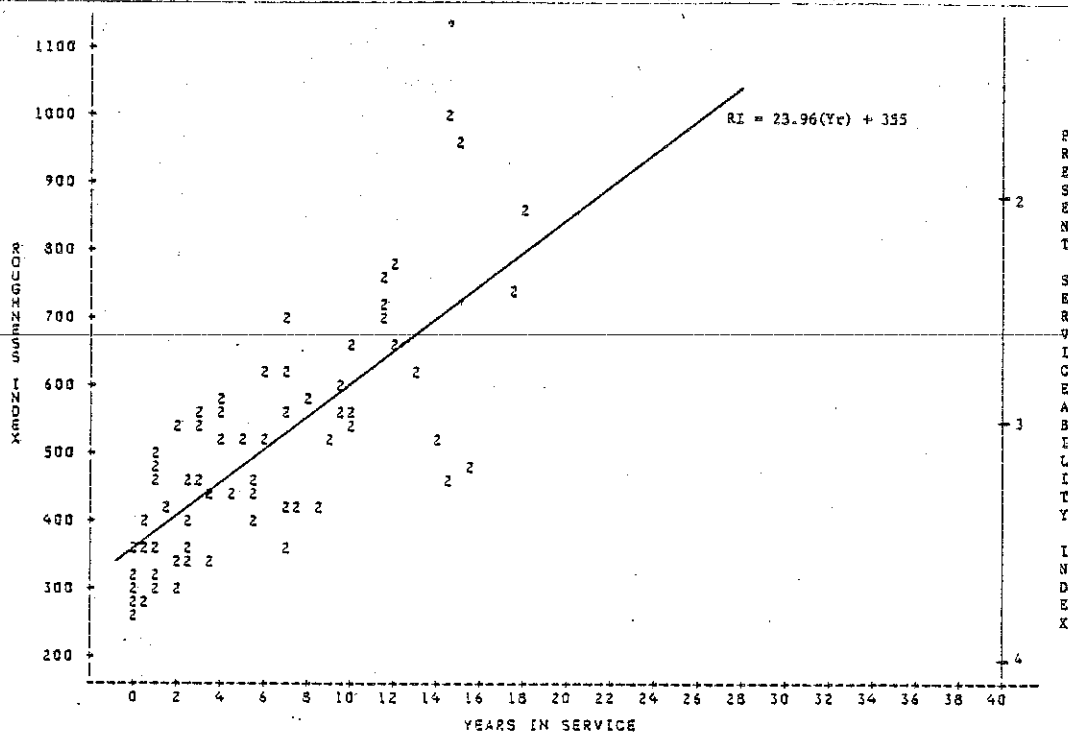
NOTE: 25 OBS HIDDEN

Figure 16. Roughness Index versus Years-In-Service: US Routes
 -- Asphaltic Concrete Overlays on Asphaltic Concrete Pavements



NOTE: 1 OBS HAD MISSING VALUES OR WERE OUT OF RANGE 2 OBS HIDDEN

Figure 17. Roughness Index versus Years-In-Service: US Routes -- Asphaltic Concrete Overlays on Portland Cement Concrete Pavements.



NOTE: 10 OBS HIDDEN

Figure 18. Roughness Index versus Years-In-Service: Kentucky Routes -- Asphaltic Concrete Pavements.

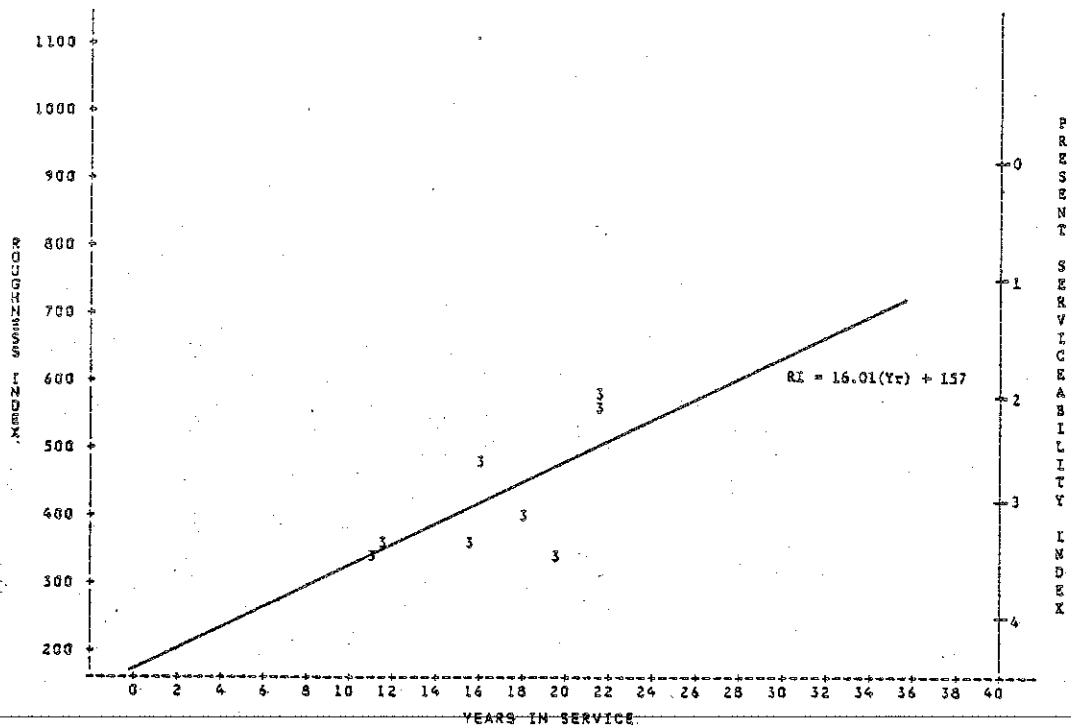


Figure 19. Roughness Index versus Years-In-Service: Kentucky Routes -- Asphaltic Concrete Overlays on Asphaltic Concrete Pavements.

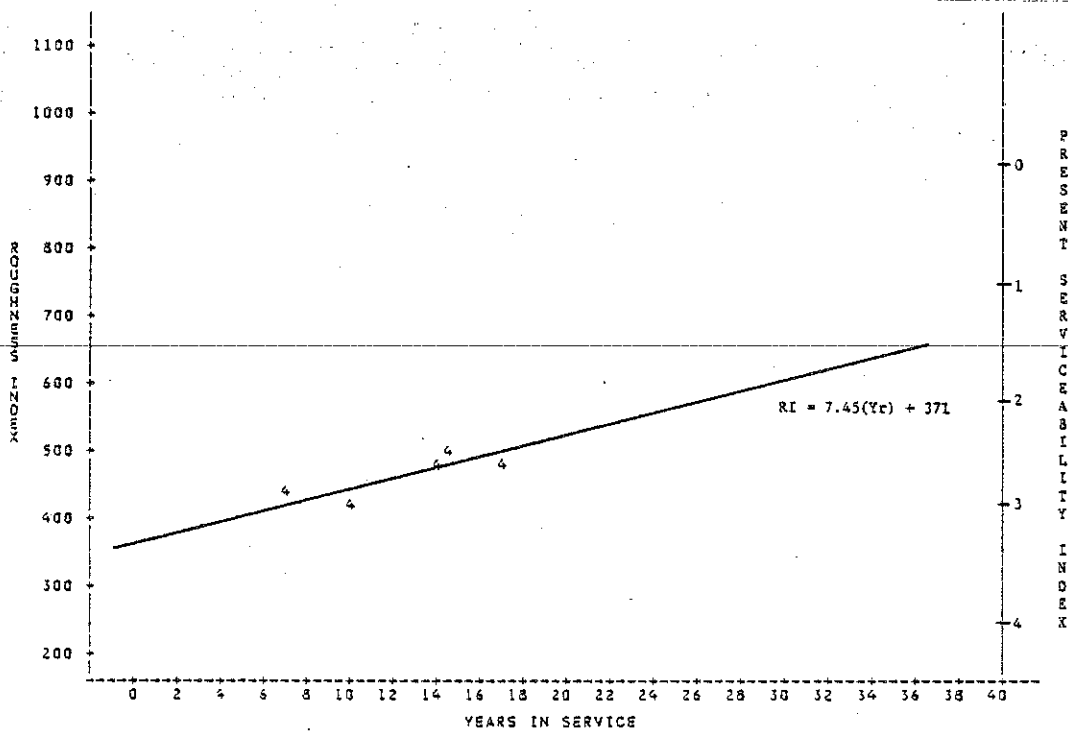
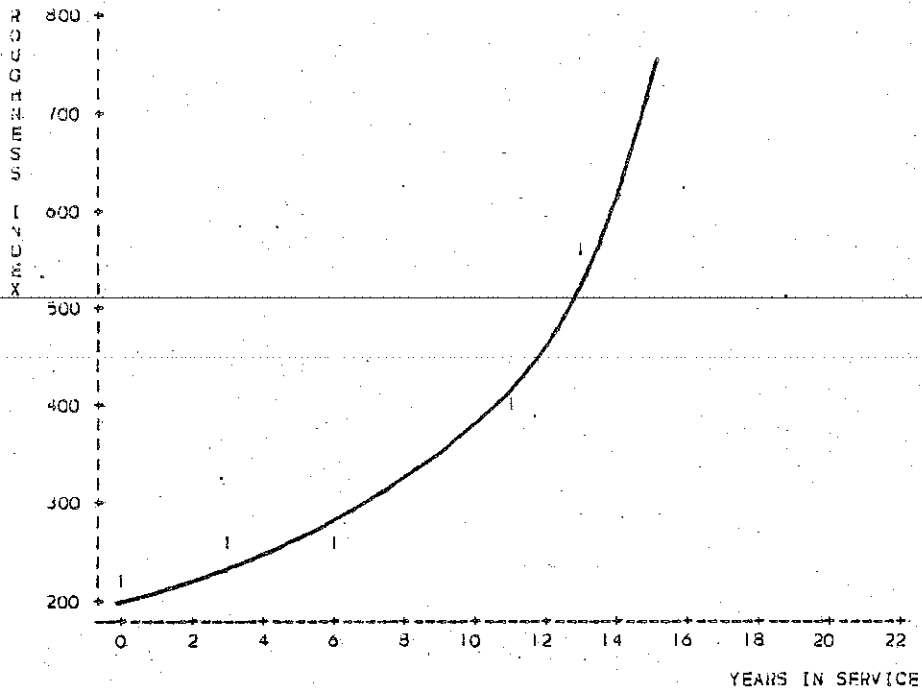


Figure 20. Roughness Index versus Years-In-Service: Kentucky Routes -- Asphaltic Concrete Overlays on Portland Cement Concrete Pavements.



NOTE: | OBS HAD MISSING VALUES OR WERE OUT OF RANGE | OBS HIDDEN

Figure 21. Roughness Index versus Months-In-Service:
Example of a Nonlinear Relationship.

were selected to encompass available data. Therefore, the "out of range" note is not applicable as it refers to notes on the presentations of data in this report. In all situations, the note "missing or out of range" refers to data where a portion of the data record was missing and therefore was not included in the specific plot of data.

HIDDEN OBSERVATIONS

The note regarding "hidden observations" appearing on some plots indicates that one or more observations plot in the same position on the specific graph. The position of "hidden points" is taken into account during determination of least-squares best-fit trend lines. The likelihood of the 218 observations of Figure 8, for example, having low abscissa values is not realistic since there is an equal probability of the occurrence of duplicate data for any point on the graph. It is apparent from the position of the trend line that "hidden data" do have low to medium range abscissa values coupled with low ordinate values. Thus, the line presented apparently does not represent a "best fit" for the data presented in Figure 8 with regard to data presented on the graph. However, hidden observations were included in the determination of the best-fit linear least-squares equation presented in Figure 8. The upward trend of the data apparently does indicate that a nonlinear model may be more appropriate for this particular data sample.

EFFECTS OF MAINTENANCE AND REHABILITATION

The abscissa of the graphs (Years-in-Service) is representative of time determined from original construction of each pavement section. Some variability in the observed data is related to the occurrence of patching and other spot pavement repair activities. It would have been desirable to have incorporated data for pavement patching and spot maintenance with evaluations of data regarding pavement roughness and service history. However, those data were not available.

Information regarding major overlays was available and has been incorporated into the report. Pavement roughness data were subdivided according to four general pavement types:

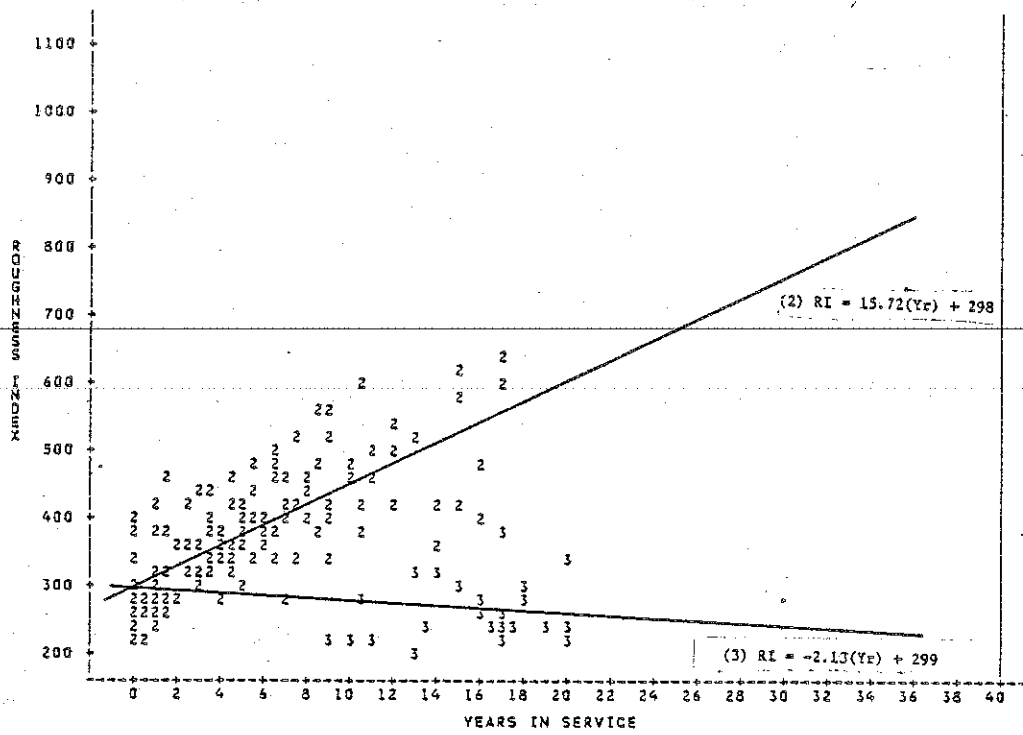
- (a) asphaltic concrete pavements,
- (b) portland cement concrete pavements,
- (c) asphaltic concrete overlays over asphaltic concrete pavements, and
- (d) asphaltic concrete overlays over portland cement concrete pavements.

The service life for overlaid pavements at the time of overlay was recorded as the number of years between initial construction and placement of the overlay.

Figures 22 through 36 illustrate various combinations of roughness data in terms of system classifications and pavement types. Linear models have been used in all situations.

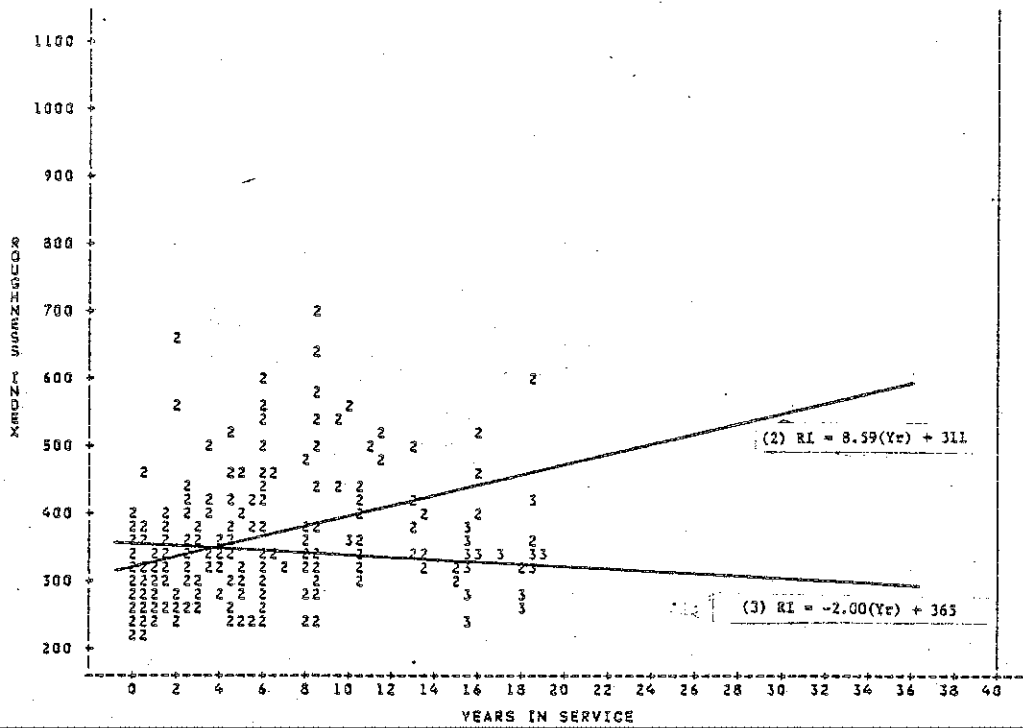
ROUGHNESS INDEX HISTORIES

The principal strategy for reducing pavement roughness normally has involved resurfacing. Overlays for structural purposes may be recommended dependent upon specific pavement conditions and usually are thicker than routine resurfacing. Figures 7 through 20 illustrate general trends in roughness versus years in service for specific pavement types. Figures 22 through 28 present combinations of data



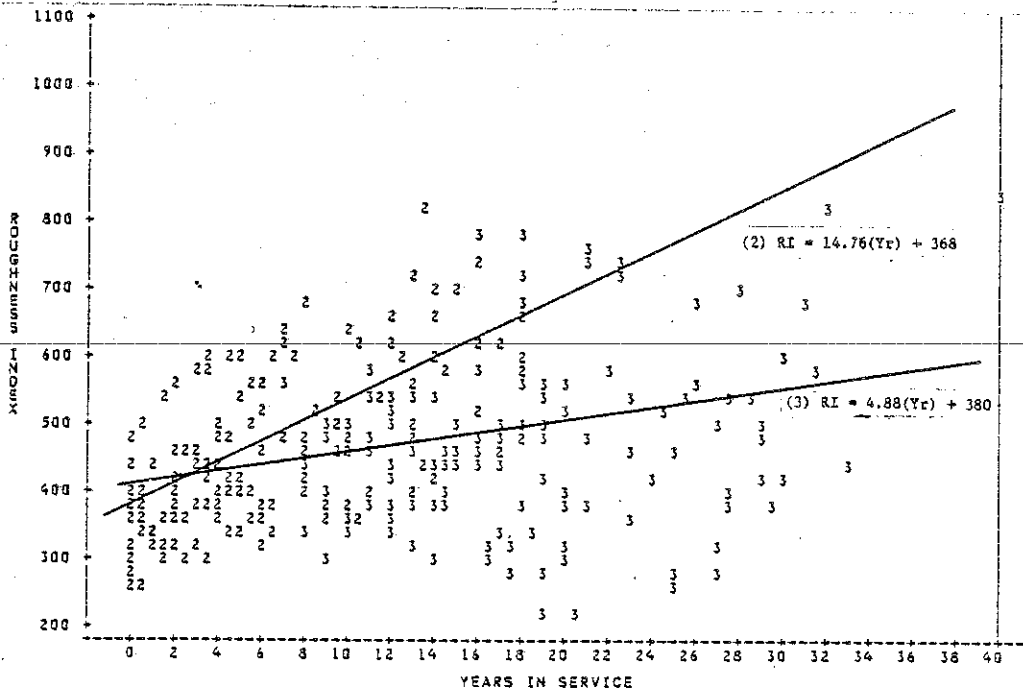
NOTE: 2 OBS HAD MISSING VALUES OR WERE OUT OF RANGE 40 OBS HIDDEN

Figure 22. Combination of Asphaltic Concrete Pavement and Asphaltic Concrete Overlays on Asphaltic Concrete Pavements: Interstates.



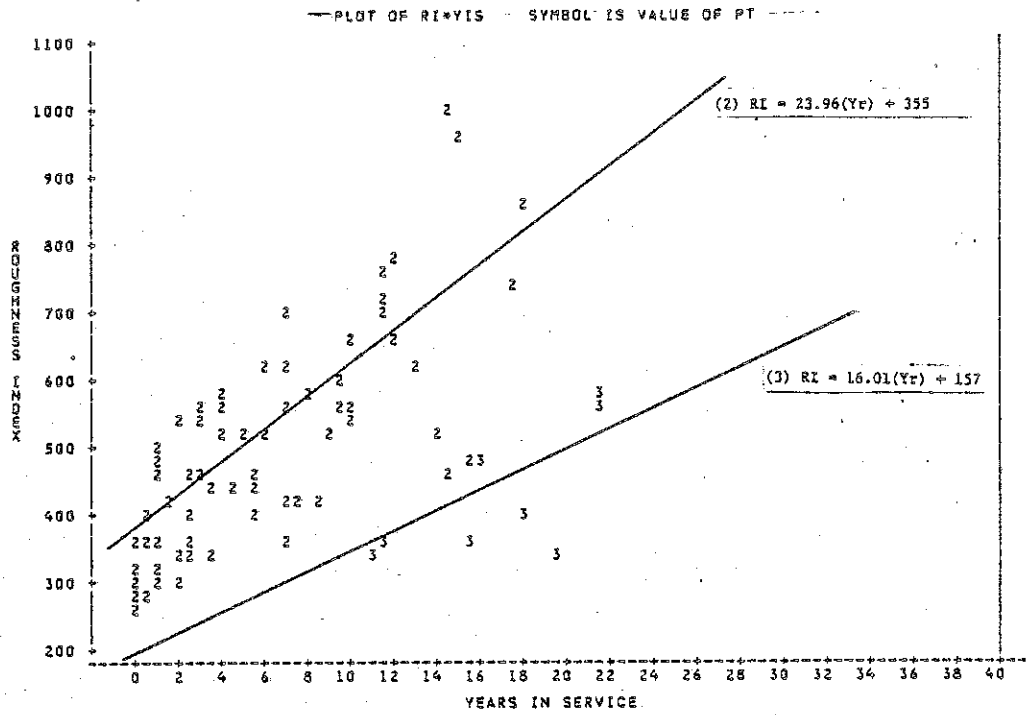
NOTE: 12 OBS HAD MISSING VALUES OR WERE OUT OF RANGE 72 OBS HIDDEN

Figure 23. Combination of Asphaltic Concrete Pavements and Asphaltic Concrete Overlays on Asphaltic Concrete Pavements: Parkways.



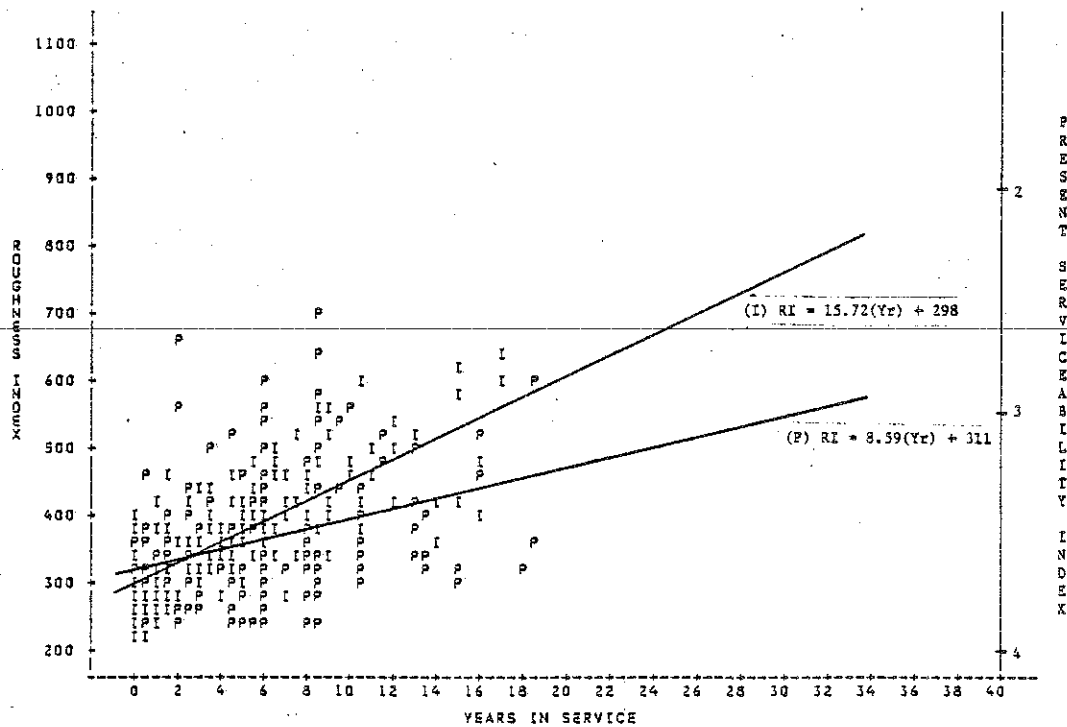
NOTE: 65 OBS HIDDEN

Figure 24. Combination of Asphaltic Concrete Pavements and Asphaltic Concrete Overlays on Asphaltic Concrete Pavements: US Routes.



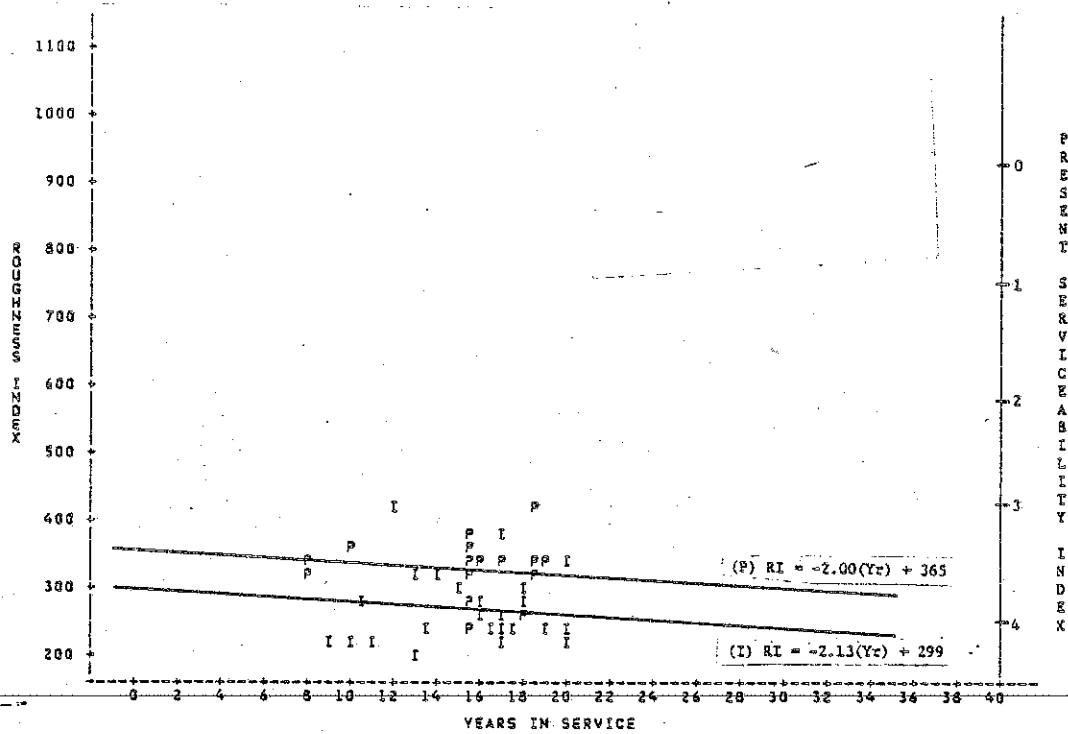
NOTE: 10 OBS HIDDEN

Figure 25. Combination of Asphaltic Concrete Pavements and Asphaltic Concrete Overlays on Asphaltic Concrete Pavements: Kentucky Routes.



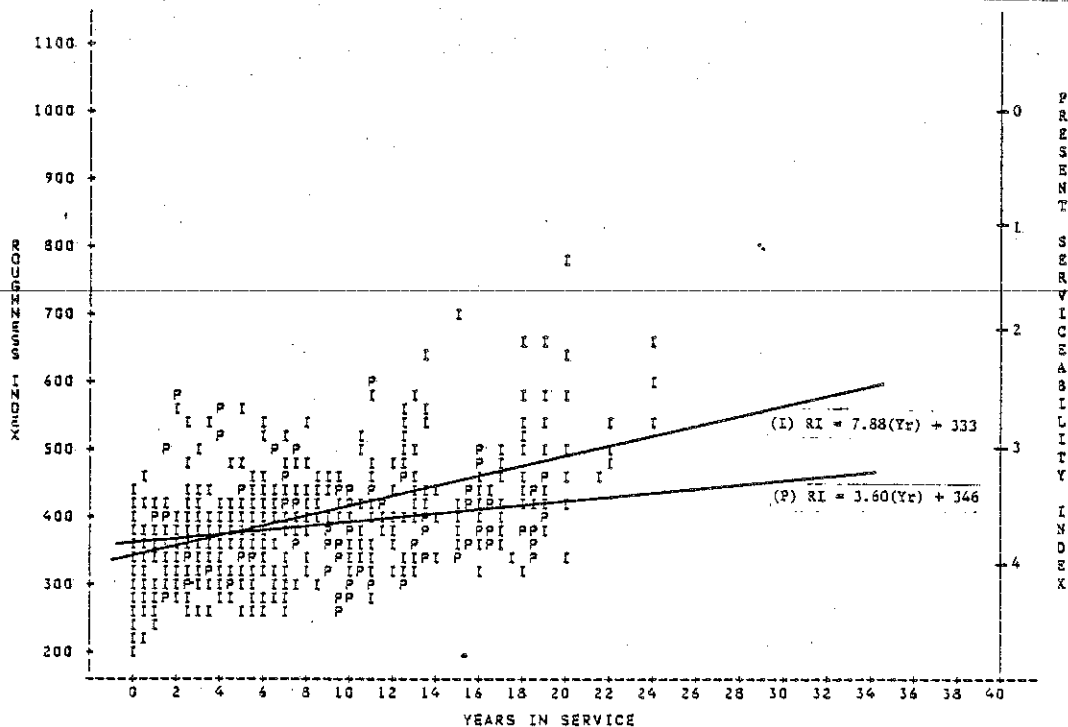
NOTE: 12 OBS HAD MISSING VALUES OR WERE OUT OF RANGE 148 OBS HIDDEN

Figure 26. Combination of Interstate and Parkways: Asphaltic Concrete Pavements.



NOTE: 2 OBS HAD MISSING VALUES OR WERE OUT OF RANGE 6 OBS HIDDEN

Figure 27. Combination of Interstate and Parkways: Asphaltic Concrete Overlays for Asphaltic Concrete Pavements.



NOTE: 2 OBS HAD MISSING VALUES OR WERE OUT OF RANGE 441 OBS HIDDEN

Figure 28. Combination of Interstate and Parkways: Portland Cement Concrete Pavements.

presented in Figures 7 through 20. Combinations include grouping of data by pavement type and/or roadway classification.

Figure 7 presents roughness data versus service life for asphaltic concrete pavements on interstate highways. Figure 9 presents limited data for asphaltic concrete pavements having been overlaid with asphaltic concrete for interstate highways. Figure 22 illustrates the combination of data from Figures 7 and 9 into one plot. Note from Figures 9 and 22 the negative slope associated with asphaltic concrete pavements overlaid with asphaltic concrete. Negative trends of pavement roughness versus service life are not expected nor are they realistic. The occurrence of negative trends may be related to normal variability associated with measurement of pavement roughness combined with a small sample of data available at the time of the evaluation (Figure 9). The major significance of those figures (Figures 7, 9, and 22) indicates reduced trends of pavement roughness versus service life for overlaid pavements when compared to non-overlaid asphaltic concrete pavements (Figure 22). Previous research (16) also has demonstrated similar trends for other highway classifications. However, the average difference in rate of change of pavement roughness versus service life for asphaltic concrete pavements compared with asphaltic concrete pavements overlaid with asphaltic concrete cannot be determined because of the disproportionate sizes of the data sample and the negative trend for overlaid pavements. It also may be seen from Figure 22 the generally lower magnitudes of initial pavement roughness for overlaid pavements compared with non-overlaid asphaltic concrete pavements.

Similar analyses also have been completed for asphaltic concrete pavements and overlaid asphaltic concrete pavements for sections of pavements on Kentucky parkways (Figures 11, 13, and 23); on U.S. routes in Kentucky (Figures 14, 16, and 24); and on Kentucky routes (Figures 18, 19, and 25). A negative trend of roughness versus service life also was observed for overlaid asphaltic concrete pavements on parkways; but again the data sample size was small and the variability large, indicating somewhat questionable statistical significance. Shallow positive trends of pavement roughness versus service life were observed for overlaid asphaltic concrete pavement for U. S. routes and Kentucky routes. The size of the data sample for overlaid asphaltic concrete pavement was much larger for U.S. routes than for other functional classifications.

In all situations, the trends of pavement roughness versus service life indicated decreased rates of change in pavement roughness for overlaid asphaltic concrete pavements when compared with non-overlaid asphaltic concrete pavements. It can be speculated that some portion of the changes in roughness during the service life of a non-overlaid asphaltic concrete pavement may be related to initial consolidation and/or stabilization of initial construction and the occurrence of spot failure locations because of non-uniform construction. Overlay or resurfacing may mask those defects. Therefore, the rate of increase in pavement roughness versus service life for overlaid asphaltic concrete pavements increases at a reduced rate when compared to non-overlaid asphaltic concrete pavements.

Analyses of portland cement concrete pavements also are presented. Figure 8 presents data for portland cement concrete pavements on interstate highways whereas Figure 10 presents data for portland cement concrete pavements overlaid with asphaltic concrete for interstate

pavements. Note from Figures 8 and 10 that the rate of increase in roughness versus service life is greater for overlaid pavements (Figure 10) than for non-overlaid portland cement concrete pavements (Figure 8). The available data sample in Figure 10 is small relative to Figure 8. Therefore, rates of change in roughness versus service life may not be statistically significant. However, increased trends in roughness may be anticipated for portland cement concrete pavements overlaid with asphaltic concrete because of reflective cracking of the asphaltic concrete, which typically occurs after the overlay has been in service for one or more years.

Figure 12 illustrates pavement roughness data versus service life histories for portland cement concrete pavements on Kentucky parkways. The rate of increase of roughness versus service life is much less for parkway pavements when compared with data for interstate pavements. This may be attributed to lesser levels of traffic and pavement fatigue generally associated with Kentucky parkways. No data were available regarding comparisons for asphaltic concrete overlays over portland cement concrete pavements for parkway pavements versus interstate pavements.

Figure 15 illustrates pavement roughness versus service life trends for portland cement concrete pavements on U.S. routes in Kentucky. Notice the slope of the trend line is very similar to the slope for interstate pavements (Figure 8), but the intercept or initial pavement roughness level is much greater. This is somewhat contradictory of the reduced rate of increase of pavement roughness versus service life for parkway pavements. Perhaps this indicates the rate of change in pavement roughness versus service life is related more to climatic and environmental factors than traffic and that initial roughness values are primarily a function of initial construction. Figure 17 illustrates data for pavement roughness versus service life for an asphaltic concrete overlays over portland cement concrete pavements on U.S. routes. Notice the large amount of scatter in the data and also the slightly negative trend line of pavement roughness versus service life. Figure 20 presents a very limited sample of data for asphaltic concrete overlays on portland cement concrete pavements on Kentucky routes. The slope of the trend line is positive and is very similar to trends observed for non-overlaid portland cement concrete pavements.

In summary, evaluations regarding portland cement concrete pavements and asphaltic concrete overlays over portland cement concrete pavements are inconclusive and in some situations contradictory. This may be attributed to the relatively small sampling of data available for asphaltic concrete overlays over portland cement concrete pavements.

Figure 26 presents combined data for pavement roughness versus service life for asphaltic concrete pavements on interstate and Kentucky parkway pavements. The rate of increase in pavement roughness versus service life for interstate pavements is greater than the similar rate for parkway pavements. Lesser traffic volumes and lighter vehicle loadings normally associated with Kentucky parkway routes may explain in part this trend. However, some specific parkway sections in eastern Kentucky may have some of the heaviest vehicle loadings in the entire state. On the average, heavier vehicle loadings generally may be anticipated for interstate routes when compared with the norm for all parkway pavements.

Figure 27 presents combined data for roughness versus service life

for asphaltic concrete overlays over asphaltic concrete pavements on interstate and Kentucky parkway pavements. The negative trends for both interstate and parkway pavements. The available data sample is small, therefore interpretation of the rate of change of pavement roughness versus service life generally is inconclusive. It may be worthy to note generally greater levels of pavement roughness for parkway pavements than for interstate pavements. No explanation for this trend is available at this time.

Figure 28 presents combined data comparing pavement roughness versus service life trends for portland cement concrete pavements on interstate pavements versus parkway pavements. The rate of increase in pavement roughness versus time is greater for interstate pavements when compared with parkway pavements. This is consistent with trends observed for asphaltic concrete pavements presented in Figure 26.

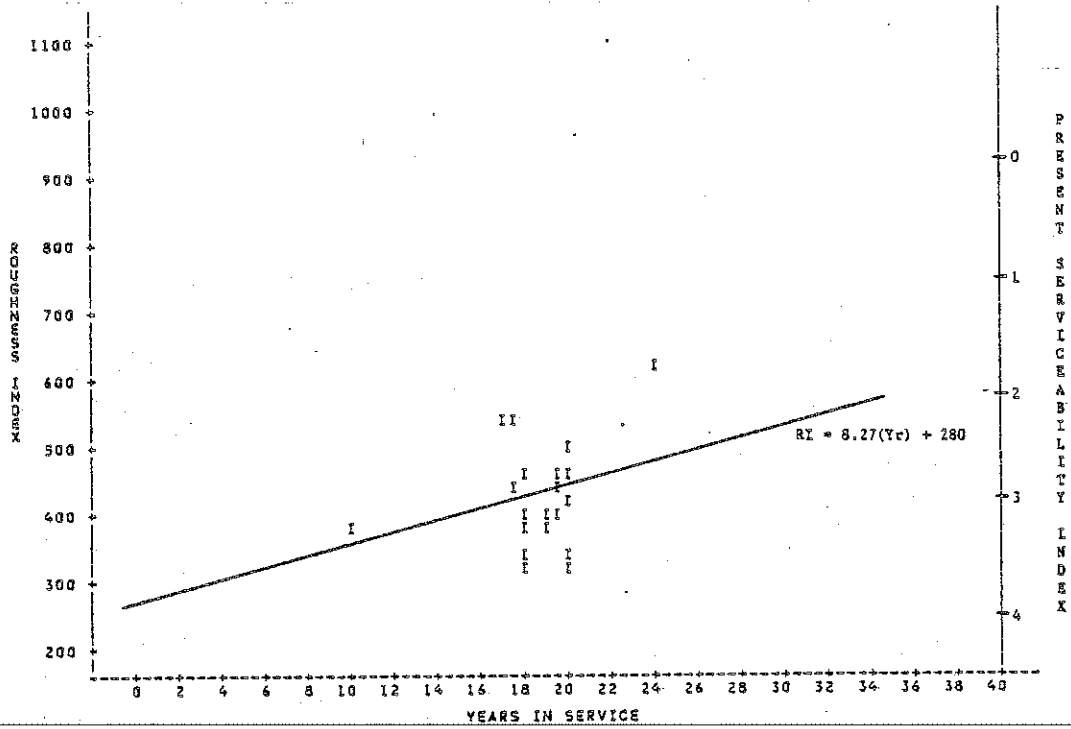
Figure 29 presents data for pavement roughness versus service life histories for asphaltic concrete overlays on portland cement concrete pavements for interstate routes. Data were not available for asphaltic concrete overlays over portland cement concrete pavements. Figures 10 and 29 are identical except for the symbols used for plotting. The data sample is small and therefore the trends may be inconclusive until additional data is available.

Figure 30 presents combined data for U.S. and Kentucky routes for asphaltic concrete pavements and asphaltic concrete overlays for asphaltic concrete pavements. The "2" symbol represents data for asphaltic concrete pavements whereas the "3" symbol represents data for asphaltic concrete overlays over asphaltic concrete pavements. The rate of increase of pavement roughness versus service life is much greater for asphaltic concrete pavements than for overlaid asphaltic concrete pavements. A trend line fitting the combined data set also is presented.

Figure 31 presents combined data for interstate and parkway routes for asphaltic concrete pavements and asphaltic concrete overlays for asphaltic concrete pavements. As in Figure 30, the symbol "2" represents data for asphaltic concrete pavements and the symbol "3" represents overlaid asphaltic concrete pavements. The rate of change in roughness versus service life is greater for asphaltic concrete pavements than for overlaid asphaltic concrete pavements, as also was observed in Figure 30. Note also the negative slope for asphaltic concrete overlays over asphaltic concrete pavements and the relatively small sampling of data. Certainly, the negative slope is not realistic, but a general trend of reduced rate of change in pavement roughness versus time for overlaid pavements is indicated by this and other data samples.

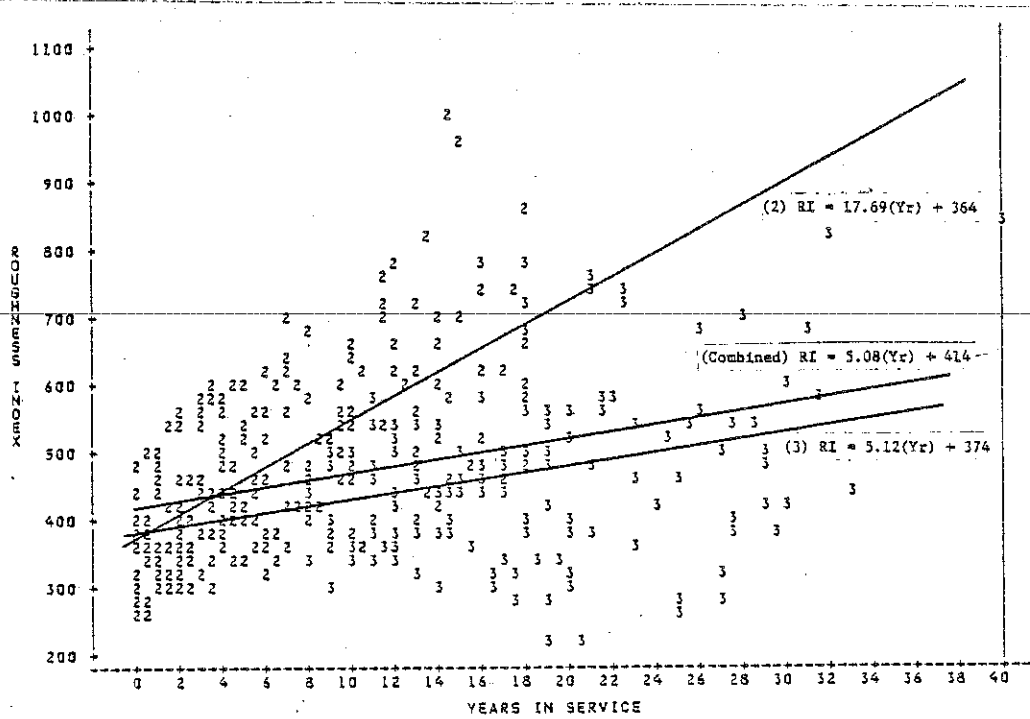
Pavement roughness versus service life data for asphaltic concrete pavements combined for U.S. and Kentucky routes are presented in Figure 32. The symbol "K" indicates data for Kentucky routes whereas the symbol "U" represents data for U.S. numbered routes. Note the trends of greater rates of change in pavement roughness versus time for Kentucky routes when compared with U.S. routes.

Figure 33 presents pavement roughness versus service life data for asphaltic concrete overlays on asphaltic concrete pavements combined for U.S. and Kentucky routes. The data are somewhat inconclusive with regard to comparisons of trends of pavement roughness versus service life for U.S. routes versus Kentucky routes since there is a significant amount



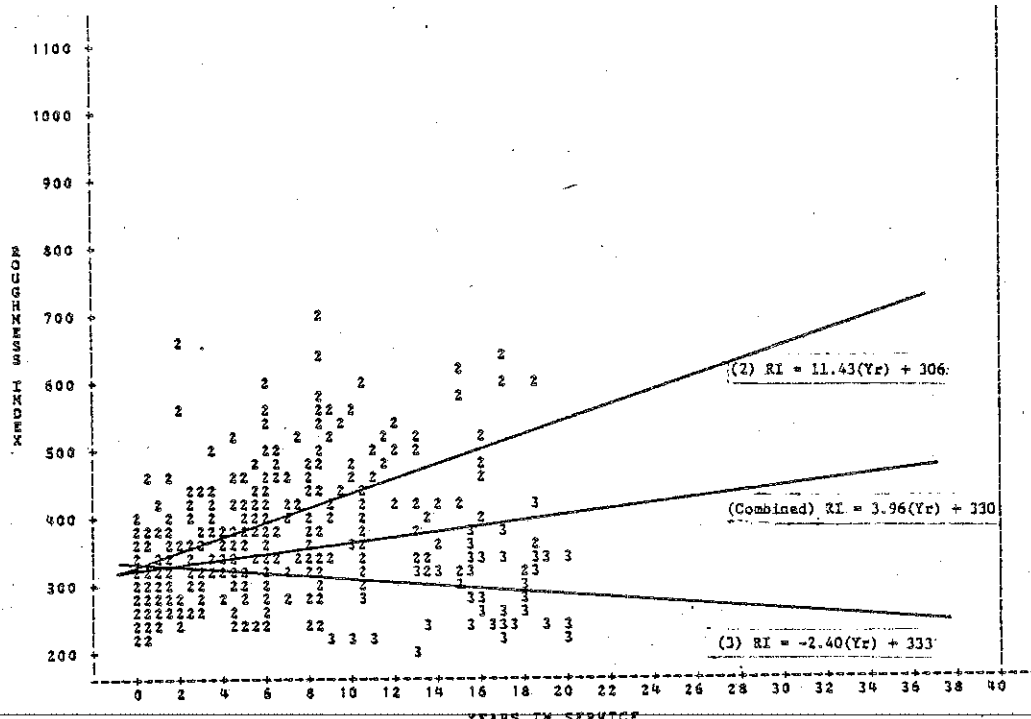
NOTE: 4 OBS HIDDEN

Figure 29. Combination of Interstate and Parkways: Asphaltic Concrete Overlays for Portland Cement Concrete Pavements.



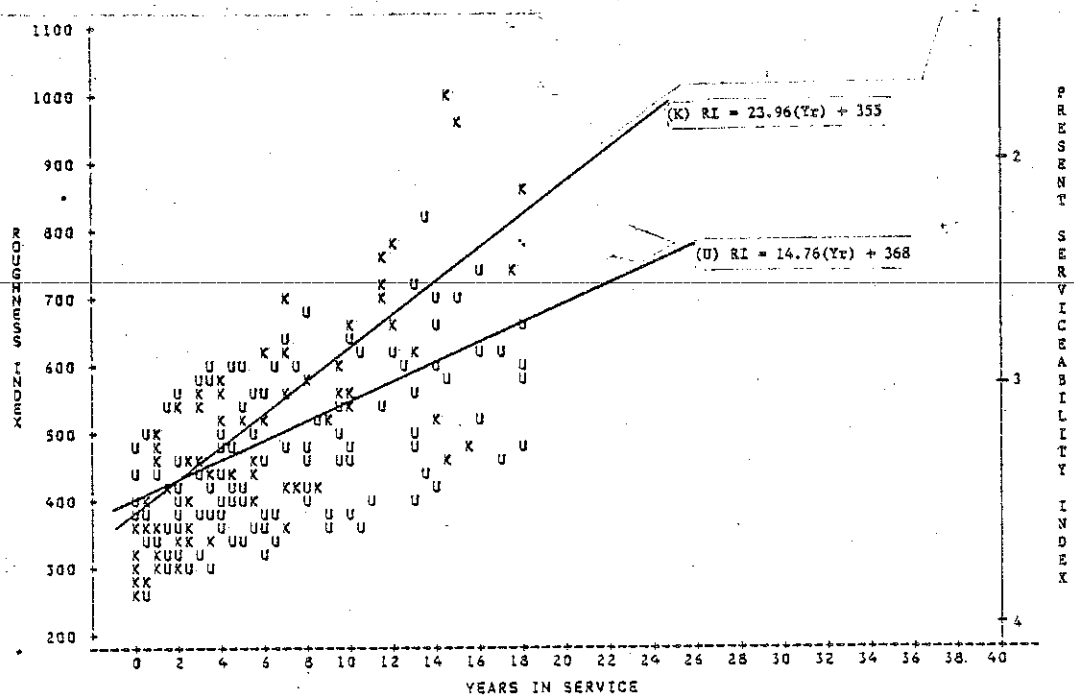
NOTE: 94 OBS HIDDEN

Figure 30. Combination of US and Kentucky Routes: Asphaltic Concrete Pavements and Asphaltic Concrete Overlays for Asphaltic Concrete Pavements.



NOTE: 14 OBS HAD MISSING VALUES OR WERE OUT OF RANGE 158 OBS HIDDEN

Figure 31. Combination of Interstates and Parkways: Asphaltic Concrete Pavements and Asphaltic Overlays on Asphaltic Concrete Pavements.



NOTE: 53 OBS HIDDEN

Figure 32. Combination of US and KY Routes: Asphaltic Concrete Pavements.

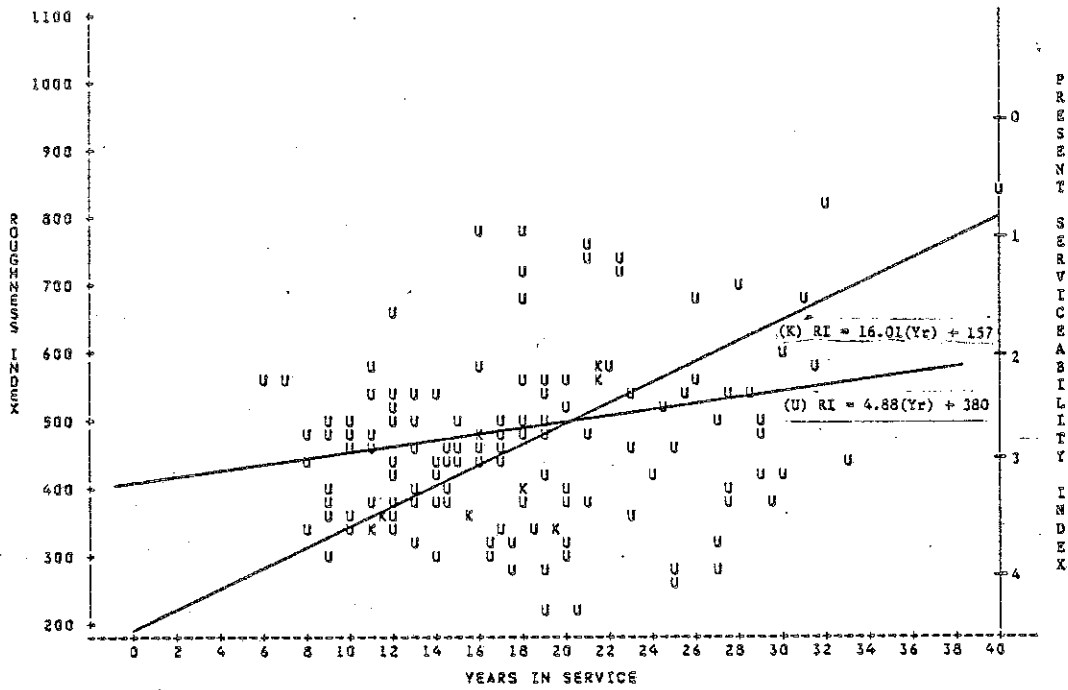
of data for U.S. pavements but only a relatively small data sample for Kentucky routes. The rate of change for pavement roughness versus service life is greater for Kentucky routes than for U.S. routes.

Figure 34 presents data relating pavement roughness versus years in service combining data for all pavement types on the interstate system. The symbol "1" represents portland cement concrete pavements; the symbol "2" represents asphaltic concrete pavements; the symbol "3" represents asphaltic concrete overlays over portland cement concrete pavements. The rate of increase in pavement roughness versus service life is in the following order of greatest to least: asphaltic concrete pavements, portland cement concrete pavements, asphaltic concrete overlays over portland cement concrete pavements, and asphaltic concrete overlays over asphaltic concrete pavements.

It might be anticipated that the rate of increase in pavement roughness versus service life is greater for original construction when compared with overlaid pavements. Pavement roughness changes with time for original construction may be related to stabilization and/or consolidation of initial construction as well as pavement fatigue and other distress-related factors. The greater rate of increase in pavement roughness for asphaltic concrete overlays over portland cement concrete was comparable to that for overlaid asphaltic concrete pavements.

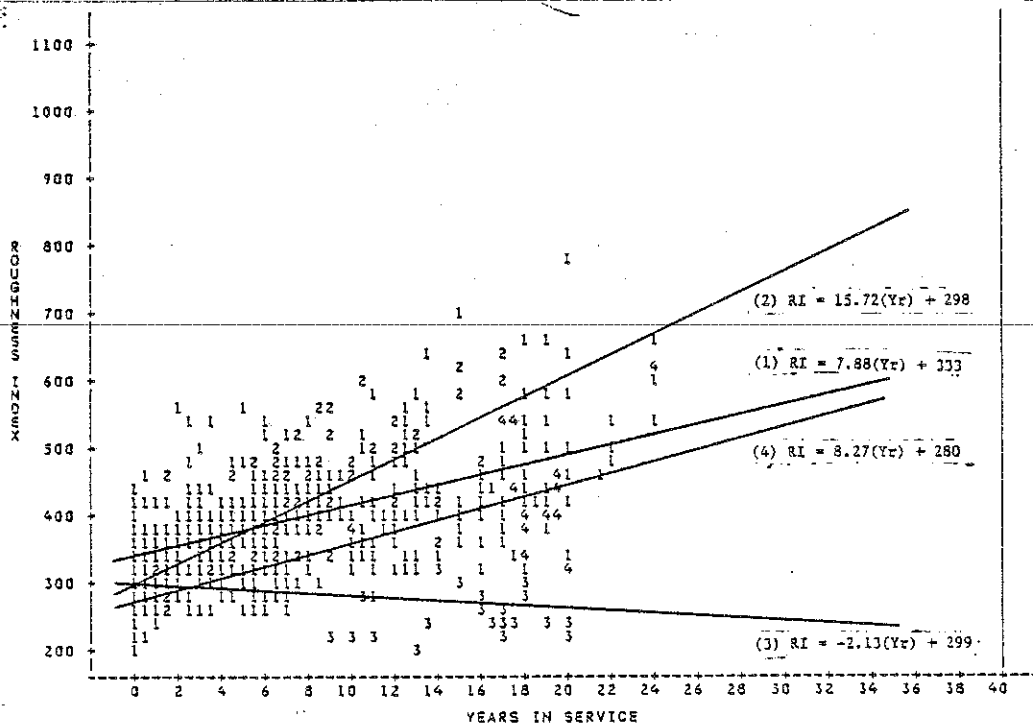
Similar data for Kentucky parkway routes are presented in Figure 35. There were no data available for asphaltic concrete overlays over portland cement concrete pavements (symbol "4"). All symbols are the same as used in Figure 34. Figure 36 presents similar data for U.S. routes. Data presented in Figure 36 are consistent with data presented in Figures 34 and 35 for rate of change in pavement roughness, except the position of trend lines for overlay pavements is reversed. Data in Figure 36 indicate greater rates of increases in roughness versus service life is greater for overlaid asphaltic concrete pavements compared with asphaltic concrete overlays over portland cement concrete pavements. Figure 37 presents similar data for Kentucky routes. The rate of increase of pavement roughness versus service life is greatest for asphaltic concrete pavements, which is consistent with data presented in Figures 34, 35, and 36. The rate of change in pavement roughness versus service life is greater for asphaltic concrete overlays over asphaltic concrete pavements than for overlays over portland cement concrete pavements. Other data generally have indicated greater rates of increase in roughness for overlaid portland cement concrete pavements than for overlaid asphaltic concrete pavements for data obtained for higher type facilities. However, the size of the data sample is small and therefore the significance of those observed trends may be questionable.

In summary, the data presented indicate the rate of increase of pavement roughness versus service life is greatest consistently for asphaltic concrete pavements for all routes when compared to other pavement types. Generally, overlaid asphaltic concrete pavements have the least increase in pavement roughness versus service life. Portland cement concrete pavements typically indicate slower rates of change of pavement roughness versus service life than asphaltic concrete pavements, although significant increases in pavement roughness may be observed as a rigid pavement nears the end of its service life and/or severe deterioration of joints occurs. Data for overlaid portland cement concrete pavement have been inconsistent compared with other pavement types. In some situations, greater rates of increases in pavement



NOTE: 27 OBS HIDDEN

Figure 33. Combination of US and KY Routes: Asphaltic Concrete Overlays on Asphaltic Concrete Pavements.



NOTE: 3 OBS HAD MISSING VALUES OR WERE OUT OF RANGE 331 OBS HIDDEN

Figure 34. Roughness Index versus Years-In-Service: Interstates -- All Pavement Types.

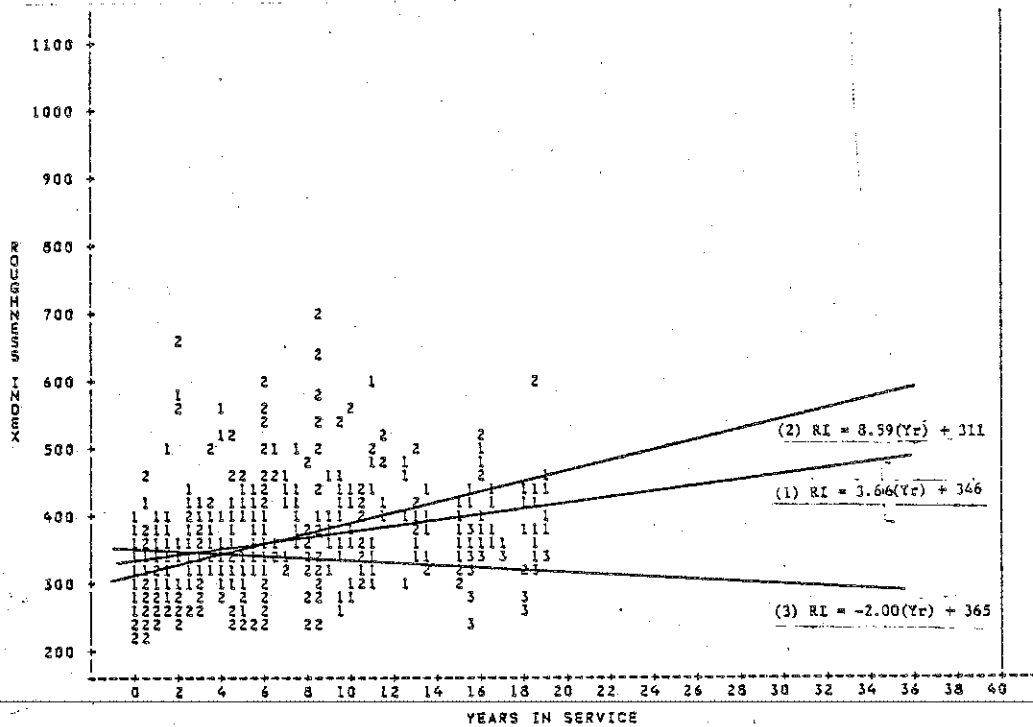


Figure 35. Roughness Index versus Years-In-Service: Parkways
 -- All Pavement Types.

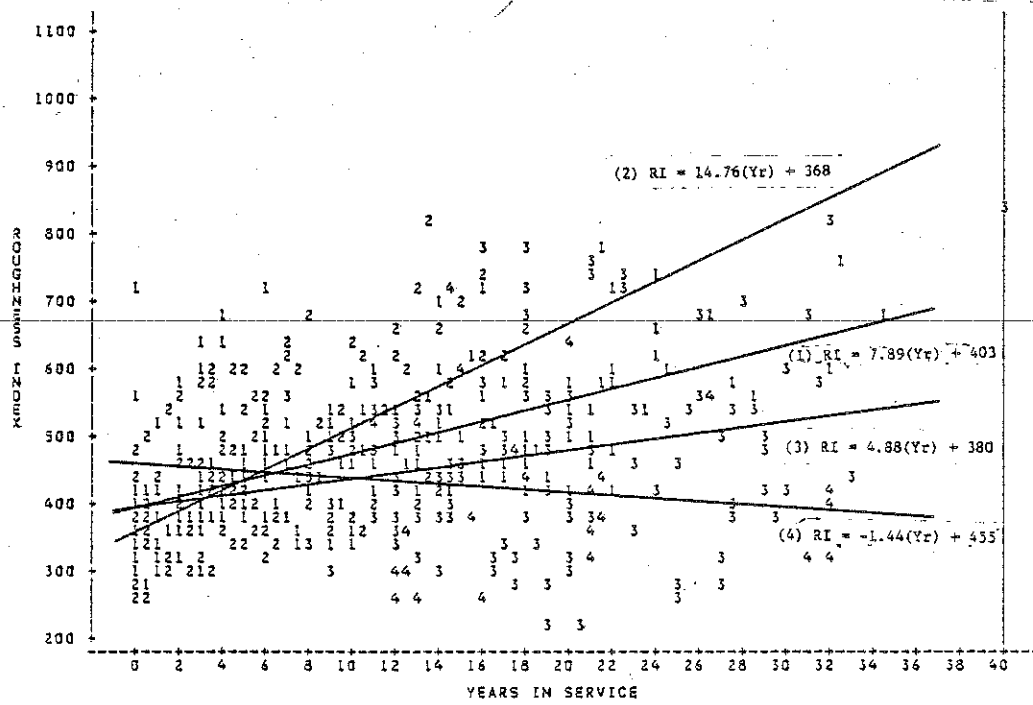
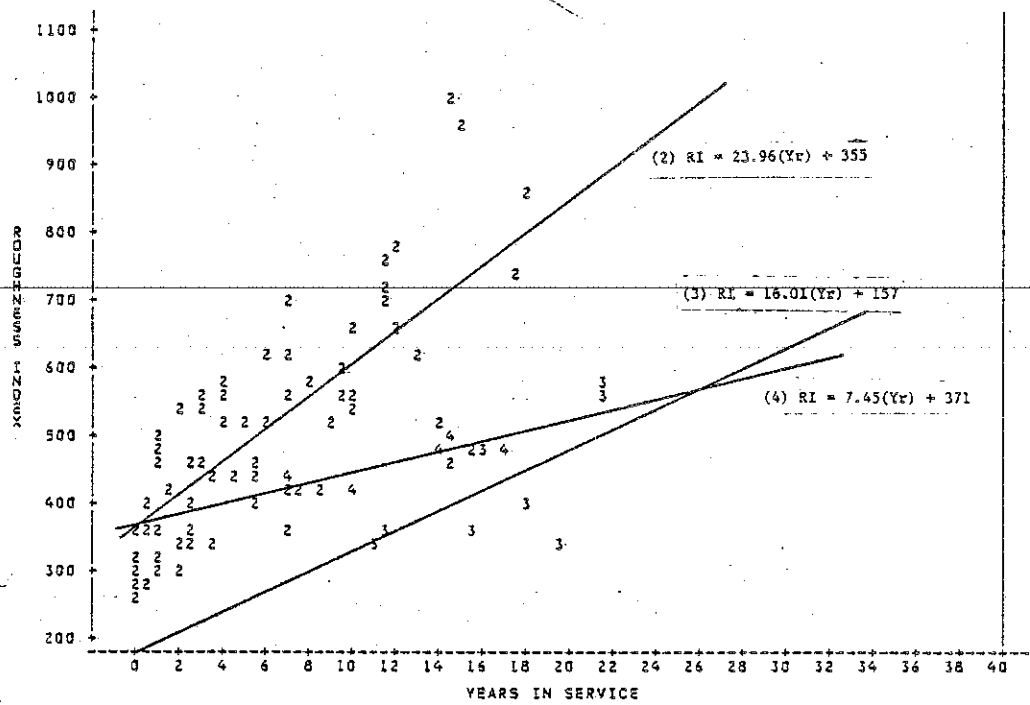


Figure 36. Roughness Index versus Years-In-Service: US Routes
 -- All Pavement Types.



roughness with service life may be observed for overlaid portland cement concrete pavements when compared with non-overlaid portland cement concrete pavements. Deterioration and pavement roughness associated with reflective cracking at the joints of the rigid pavements likely are contributing factors to those observed conditions. In other situations, asphaltic concrete overlays over portland cement concrete pavements do result in a "smoothing" of the pavement and the rate of increase in pavement roughness with service life is slowed. The sizes of data samples for overlaid pavements for some classifications were relatively small and may therefore account for observed inconsistencies.

Greater rates of increase in pavement roughness versus service life for original construction may be anticipated when compared with overlaid pavements. Stabilization and/or consolidation of original construction may contribute to the accumulation of pavement roughness in addition to increases in pavement roughness associated with pavement fatigue and other distress-related factors.

FORECAST OF ROUGHNESS INDEX

The 40-year abscissa value was selected as a convenient value that would encompass all available data. Certainly, linear models are not likely to be appropriate for prediction of roughness behavior for 40 years for a specific pavement section. However, when a number of pavement sections are combined, use of nonlinear models becomes more complex. A number of figures (Figures 15, 16, 17, 24, 30, 33, and 36) present historical roughness and service life involving a period of over 30 years. Trends established by the past 30 years may not be appropriate to predict the next 30, years but trends established over 30 years may be adequate to predict pavement roughness behavior for the next 5 or 10 years.

PAVEMENT ROUGHNESS VERSUS PAVEMENT SERVICEABILITY

A pavement should provide a smooth, safe, and comfortable ride. Therefore, pavement serviceability is a function of the road users' perceptions of pavement condition (2). The users' perceptions of pavement serviceability are a function of:

1. response to motion characterized by the particular pavement-vehicle-human interaction at a particular speed and
2. reaction to appearance characterized by such factors as cracking and patching, color, shoulder condition, etc.

Any serviceability measure is supposed to simulate the highway user's perception of the ride quality. The AASHTO terminology for such a rating is the "Individual Present Serviceability Rating." The mean of individual ratings has been termed "Present Serviceability Rating" (PSR).

The concept of a Present Serviceability Index (PSI) was first presented by Carey and Irick (1, 2, 19) and correlated user opinions with measurements of road roughness (measured using a roughometer or profilometer), cracking, patching, and rutting. The scale for the Present Serviceability Index (PSI) developed by Carey and Irick varied from 0 to 5 with 0 representing an extremely poor pavement. It is conceivable that a perfect pavement (PSI = 5) may never be constructed. Present Serviceability Ratings from the AASHTO Road Test were correlated

with measurements for roughness, cracking, patching, and rutting. The equation evolving from those analyses has taken the general form of:

$$PSI = A_0 + A_1(R) + A_2(F_1) + A_3(F_2)$$

in which A = regression coefficients,
R = a measure of pavement roughness, and
F = physical measures of cracking patching,
rutting, etc.

Studies indicate approximately 95 percent of the serviceability of a pavement is attributable to the roughness of the surface profile (1, 2, 18). As a result, equations have been developed in Kentucky relating Present Serviceability Index (PSI) and pavement roughness (16, 19):

Rigid Pavements -- $PSI = 6.01 - 0.006 RI,$

Flexible Pavements -- $PSI = 4.65 - 0.003 RI,$ and

Flexible Overlays -- $PSI = 5.53 - 0.006 RI,$

in which PSI = present serviceability index, and
RI = roughness index.

These equations were developed in the 1960's and as such represent Present Serviceability Indices compatible to the road users' perceptions and attitudes and the data available at that time. There has been considerable discussion relative to the applications of these equations to current perceptions and attitudes. Should current and future research confirm a shift in attitude toward acceptable levels of pavement serviceability, modification is essential. Additional research also is needed to define terminal serviceability levels for the various functional classifications of highways. For example, in the 1970's, engineers felt that interstate pavements should be programmed for an overlay at a PSI of 3.5 and should be overlaid by the time the PSI reaches 3.25. However, this attitude considered the safety and operational factors of a 70-mph speed limit. With the 55-mph speed limit, the public may now be willing to accept a lower level of serviceability (26, 27).

The interstate and toll road systems in Kentucky have provided a set of performance histories of pavements and other highway features. There have been many opportunities for in-service proof testing of design and performance concepts. Pavement life should not be confused with road-life statistics. Road life encompasses roadway geometry and other attributes of the highway. Pavement-life studies have been confined to pavement conditions such as rutting, wear, cracking, skid resistance, faulting, and blowups. Pavement roughness histories are used as inputs to the present "Performance Monitoring System" but are more directly usable in a pavement management system. Implementation of a pavement management system requires statewide inventory of pavements and cross referencing of traffic and accident files, costs, and other historical data. Roughness data could be used to establish long-range planning and programming priorities. Roughness data could also be used in short-term situations to select those pavements requiring additional evaluation and analysis for maintenance, resurfacing, rehabilitation, or reconstruction activities.

IMPLEMENTATION OF RESEARCH

Pavement roughness data have been used to predict pavement serviceability for a number of years. Research has indicated that pavement roughness is a major contributor to the motoring public's perception of pavement serviceability. Other factors relating to pavement serviceability include cracking, patching, and rutting (1, 2, 19) Other studies (1, 2, 18) have indicated that over 90 percent of the motoring public's perception of pavement serviceability is attributable to roughness of the pavement surface profile. Thus, pavement roughness measurements have been used (and are currently being used) by Kentucky pavement engineers to estimate pavement serviceability.

Knowledge of historical trends of pavement roughness versus service life for various pavement types and functional or operational classifications may be used to anticipate future needs for pavement maintenance, resurfacing, rehabilitation, restoration and/or pavement reconstruction (26). Data presented in this report provide for analyses of trends in pavement roughness versus service life current for data available at the time of preparation of this report. The data may be used in combination with other pavement management activities to project future trends of pavement roughness and the associated levels of pavement serviceability used to anticipate future pavement maintenance and rehabilitation needs. Therefore, the major emphasis regarding implementation of information presented in this report involves projection of future trends of pavement roughness and associated pavement serviceability for planning and pavement management needs.

Caution should be exercised with regard to a number of trends presented in this paper. Negative trends in pavement roughness versus service life were observed in many situations where the size of the data sample was small. Additional study is required to define more adequately those trends where inconclusive and/or unrealistic results were indicated.

SUMMARY AND CONCLUSIONS

The primary function of any road, street, or highway is to provide safe, comfortable, and efficient movement of people and goods. The road users' perceptions of the quality of transportation services being provided certainly affects the attitudes and actions of transportation officials. Analyses of historical pavement roughness data may be used as a tool to provide needed information concerning present and anticipated pavement conditions as a guide for management decisions.

This report documents research relative to development and evaluation of historical pavement roughness inventories. Pavement roughness inventories may be used to forecast anticipated maintenance, resurfacing, rehabilitation, restoration, and in some situations reconstruction needs. Roughness trends may be used to establish the need for more extensive and sophisticated analyses of individual pavement sections.

Additional study is required to establish the current relationships between road-user attitudes relative to acceptable levels of pavement serviceability and measured pavement roughness. Although linear models were used in this study to define relationships of pavement roughness

versus service life, additional study is required to refine those relationships. Additional historical roughness data should be obtained to confirm the results of this study.

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APPENDIX A
CORRELATIONS FOR
VEHICLE AND EQUIPMENT REPLACEMENTS

VEHICLE
REPLACEMENTS

STATE SEDAN
NUMBER

MODEL

SERVICE PERIOD

322	1957 FORD	Jan 1957 - May 1963
551	1962 FORD GALAXIE	May 1963 - Jul 1968
318	1968 FORD GALAXIE	Jul 1968 - Jun 1977
216	1976 PLYMOUTH GRAN FURY	Jun 1977 - Apr 1980
2678	1980 FORD LTD	Apr 1980 - Present
2679	1980 FORD LTD	Apr 1980 - Present

DERIVATION OF ROUGHNESS
INDEX EQUATIONS

SYMBOLS

G - acceleration (g's)

K - proportionality constant (volt-second/volt)

R - integrator range scale (volt-second)

RI - roughness index (g's x 10⁴)

Note: RI with a subscript denotes roughness index for a given test automobile.

T - integration time (seconds)

T_C - calibration factor (obtained each time equipment is turned on by applying a constant voltage (3 v) for a constant time (100 seconds) and recording the clear time (T_C))

T_{CL} - E-cell clear time following integration

t - time (seconds)

V_a - amplifier output (volts)

V_c - integrator full-scale output voltage (volts)

V_{dvm} - integrator output voltage (volts)

V_r - integrator input voltage (volts)

In 1957, a manual method of analyzing acceleration recordings (using Sedan 322) was devised. Areas under the vertical acceleration trace were summed with the aid of a compensating polar planimeter. The equivalent feet/second² x second, or g-second, were divided by the length of the measured chart (in seconds) to obtain average g's for the test section. The expression for a roughness index in terms of whole numbers was as follows:

$$RI = (|G(t)|dt/T) \times 10^4 \quad 1$$

or

$$RI = G_{avg} \times 10^4 \quad 2$$

A replacement vehicle (Sedan 551) was acquired in 1963, and a correlation of roughness measurements yielded regression equations, in terms of RI for the vehicles involved, as follows:

Bituminous Pavements

$$RI_{322} = 1.11 RI_{551} - 84 \quad 3$$

Concrete Pavements

$$RI_{322} = 1.10 RI_{551} - 109 \quad 4$$

In 1964, instrumentation (ARMS) was added to automatically sum vertical accelerations. The derivation of the ARMS equation follows:

$$V_r T = KV_{dvm}$$

in which $K = R/V_c$. Thus

$$V_r T = RV_{dvm}/V_c$$

$$\text{or } V_r T/T = V_r = RV_{dvm}/V_c T. \quad 5$$

If the rectifier characteristic equation is given by

$$V_a = (V_r/0.886) + 0.13, \quad 6$$

then

$$V_a = (RV_{dvm}/0.886 V_c T) + 0.13. \quad 7$$

The calibration of the output of the amplifier is 9 volts = 0.5 g, but the assumed rectifier characteristics curve does not intersect the rectifier characteristics curve at that point. Taking a point of intersection, such as 0.1 g, where $V_a = 1.8$ volts, by proportion any other value of G may be found for a given V_a . Thus

$$G/0.1 = V_a/1.8$$

or

$$G = 0.1 V_a/1.8 = 0.0555 V_a.$$

Substituting for V_a ,

$$G = 0.0555 (1.13 RV_{dvm}/V_c T) + 0.13$$

or

$$G = (0.0627 RV_{dvm}/V_c T) + 0.00722. \quad 8$$

Substituting G from Equation 8 into Equation 2, the ARMS equation for RI becomes

$$RI_{ARMS} = (627 RV_{dvm}/V_c T) + 72. \quad 9$$

Since $RI_{ARMS} = RI_{551}$, substituting for RI_{551} in Equations 3 and 4 gives:

Bituminous Pavements

$$RI_{322} = (697 RV_{dvm}/V_c T) - 4 \quad 10$$

Concrete Pavements

$$RI_{322} = (689 RV_{dvm}/V_c T) - 29 \quad 11$$

In 1965, the original tires on Sedan 551 were replaced with ASTM E-17 Standard Skid Test Tires. A roughness correlation between the old and new sets of tires yielded the following regression equations:

Bituminous Pavements

$$Y = 1.001 X + 23 \quad 12$$

Concrete Pavements

$$Y = 1.037 X + 21 \quad 13$$

in which Y = RI (original tires) and X = RI (E-17 tires). Substituting X from Equations 12 and 13 into Equations 10 and 11, respectively,

Bituminous Pavements

$$RI_{322} = (697 RV_{dvm}/V_c T) + 19 \quad 14$$

Concrete Pavements

$$RI_{322} = (714 RV_{dvm}/V_c T) - 9 \quad 15$$

In March 1968, a new J29B5 rectifier was installed in the ARMS instrumentation. The rectifier characteristics equation was

$$V_a = 1.12 V_r + 0.14. \quad 16$$

The new ARMS equation, obtained by similar mathematical manipulations as Equation 7 and 8, became

$$RI_{ARMS} = (622 RV_{dvm}/V_c T) + 78. \quad 17$$

Equation 17, therefore, replaced Equation 9 and the foregoing RI equations for both pavement types, involving vehicle and tire correlations, were redetermined. The results were

Bituminous Pavements

$$RI_{322} = (692 RV_{dvm}/V_c T) + 25 \quad 18$$

Concrete Pavements

$$RI_{322} = (709 RV_{dvm}/V_c T) - 3 \quad 19$$

Sedan 551 was replaced in 1968 with Sedan 318. Results of the vehicle correlation also reflected changes in the ARMS instrumentation due to replacement of a rectifier for measurements involving Sedan 318.

The regression equations in terms of RI were

Bituminous Pavements

$$RI_{322} = 0.959 RI_{318} + 24 \quad 20$$

Concrete Pavements

$$RI_{322} = 0.935 RI_{318} + 38 \quad 21$$

Since Equations 18 and 19 were used in computing RI_{318} , then for

Bituminous Pavements

$$RI_{322} = (655 RV_{dvm}/V_c T) + 48 \quad 22$$

Concrete Pavements

$$RI_{322} = (655 RV_{dvm}/V_c T) + 35 \quad 23$$

Equations 22 and 23 were used throughout the 1968, 1969, and 1970 testing and analysis programs.

In 1977, a replacement vehicle (Sedan 216) was acquired. The following equations were used until 1979:

Bituminous Pavements

$$RI_{322} = (908 RI_{CL}/T T_C) - 100$$

Concrete Pavements

$$RI_{322} = (989R T_{CL}/T T_C) - 168$$

In 1979, the ARMS instrumentation was replaced with a Mays Ride Meter and an initial correlation for a test speed of 50 mph yielded the following equations:

Bituminous Pavements

$$RI_{216} = 4.22 (\text{Mays RI}) + 78.0$$

Concrete Pavements

$$RI_{216} = 2.42 (\text{Mays RI}) + 156.0$$

Bituminous/Concrete Pavements

$$RI_{216} = 1.26 (\text{Mays RI}) + 322.0$$

in which Mays RI = 6.4 (Inches of Chart)/Miles Traversed.

Sedan 216 was replaced by two vehicles (Sedans 2678 and 2679) in 1980, and the following equations were used for a test speed of 50 mph:

Bituminous Pavements

$$\begin{aligned} \text{RI}_{216} &= 5.91 \text{ (Mays RI)} - 27.7 \\ \text{RI}_{2678} &= 4.46 \text{ (Mays RI)} - 83.1 \\ \text{RI}_{2679} &= 4.53 \text{ (Mays RI)} - 108.1 \end{aligned}$$

Concrete Pavements

$$\begin{aligned} \text{RI}_{216} &= 2.73 \text{ (Mays RI)} + 144.9 \\ \text{RI}_{2678} &= 2.64 \text{ (Mays RI)} + 94.9 \\ \text{RI}_{2679} &= 2.93 \text{ (Mays RI)} + 50.0 \end{aligned}$$

Bituminous/Concrete Pavements

$$\begin{aligned} \text{RI}_{216} &= 1.49 \text{ (Mays RI)} + 296.9 \\ \text{RI}_{2678} &= 1.73 \text{ (Mays RI)} + 239.5 \\ \text{RI}_{2679} &= 1.85 \text{ (Mays RI)} + 219.0 \end{aligned}$$

Equations for a test speed of 35 mph were

Bituminous Pavements

$$\text{RI}_{2678} = 4.20 \text{ (Mays RI)} + 23.5$$

Concrete Pavements

$$\text{RI}_{2678} = 2.65 \text{ (Mays RI)} + 110.4$$

Bituminous/Concrete Pavements

$$\text{RI}_{2678} = 1.71 \text{ (Mays RI)} + 273.0$$

All Pavements

$$\text{RI}_{2679} = 2.65 \text{ (Mays RI)} + 11.0$$

A correlation was not made in 1981; therefore, the 1981 equations were identical to those used the previous year.

APPENDIX B

DISTRIBUTIONS OF ROUGHNESS DATA

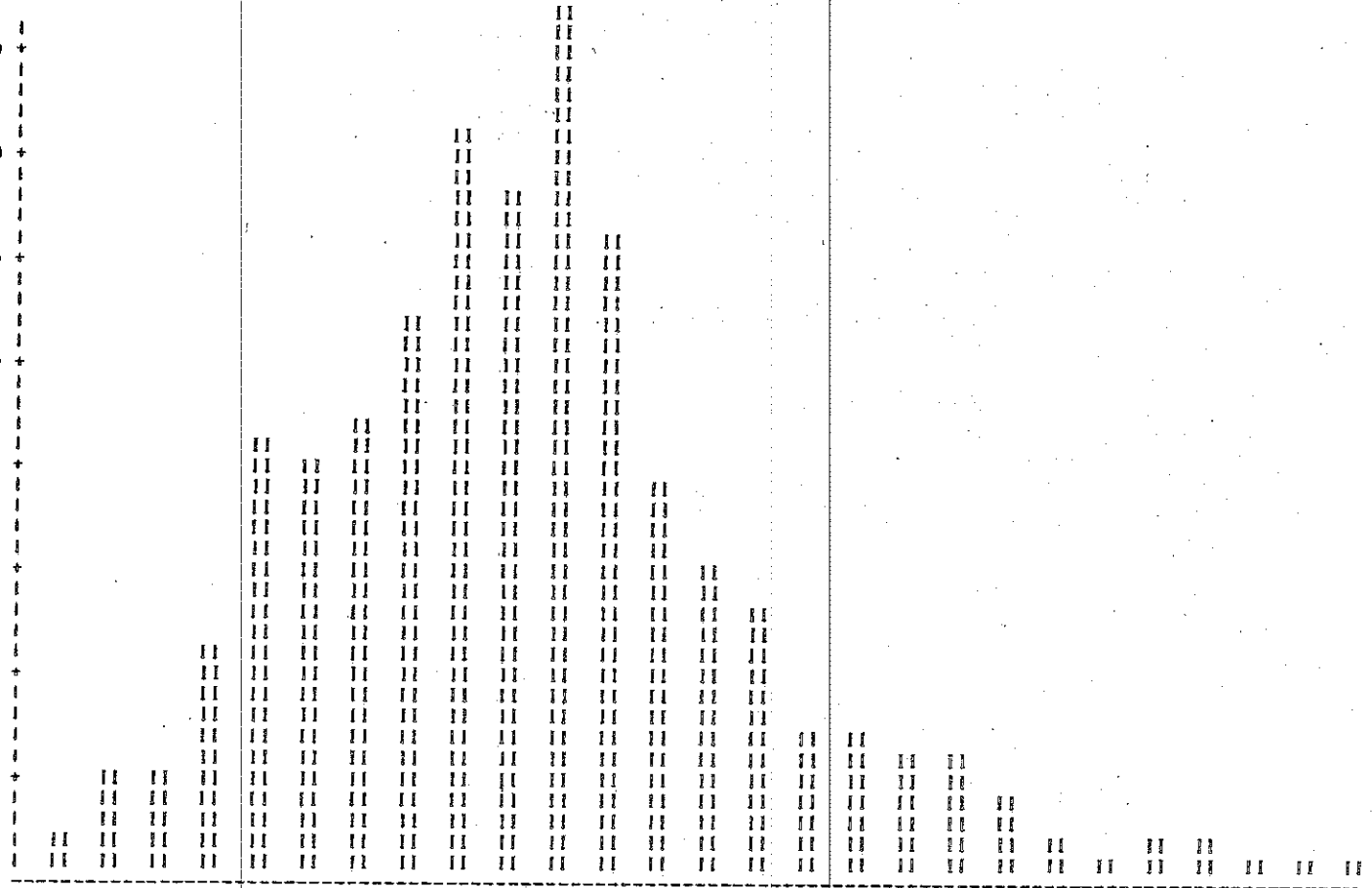
INTERSTATE ROUTES
 DISTRIBUTION OF ROUGHNESS
 ALL PAVEMENTS

NUMBER OF
 SECTIONS

80 +
 70 +
 60 +
 50 +
 40 +
 30 +
 20 +
 10 +

200 220 240 260 280 300 320 340 360 380 400 420 440 460 480 500 520 540 560 580 600 620 640 660 680 700 780

ROUGHNESS INDEX



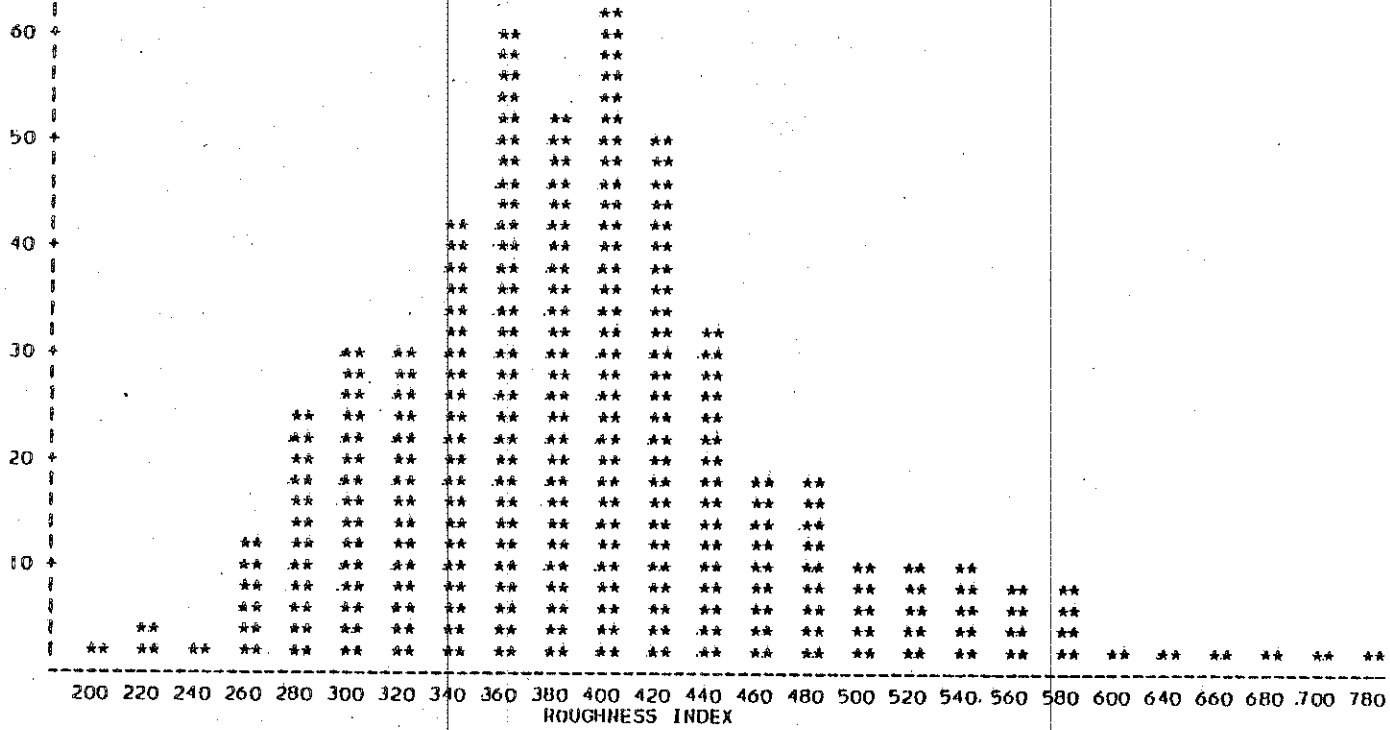
INTERSTATE ROUTES
 DISTRIBUTION OF ROUGHNESS
 ASPHALTIC CONCRETE PAVEMENTS

NUMBER OF
 SECTIONS

	220	240	260	280	300	320	340	360	380	400	420	440	460	480	500	520	560	580	600	620	660	
10 +																						
9 +																						
8 +																						
7 +																						
6 +																						
5 +																						
4 +																						
3 +																						
2 +																						
1 +																						

INTERSTATE ROUTES
 DISTRIBUTION OF ROUGHNESS
 PORTLAND CEMENT PAVEMENTS

NUMBER OF
 SECTIONS



INTERSTATE ROUTES
 DISTRIBUTION OF ROUGHNESS
 ASPHALTIC CONCRETE OVERLAYING
 ASPHALTIC CONCRETE PAVEMENTS

NUMBER OF
 SECTIONS

5 +

4 +

3 +

2 +

1 +

200

220

240

260

280

300

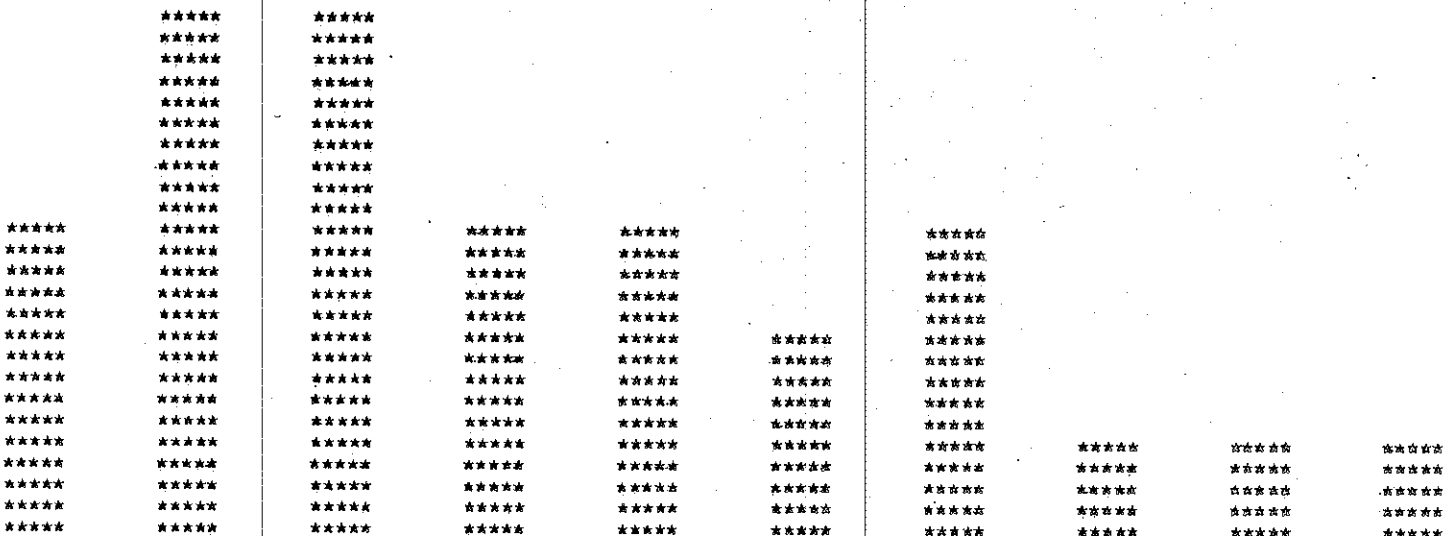
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340

380

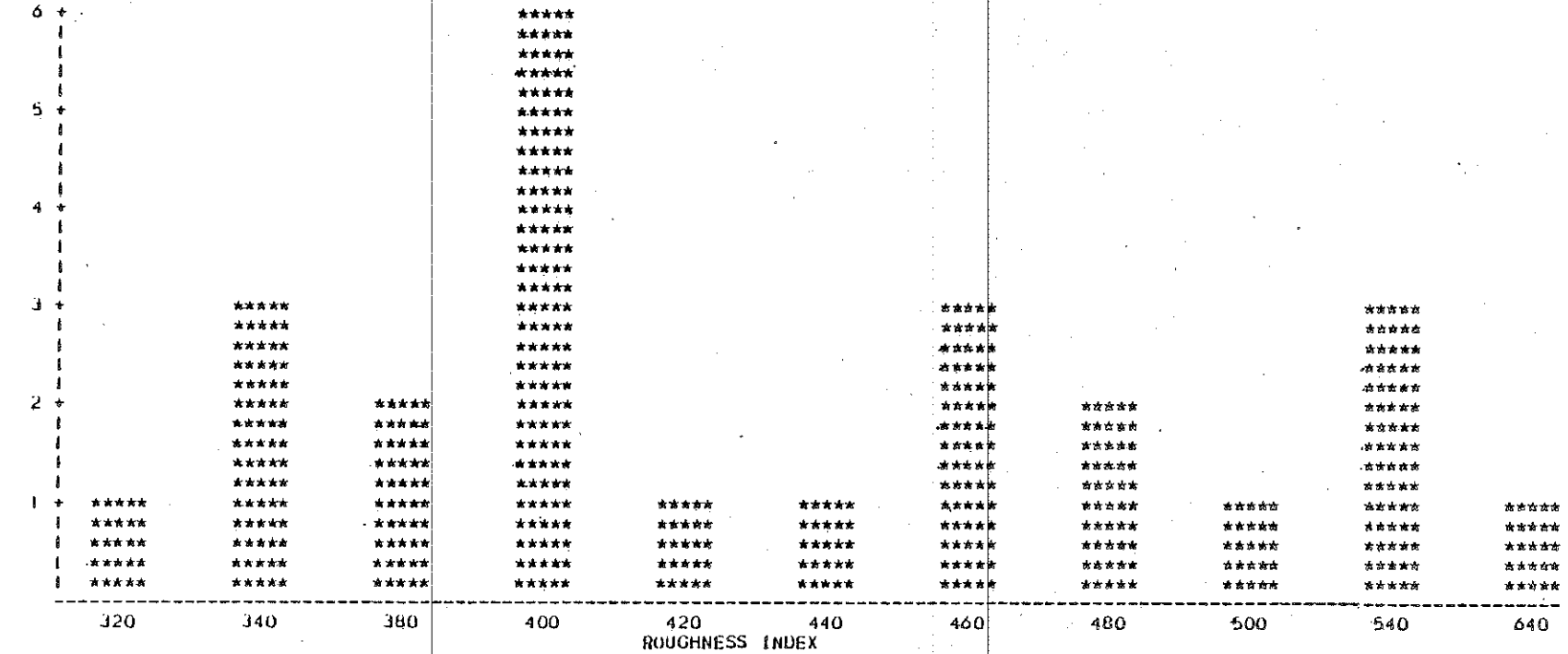
420

ROUGHNESS INDEX



INTERSTATE ROUTES
DISTRIBUTION OF ROUGHNESS
ASPHALTIC CONCRETE OVERLAYING
PORTLAND CEMENT CONCRETE PAVEMENT

NUMBER OF
SECTIONS



PARKWAY ROUTES
DISTRIBUTION OF ROUGHNESS
PORTLAND CEMENT CONCRETE PAVEMENTS

NUMBER OF SECTIONS

