PAVEMENT ROUGHNESS: MEASUREMENT AND EVALUATION

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Vertical accelerations of a passenger traveling in an automobile on a section of road at 51.5 mph (23.0 m/s) are automatically summed. A roughness index is obtained by dividing this sum by the time elapsed during the test. Continuity in measurements since 1957 has been preserved through correlations among successive vehicles involved and reference pavements. In general, bituminous construction has smoother riding surfaces than concrete construction. The smoothness of concrete pavements, however, has improved on those projects where slip-form paving was used. Interstate highway and parkway construction continues to yield smoother pavements than other major construction. The rate of increase in roughness was found to be different for each pavement type and varied according to the original or as-constructed roughness of the pavement, structural number, and type of highway facility involved.

•IN EARLY road-roughness testing in Kentucky, local irregularities in pavement profiles were detected by a roller type of straightedge. Although this method continues to be used to control construction tolerances, it was recognized in the early 1950s that a rapid method of recording profile characteristics more closely associated with riding quality was needed. Attention was then directed toward the response of a vehicle traveling on a highway at a normal speed. Various parameters associated with vehicles in motion were investigated; this led to the adoption of a triaxial arrangement of accelerometers mounted on the chest of a test passenger. Multichannel recording equipment was installed in an automobile to record passenger accelerations (1). A number of analytical approaches were tried (2). Finally, it was decided to sum the area under the vertical acceleration trace only and to express this measurement in terms of a roughness index (3, 4). The manual method of analysis was both tedious and time-consuming. Subsequently, instrumentation was added to automatically sum the vertical accelerations. This automatic system enabled an extensive survey program. Several variables affecting the results were investigated, and test procedures were developed to minimize their influences (5). Subsequent investigations have been concerned with the frequency content of vertical accelerations and the contribution of various frequencies to the roughness index. Test sedans were periodically replaced. Each change required a correlation between the old and the replacement vehicle.

Roughness measurements were obtained on more than 50 representative bituminous and concrete paving projects completed before 1957. Those projects have been retested periodically. Major bituminous and concrete paving projects completed since 1957 have also been added to the testing program and periodically retested. Projects largely involved Interstate highways and parkways (expressways). By 1970, 234 projects were being monitored for roughness.

Measurements were used to evaluate quality of workmanship and construction, to quantify rates of deterioration, and to identify contributing causes. Roughness indexes were related to service age, cumulative traffic, and equivalent axle loads (EAL).

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AUTOMOBILE METHOD OF RIDE-QUALITY TESTING

Instrumentation

The automatic roughness-measuring system (ARMS) is shown in Figure 1. The accelerometer is powered and balanced by circuits in the control console. The output signal is amplified and rectified by a selenium bridge and integrated by a solion cell. The integrator output is read on a dc digital voltmeter, which is also used for monitoring the ARMS in performing component adjustments and for calibrations. A recorder provides a chart for visual field or laboratory inspection. Figure 2 shows the instrumentation installed in the automobile and the test passenger with the accelerometer on his chest.

Procedures

Pressure in the tires was adjusted to 24 $lb/in.^2$ (1.7 kg/cm^2) when cold and did not exceed 28 $lb/in.^2$ (2.0 kg/cm^2) during a test; the gas tank was at least half full. The instrumentation power was turned on at least 10 minutes prior to testing to allow for adequate warm-up. Temperature in the vehicle was maintained at about 75 F (24 C). The accelerometer was balanced and calibrated; integrator output was nulled, and a full-scale calibration was performed.

The test passenger, of medium build and frame and weighing 150 to 170 lb (68 to 77 kg), was seated erectly, but relaxed, in the right front seat of the test vehicle with his arms resting in his lap. The accelerometer, mounted on an aluminum platform, was suspended from a cloth strap looping over his shoulders and behind his neck and resting against his chest. A mirror mounted on the right sunvisor permitted the test passenger to view a bubble level on the mounting platform to maintain the proper positioning of the accelerometer.

Sufficient starting distance preceded the test section to permit the vehicle to attain the test speed, normally 51.5 mph (23.0 m/s). At the end of each test excursion, the integrator output and elapsed time were recorded, and, by substitution into the appropriate equation (6), a roughness index (RI) was calculated. If a retest yielded an RI differing by more than ±4 percent, the pavement was retested. The closest values were averaged. Roughness measurements were not conducted under rainy or wet conditions or at temperatures below 45 F (7 C).

Vehicle Replacements

During the past 13 years, 3 full-sized Ford sedans have been employed in roughness testing: a 1957 Ford from January 1957 to May 1963, a 1962 Ford Galaxie from May 1963 to July 1968, and a 1968 Ford Galaxie from July 1968 to the present. Odometers in the first 2 vehicles at the time of retirement from roughness testing indicated approximately 90,000 miles (145,000 km).

Each vehicle replacement required a correlation of roughness measurements obtained with the old and replacement vehicles. Test sections of both flexible and rigid pavements were selected to represent pavements with excellent to poor ride qualities. The correlation in 1963 was primarily conducted on 2-lane roadways that exemplified the prevailing routes of travel. By 1968, emphasis in roughness testing was shifted to Interstate highways and parkways, and correlation between vehicles, therefore, was conducted on those projects. Consequently, the range in pavement roughness was greatly reduced, and pavements having very high RI values were no longer available.

Results of vehicle correlations in 1968 are shown in Figure 3. Separate linear regression equations were warranted for each pavement type. Because of the high vehicle correlations, periodic replacement of the test automobile has not perceptibly affected continuity in roughness measurements. Equations used in calculating the roughness index incorporated, among other considerations, differences in ride quality of the automobiles. Thus, all measurements are relative to the original test vehicle.

Figure 1. Automatic roughness-measuring system.

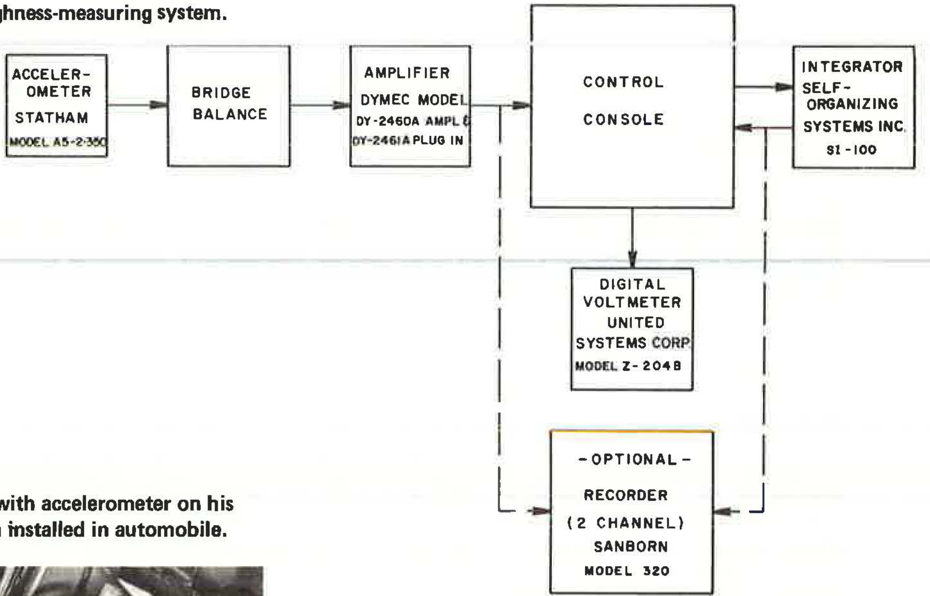


Figure 2. Test passenger with accelerometer on his chest and instrumentation installed in automobile.

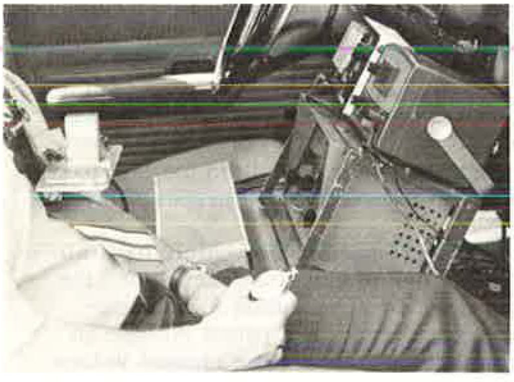
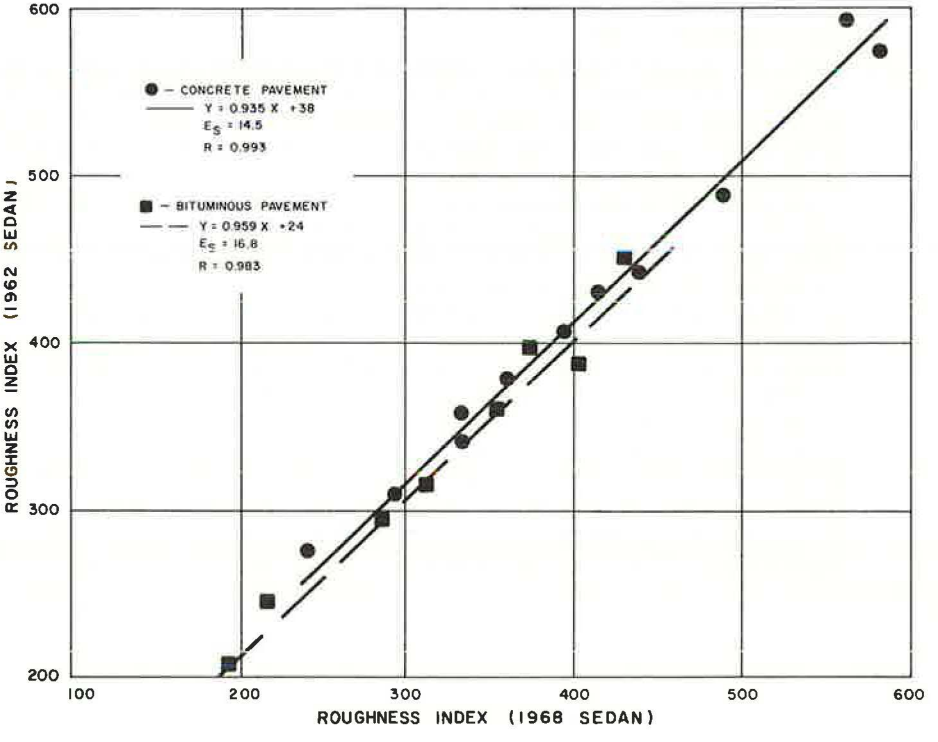


Figure 3. 1968 vehicle correlation.



Tire Replacement

Tires on the test vehicles were replaced with identical kind. The new tires were preconditioned on the test automobile, or another sedan, for at least 500 miles (800 km) prior to their use in roughness testing. The front end of the automobile was then inspected and aligned, and the tires were balanced. Tires were not permitted to wear below $^1/_8$ in. (3.2 mm) tread depth and were replaced when flat spots, out-of-roundness, or any other defects were detected. Performance of replacement tires was checked on reference surfaces.

Reference Surfaces

The dynamic response of the test vehicle was continuously monitored to achieve reliable roughness measurements. Deterioration of the suspension system or tires affects test results and may introduce serious errors. Two low-traffic roadway sections, one bituminous and one concrete, were selected as reference surfaces and periodically tested.

The addition or removal of weights from the vehicle was found to be the most expeditious procedure by which to alter test results. In the event the RI on the reference surfaces was judged to be too high, addition of weights improved the ride quality and thereby reduced the RI. Before such remedies were applied, however, a careful investigation was initiated to pinpoint the source of the problem. Some fault was usually found with one or several tires due to improper front-end alignment or wheel balance, and the defective tires were replaced or the wheels were rebalanced and the front end aligned. Close attention was always given to regular maintenance of the vehicle.

Measurements on the 2 reference surfaces were at times supplemented with measurements on other pavements for which previous data were available before final judgment was made as to vehicle condition. At times, roughness data were simply corrected on the basis of previous measurements obtained on the reference pavements when their retesting yielded values outside acceptable limits. These procedures were generally satisfactory in providing reasonable means to ensure short-term and, to a lesser extent, long-term reproducibility of roughness measurements.

Most pavements become rougher with age. Available evidence suggested that the reference pavements have become rougher, but not nearly so much as most other projects under surveillance. Data revealed a slight trend toward increased RI during a 3-year period. Whether this increase can be attributed solely to changes in the pavement profile or to the deterioration in ride quality of the vehicle cannot be conclusively stated. Discrepancies created by using data from the reference surfaces as outlined created errors in roughness measurements and, thus, underrated the roughness of pavements with the passing of time. The end result, of course, is that recently constructed pavements may indicate a somewhat smoother ride quality than their surface profiles may warrant, and retesting of projects constructed several years ago may show less deterioration than had actually occurred.

Frequency Composition of Measured Accelerations

Accelerations sensed with the accelerometer reflect the composite characteristics of the pavement profile, vehicle, and passenger. The pavement profile, therefore, cannot be specifically described unless the frequency response of the entire system between the sensor and the pavement is known. We were somewhat compelled to inspect the measured accelerations in terms of discrete frequency ranges and to note their contribution to the roughness index.

A bituminous surface and a concrete surface having nearly the same roughness indexes were selected for this analysis. The pavements could be described as representative of those pavement types in terms of their wavelength characteristics. A filtering device was incorporated into the ARMS instrumentation to allow recording of filtered output. Pavement sections were tested repeatedly with the filter acting as a low-pass filter. Several frequency ranges were used.

A roughness index was also obtained for each frequency range. Results of the low-pass filter measurements are shown in Figure 4 in terms of cumulative percentage of the total roughness index. Several observations are noteworthy. First, profile characteristics of the 2 pavements were quite different, even though their roughness indexes were the same. Profile amplitudes associated with shorter wavelengths were somewhat larger on concrete pavements than on bituminous pavements. Second, accelerations associated with 20- to 100-ft (6- to 31-m) waves contributed a major portion of the roughness index. Third, acceleration frequencies of 1 Hz or less contributed significantly to the RI even though their amplitudes were quite low. The explanation for what appears to be a contradiction lies with the method by which the RI was obtained. The method entailed summing of acceleration signals, or areas under the acceleration trace, which were random in nature. The higher frequency signals were superimposed on the lower frequencies and thereby added to or subtracted from the amplitude of the lower frequency signals. The net effect was a disproportionately lower contribution from the higher frequency accelerations.

Test Speed

It was recognized that the ride quality of vehicles changes with speed; therefore, a standard speed was necessary if pavements were to be compared and rated. A speed of 51.5 mph (23.0 m/s) was chosen because it approximated the average running speed on rural roads at that time. Statewide road improvement programs and construction of the Interstate and parkway systems have significantly raised running speeds, which now approach 70 mph (31 m/s) on expressways.

Sections on Interstate highways were selected for testing at 51.5 mph (23.0 m/s) and 70 mph (31 m/s). Data and results of linear regression analysis are shown in Figure 5. The following observations are made.

1. Profile characteristics of the 2 pavement types were sufficiently dissimilar to warrant separate regression equations.
2. Roughness indexes at 70 mph (31 m/s) were significantly higher than at the normal test speed. On bituminous pavements, the RI was 44 percent to 49 percent higher. On concrete pavements, the RI was 23 to 28 percent higher.
3. Differences between RI for the 2 speeds were somewhat affected by the roughness level of the road. On rougher pavements, the percentage differences between RI for the 2 speeds were the greatest.
4. Pavement profile characteristics for the same type of pavements were rather similar as reflected by the statistical parameters for the regression lines.

Figure 5 shows the influence of speed on roughness measurements and permits extrapolation of roughness indexes to higher test speeds. The measurements were made with the 1962 vehicle and not with the current test automobile, and, as pointed out earlier, each automobile responds somewhat differently to roadway excitations.

EVALUATION OF PAVEMENT ROUGHNESS

There are 2 sources of roughness: that which is built or constructed into the pavement and that which develops after construction through use or abuse. It is recognized that a pavement may change with age even if it were not used at all; embankments settle, and the pavement heaves. Heavy loads, and especially overloading, cause damage and may induce roughness. Roughness has been one of the major factors considered in resurfacing programs, and a history of the development of roughness is a significant descriptor of the service life of a pavement. Initial roughness thus alludes to the construction process and to quality of workmanship; changes in roughness with age and traffic are meaningful from the standpoint of structural design of pavements.

To this end, testing for roughness has been continued since 1957; some historical records include one or more resurfacings. All Interstate and parkway projects and many major construction projects have been tested for initial or as-constructed roughness. Insofar as possible, outer lanes on 4-lane roads have been tested annually; inside lanes of several selected projects have also been tested.

Figure 4. Roughness index with increasing acceleration frequencies obtained with low-pass filter.

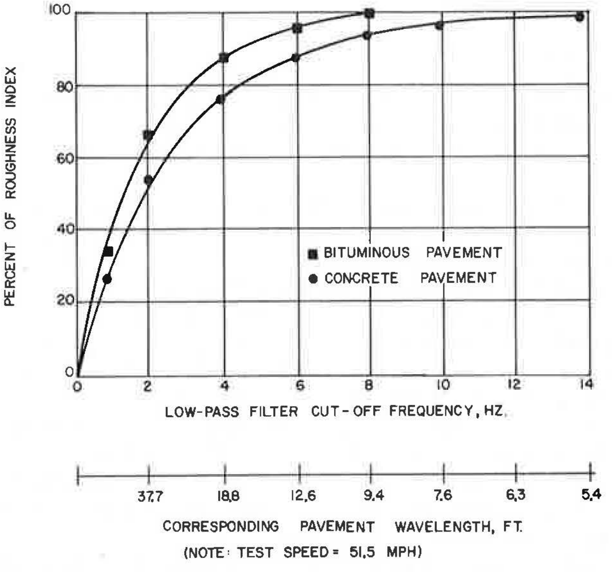
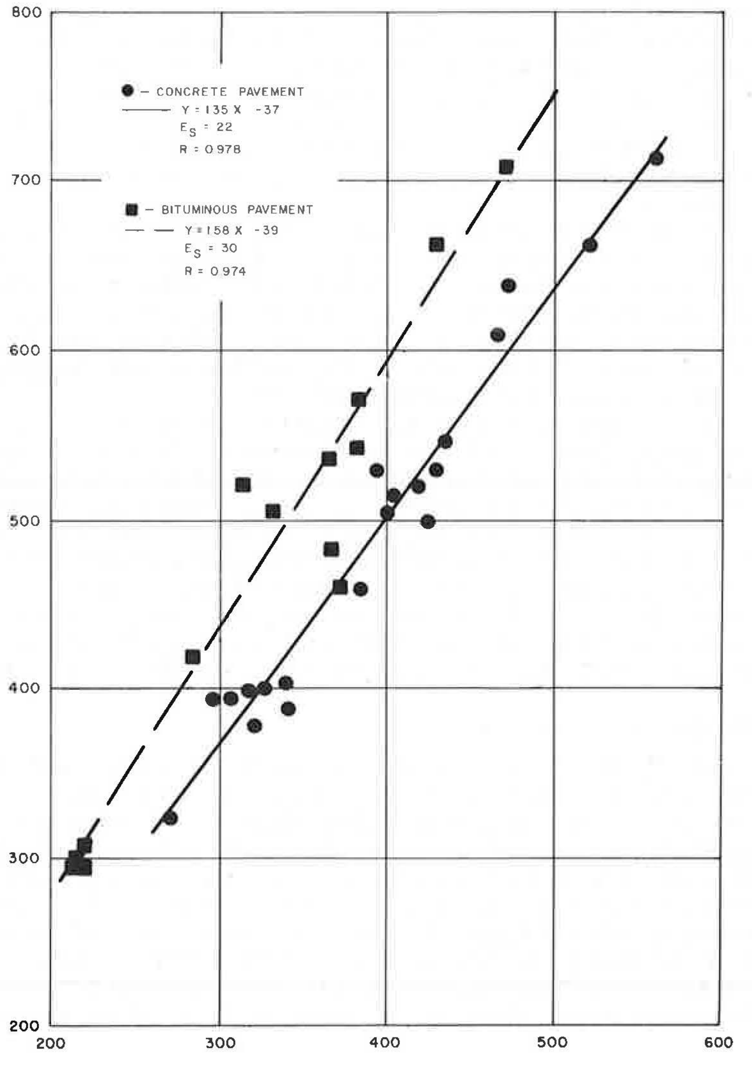


Figure 5. Roughness indexes at test speeds of 51.5 and 70 mph on bituminous and concrete pavements.



Constructed Roughness

Since 1959, Interstate, parkway, and other major roads tested totaled approximately 4,000 lane-miles (6,400 lane-km) and involved 177 projects, of which 71 were bituminous. The remaining 106 projects were concrete and included 14 projects constructed by slip-forming.

Distribution of initial roughness values is shown in Figure 6. Word ratings were first introduced in 1962 (4) and have remained unaltered, although they were established from a limited data set. By 1970, 55 percent of the concrete pavements and 71 percent of the bituminous pavements were rated excellent or good.

At the time of construction, roughness generally showed small variation throughout the length of a particular lane or among lanes. There were some notable exceptions. The greatest differences between any 2 lanes in Interstate and parkway construction were 41 and 36 percent for bituminous and concrete pavements respectively. Within each paving project, concrete pavements showed the smallest differences between the smoothest and the roughest lanes—an average of 13 percent. On bituminous pavements, the differences averaged 17 percent. On the whole, the smallest differences in roughness, of course, were found between adjoining lanes—3 percent in bituminous construction and 1 percent in concrete construction.

Comparisons of roughness indexes for Interstate, parkway, and other pavements for each construction year are given in Table 1. Parkways were somewhat smoother than Interstate highways, and other major construction projects were usually rougher than either. These comparisons are valid only for the same test speed (51.5 mph, 23.0 m/s). When additional consideration was given to driving speeds, such as 70 mph (31 m/s) on Interstate highways and parkways and 60 mph (27 m/s) on other highways, the ride quality was significantly reduced. Whereas direct comparisons were made at the standard testing speed, tests made at permissive running speeds showed clearly that control of pavement profile quality is not improved in commensurate proportion to design speed.

According to the roughness index, bituminous construction yielded smoother riding surfaces than concrete construction. As discussed earlier, caution should be exercised in directly comparing pavements having different surface characteristics. Concrete pavements typically exhibit a greater proportion of shorter wavelength irregularities that do not contribute significantly to the roughness index obtained with the Kentucky method of roughness testing, but they may be annoying to the driver and, therefore, influence ride-quality judgments.

The smoothness of concrete pavements was improved on those projects where slip-form paving (7) was used, with the exception of the first 2 projects completed in 1967. One project constructed in 1968 with continuous reinforcement and slip-form paving exhibited particularly excellent ride quality. Bituminous pavements constructed in the past several years, however, have not materially improved when contrasted with paving in the earlier years of Interstate and parkway construction. Voluntary adoption of electronic screed controls on pavers probably accounts for earlier quality improvements. Figure 7 shows the average roughness indexes of projects for each construction year on 4-lane Interstate highways and parkways. The median roughness for all projects was 270 for bituminous pavements and 325 for concrete pavements.

Bituminous Resurfacing

In 1957, more than 50 bituminous pavements were tested for roughness in connection with a pavement design study (8). These pavements represented a high type of construction and were located throughout Kentucky. Monitoring for roughness has continued although most of the pavements have been resurfaced. Bituminous overlays significantly reduced roughness; the average reduction in roughness index was 36 percent. Bituminous overlays on several concrete pavements exhibited similar improvements—an average of 39 percent. The greater reduction in roughness seemed to be realized on the rougher pavements as indicated by data given in Table 2. Cited improvements, however, are not precise because measurements were not made just prior to or shortly after resurfacing. Either the terminal roughness of the pavement was not obtained in

Figure 6. Initial roughness values for newly constructed bituminous and concrete pavements.

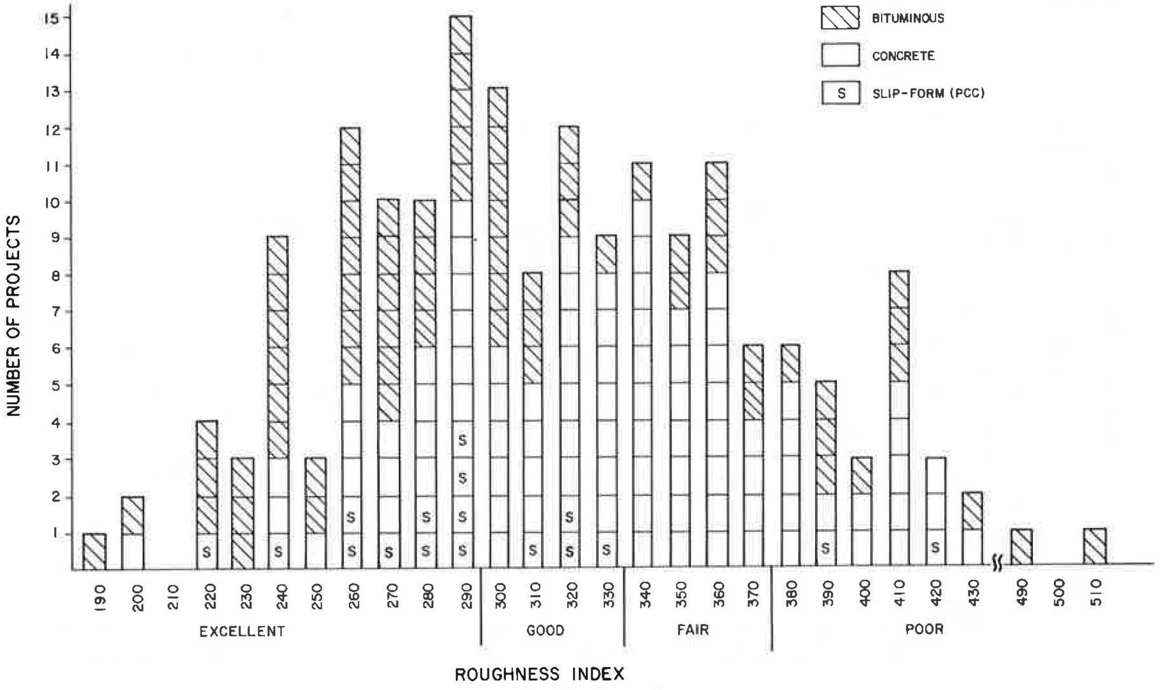


Table 1. Constructed roughness of pavements.

Pavement	Construction Year	Interstate Number of Projects	Interstate Avg RI	Parkway Number of Projects	Parkway Avg RI	Combined Avg RI	Others Number of Projects	Others Avg RI
Concrete (conventional)	Before 1962	10	331			331	4	382
	1962	8	332	9	332	332	2	325
	1963	7	329	12	302	312	3	350
	1964	3	337			337	1	300
	1965	3	317	4	325	322	1	420
	1966	4	340			340	1	410
	1967	6	368			368		
	1968	3	343	3	290	317		
	1969	3	297	2	360	322		
	Avg		334		317	328		363
Concrete (slip-form)	1967	2	405			405		
	1968	5	276	3	273	275		
	1969	4	285			285		
	1970			3	305	305		
	Avg		303		289	298		
Bituminous	Before 1962	2	295			295	8	362
	1962	2	330			330	6	368
	1963	2	355	13	277	287	3	303
	1964	3	270			270	2	290
	1965	2	260	3	233	244	3	267
	1966						5	320
	1967	2	280			280		
	1968	2	265	7	269	268		
	1969	4	262			262	2	325
	Avg		286		269	275		332

Figure 7. Average roughness index for each construction year on bituminous and concrete pavements of 4-lane Interstate and parkway highways.

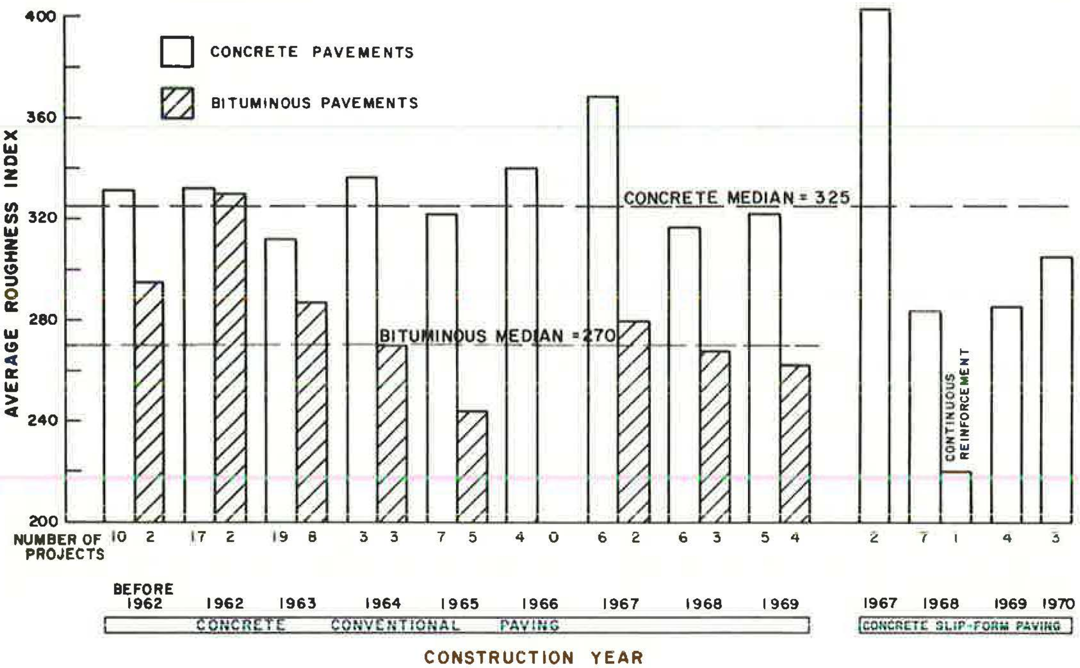


Table 2. Roughness of resurfaced flexible pavements.

Item	Before Resurfacing			After Resurfacing		
	Number of Projects	Avg Years in Service	Avg RI	Avg RI	Avg RI Improvement (percent)	Avg Annual RI Change Since Resurfacing (percent)
RI Range						
900	2	Unknown	942	538	43	0.9
800-900	4	9	819	456	44	2.3
700-800	9	11	744	489	34	1.8
600-700	8	12	658	425	35	3.2
500-600	6	11	566	392	31	3.7
Year Resurfaced						
1958	2	8	898	562	37	1.7
1959	3	9	745	485	34	2.4
1961	4	8	752	389	48	2.4
1962	5	11	718	500	30	0.6
1963	3	12	750	448	40	3.4
1964	3	12	585	437	25	6.3
1965	1	6	635	370	42	1.6
1966	6	13	662	442	33	3.1
1967	1	17	710	390	45	
1968	1	9	565	355	37	6.3
Avg		10.8	707	450	36	2.7

the year of resurfacing or the pavement was tested a year after resurfacing. Several pavements were excluded from consideration because the measurements were delayed by more than a year.

Criteria governing selection of the projects for resurfacing were not documented. Roughness data do suggest that strong consideration was given to pavement serviceability; and, of course, serviceability is foremost related to roughness. Figure 8 shows that the rougher pavements were generally chosen for resurfacing, and, in spite of ongoing deterioration of pavements with age, the remaining surfaces exhibited at least the same roughness as they did in the preceding years. The net result of resurfacing efforts on the subject pavements was a substantial improvement in ride quality by 1970. Although these pavements were not statistically chosen, they may be considered representative of the older, higher type of construction on U.S. and state routes. Therefore, a reasonably legitimate claim may be made that ride quality on most 2-lane highways in Kentucky has materially improved since 1957.

Roughness Inventory

The latest available test results for various highways are given in Table 3. Interstate highways and parkways had lower roughness indexes than other roads; however, ride quality of high-speed facilities diminished significantly when tested at the speed limit. In other words, a person traveling 70 mph (31 m/s) on an Interstate highway may experience more discomfort than he would traveling 50 mph (22 m/s) on a 50-mph (22-m/s) road.

Bituminous overlays on older surfaces have eliminated many of the very rough pavements in Kentucky. Only a few road sections in the current inventory had RI's higher than 600; in 1960 almost half of the projects monitored were rougher.

Service Roughness

After being tested for as-constructed roughness, each project was periodically retested to monitor changes in roughness during the life of the pavement. On Interstate, parkway, and other multilane roads, the outside lanes were usually tested. A cursory inspection of data indicated that increases in roughness were associated with time-dependent variables or influences. This increase was quantified and the contributing influences were identified by relating roughness to service period, cumulative traffic, and equivalent axle load. Cumulative traffic for a given lane was determined from lane distribution factors, average daily traffic, and the number of days the pavement was in service. EAL was calculated according to the modified AASHO procedures and traffic parameters developed by Deacon and Deen (9).

Roughness data for every Interstate highway and parkway project were plotted versus time in service, cumulative traffic, and EAL. Curves were manually fitted for all projects for which 4 or more roughness measurements were available. No attempt was made to delete any data, even though some roughness measurements were obviously in error when contrasted with measurements in preceding or subsequent years or both. A straight line was found to best describe the relations although there were notable exceptions. Computerized, linear regression analysis provided equations of best fit straight lines. Graphs of 6 bituminous pavements are shown in Figure 9 for illustration. Similar procedures and analyses were employed for bituminous concrete, bituminous overlays on bituminous base, and concrete pavements involving other high type of construction projects on U.S. and state highways. However, roughness data were related only to months in service and cumulative traffic.

The rate of increase in roughness, expressed here as the slope of regression lines, was different for each pavement type, as shown in Figures 10 through 16, and varied according to the original or as-constructed roughness of the pavement. Concrete pavements on Interstate highways and parkways deteriorated at a considerably lower rate than the bituminous pavements on the same type of facility. On bituminous pavements, the smoother constructed surfaces deteriorated more rapidly, with the exception of the 4-lane parkways. On the other hand, concrete pavements on U.S. and Interstate highways deteriorated more rapidly on projects where the constructed roughness was the highest. Here again, parkways exhibited opposite trends.

Figure 8. Average roughness index of bituminous pavements monitored since 1957.

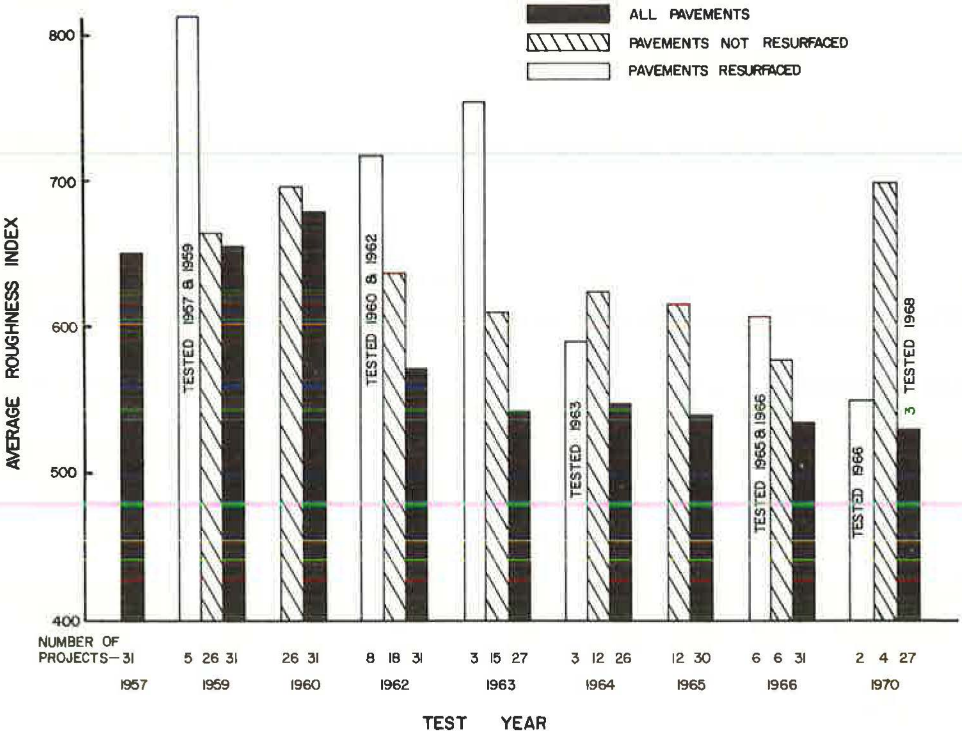


Table 3. Roughness of various highways.

Pavement	Highway	Number of Projects	Roughness Index Median	Roughness Index Avg	Equivalent, Median RI[a] 60 mph	Equivalent, Median RI[a] 70 mph
Bituminous	Interstate	19	350	345		515
	Parkway	23	325	358		475
	U.S. and state	80	465	444	540	
Concrete	Interstate	58	350	354		435
	Parkway	36	345	357		430
	U.S. and state	18	440	457	495	

[a]Extrapolated from data shown in Figure 4.

Figure 9. Relation of roughness index and pavement age, cumulative traffic, and EAL for 6 bituminous Interstate projects.

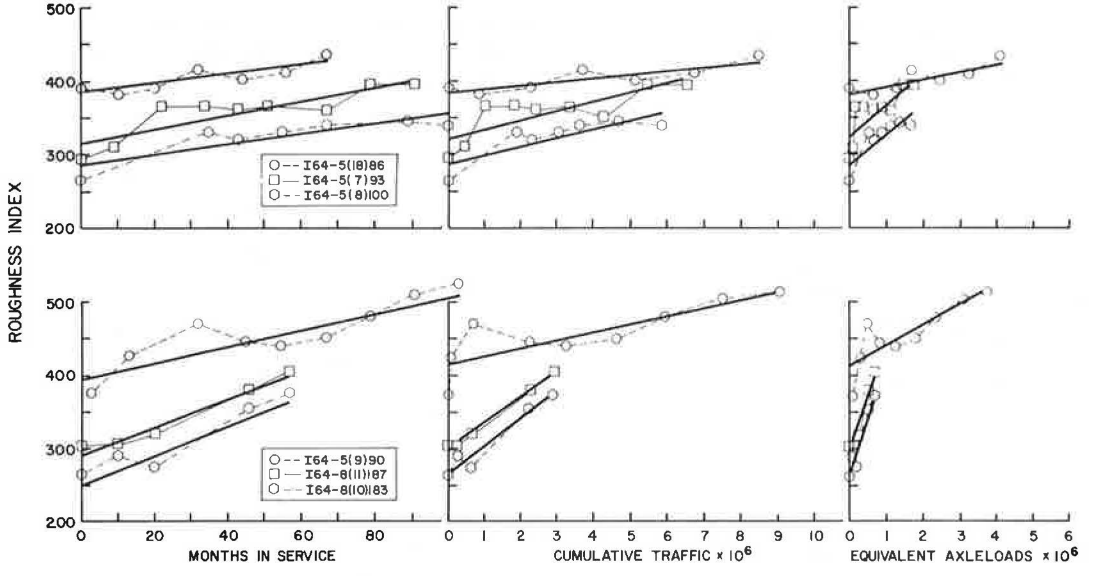


Figure 10. Combined regression equations relating roughness to age of bituminous pavements on Interstate highways.

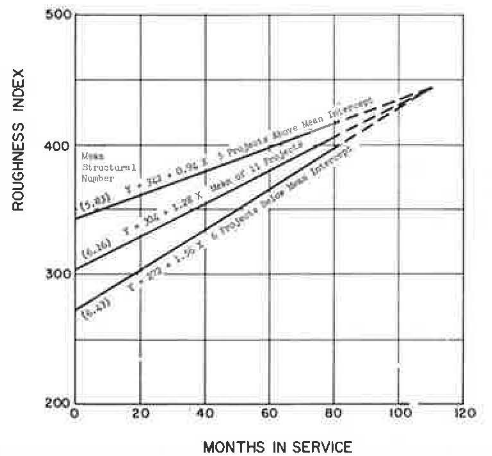


Figure 11. Combined regression equations relating roughness to age of bituminous pavements on 4-lane parkways.

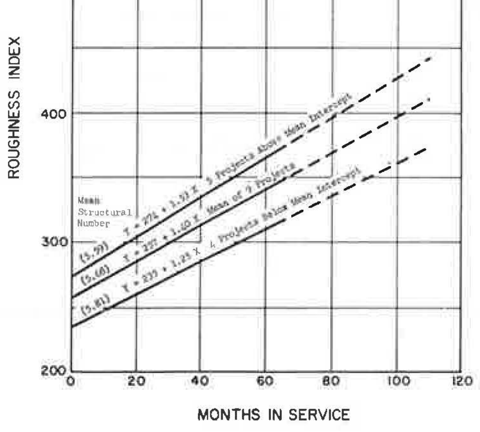


Figure 12. Combined regression equations relating roughness to age of concrete pavements on Interstate highways.

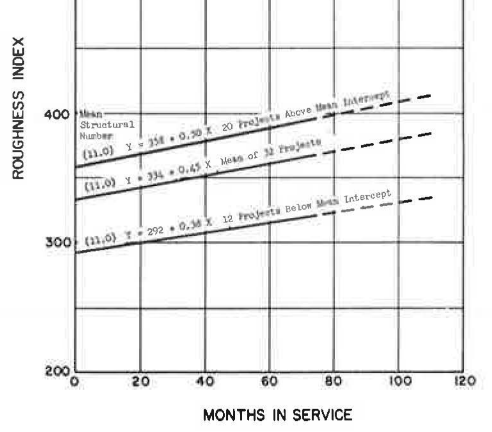


Figure 13. Combined regression equations relating roughness to age of concrete pavements on parkways.

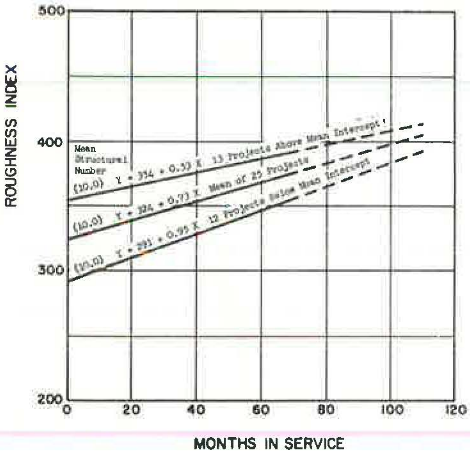


Figure 14. Combined regression equations relating roughness to age of concrete pavements on U.S. highways.

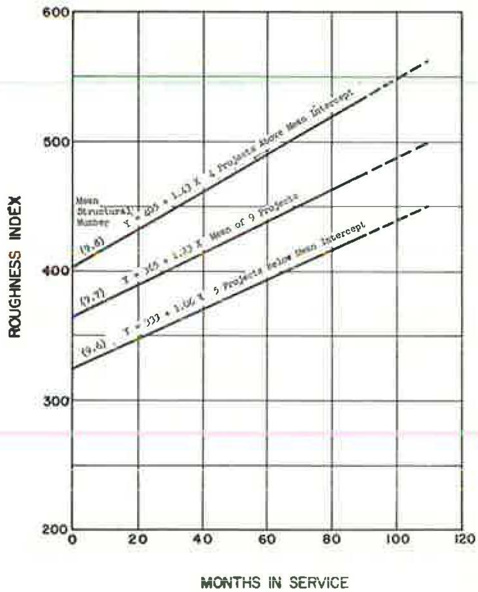


Figure 15. Combined regression equations relating roughness to age of bituminous pavements on U.S. and state highways.

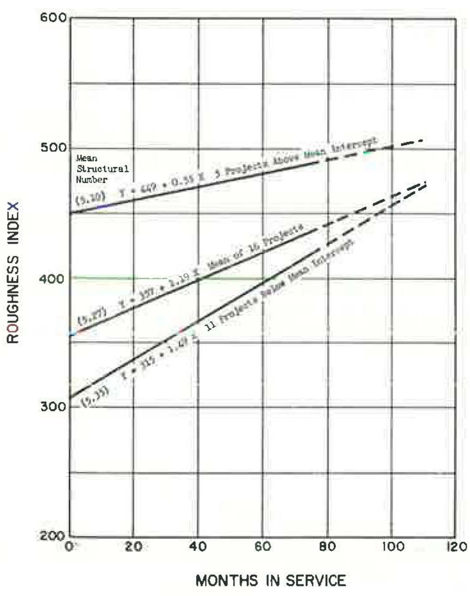
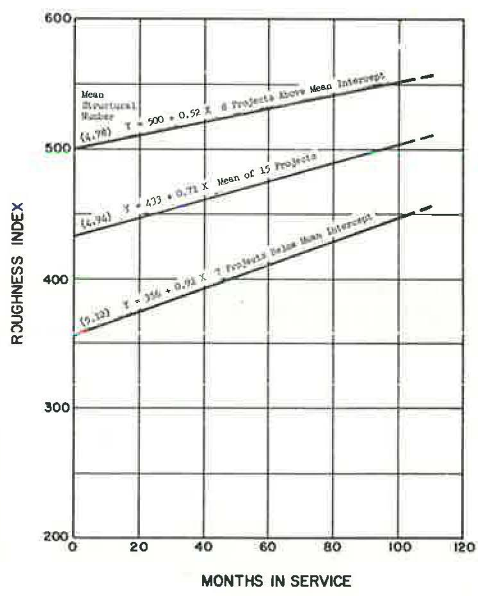


Figure 16. Combined regression equations relating roughness to age of bituminous resurfacing on U.S. and state highways.



Structural numbers (SN) for bituminous pavements were calculated and ranged between 2.9 and 7.0. No conclusive evidence was found to suggest that the SN had a significant bearing on the rate of increase in roughness. An interesting trend, however, was noted between the magnitude of the as-constructed RI and SN when several bituminous projects for a given highway facility were combined. In every case, the smoother constructed pavements were associated with a higher structural number. Concrete pavements were designed with a fixed SN of 11 for Interstate highways. On U.S. highways, the SN was either 9 or 10. A definite trend of increasing roughness was noted as the structural number decreased.

Correlations between RI and service period, cumulative traffic, and EAL yielded equally valid statistical results (6). The contribution of traffic and loading to roughness, therefore, could not be isolated from service period. Each of the parameters was time dependent and correlated well with one another. Further consideration must be given to other unaccounted influences, such as rate of differential settlement and rutting, and the interrelations among parameters considered.

In general, pavements involving high type of construction do not exhibit rapid changes in roughness. For example, several bituminous pavements on I-64 and I-75 required resurfacing because of severe cracking in the surface course and significant depth of rutting in the wheelpaths. Yet, the RI of those projects had increased by only 50 to 145 above the as-constructed roughness. The level of service provided by these highways in regard to roughness, therefore, was foremost related to the as-constructed roughness of the pavements.

The pavement serviceability performance concept originated in conjunction with the AASHO Road Test. Determination of present serviceability index (PSI), a scalar expression of pavement condition, has continued on a limited basis for Interstate projects. The PSI can be obtained either directly from the roughness index by using appropriate regression equations or from roughness measurement and a survey of the pavement by quantifying the extent of major cracking, patching, and rutting depth. The choice as to which yields the proper expression of pavement serviceability has been of some concern. The PSI determined from RI alone was consistently higher. If the PSI is to be used as an expression of pavement condition, the better choice would be to use the equations that incorporate cracking, patching, and rutting. Although it can be argued that serviceability is important from the standpoint of the road user, insidious fatigue of the structure is not necessarily manifested in roughness or serviceability at the half-life stage. Fatigue is revealed only by breakup of the pavement. Therefore, if fatigue were the only factor affecting roughness, trend lines [for 18-kip (8,200-kg) axles] for all pavements considered would be horizontal; that is to say, none would show an increase in roughness. Therefore, any increasing roughness surely becomes attributable to other causes. The question then arises as to whether the available regression equations properly characterize high type of construction. A Purdue University study (10) considered test sections on primary and secondary roads, none of which was comparable to Interstate highways. Surely the pavement rater would apply somewhat different standards for those highways and would, therefore, rate them accordingly.

SUMMARY AND CONCLUSIONS

Accelerometer measurements of a passenger's torso, using the automatic roughness-measuring system, has been an invaluable tool in evaluating roughness of road surfaces in terms that are closely associated (here by inference only) with riding comfort. The test can be conducted at a speed that is compatible with the normal flow of traffic and, thereby, can be carried out with maximum safety to testing personnel. Test results are available immediately and are closely repeatable. Reasonably good long-term reproducibility of test results has been achieved through strict adherence to carefully developed procedures and practices. Replacement of test vehicles has not seriously detracted from continued data collection. The automobile as a testing device does present inherent deficiencies and limitations; and the measurements, in the form of either roughness index or an acceleration recording, do not fully characterize the pavement.

In general, bituminous construction has yielded smoother riding surfaces than concrete construction. No major improvements in workmanship were noted on bituminous pavements in Kentucky since 1962. The roughness of concrete pavements, however, was improved on those projects where slip-form paving was used. A pavement constructed in 1968 with continuous reinforcement and slip-form paving exhibited especially excellent ride quality and may be indicative of results from similar construction in the future. Interstate highway and parkway construction continues to yield smoother pavements than other major construction. These comparisons, of course, are valid only for the same speed of travel, for the tests were conducted at 51.5 mph (23 m/s). However, roughness was found to be related to vehicle speed; and when consideration was given to actual travel speed, such as 70 mph (31 m/s) on Interstate highways and parkways and 50 mph (22 m/s) on other highways, the ride quality became significantly degraded on the higher speed facilities and greatly offset cited improvements. Assessments and requirements for pavement roughness, therefore, must be coupled with due consideration to the anticipated speed of travel for each highway facility.

Bituminous overlaying of the older surfaces has eliminated most of the very rough pavements. As a result of these resurfacing efforts, a reasonably valid claim may be made that the ride quality on most primary, 2-lane highways has materially improved since 1957 in spite of the ongoing deterioration of pavements with age, increased traffic, and vehicle loads.

The rate of deterioration in roughness was found to be different for each pavement type and varied according to the original or as-constructed roughness of the pavement, structural number, and type of highway facility involved. Concrete pavements on Interstate highways and parkways deteriorated at a considerably lower rate than bituminous pavements on the same facilities. An interesting trend was found between as-constructed roughness, structural number, and rate of pavement deterioration. On Interstate highways, the smoother constructed surfaces of bituminous pavements deteriorated more rapidly, while the rougher surfaces of concrete pavements deteriorated more rapidly. Completely opposite trends, however, were realized on parkways. For a given highway facility involving bituminous construction, the lower original roughness indexes were associated with those projects where the structural numbers were higher. A definite trend to increased roughness was noted for concrete pavements as the structural number decreased.

The correlations between roughness index and service period, cumulative traffic, and EAL were valid. The contribution of traffic or loading to roughness, therefore, could not be isolated from service period. Each of the parameters was time dependent and correlated well. Further consideration must be given to other unaccounted influences, such as rate of differential settlement and rutting, and the interrelations among parameters considered. Refined measurement of pavement roughness and improved information on volume, distribution, and composition of traffic may be needed to clearly identify those elements that cause pavements to become rougher.

Pavements involving high type of construction generally do not exhibit rapid changes in roughness. The level of service provided by these highways in regard to roughness, therefore, is foremost related to the as-constructed roughness of the pavement. Clearly then, every effort should be pursued to construct the smoothest possible surfaces. Other considerations such as structural adequacy of the total pavement system, structural integrity of the surface course, and slipperiness will primarily dictate the need for resurfacing.

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