PAVEMENT ROUGHNESS: MEASUREMENT AND EVALUATION

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ABSTRACT

Vertical accelerations of a passenger in an automobile are automatically summed while traveling a section of road at 51.5 mph (23.0 m/s). 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 yielded smoother-riding surfaces than concrete construction. The smoothness of concrete pavements, however, has improved on those projects where slip-form paving was used. Interstate and parkway (expressway) 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 the type of highway facility involved.
INTRODUCTION

In early road-roughness testing in Kentucky, local irregularities in pavement profiles were detected by a roller-type straight edge; and, while this method continues to be used to control construction tolerances, it was recognized in the early 1950's that a rapid method for recording profile characteristics more closely associated with riding quality was needed. Attention was then directed towards the response of a vehicle traveling a highway at a normal driving 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. Multi-channel 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 over 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 the interstate and parkway (expressway) routes. By 1970, a total of 234 projects were being monitored for roughness.

Measurements were used for the following purposes: 1) to evaluate quality of workmanship and
construction, 2) to quantify rates of deterioration, and 3) to identify contributing causes. Roughness indexes were related to service age, cumulative traffic, and equivalent axleloads (EAL's).

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 solin cell. The integrator output is read on a d.c. digital voltmeter. The voltmeter 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.

Procedures

Pressure in the tires is adjusted to 24 psi (1.7 kg/cm²) when cold and not to exceed 28 psi (2.0 kg/cm²) during a test, and the gas tank is checked to insure that it is at least one-half full. The instrumentation power is turned on at least ten minutes prior to testing to allow for adequate warm-up. Temperature in the vehicle is maintained at about 75°F (24°C). The accelerometer is then balanced and calibrated. Integrator output is nulled and a full-scale calibration is performed.

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

Sufficient starting distance precedes 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 are recorded; and, by substitution into the appropriate equation (6), a roughness index (RI) is calculated. If a retest yields an RI differing by more than (±) 4 percent, the pavement is retested. The closest values are averaged.

Roughness measurements are not conducted under rainy or wet conditions or at temperatures below 45°F (7°C).
Vehicle Replacements

During the past 13 years, three full-size Ford sedans have been employed in roughness testing:

- 1957 Ford January 1957 - May 1963
- 1968 Ford Galaxie July 1968 - Present

Odometers in the first two vehicles at the time of retirement from roughness testing indicated approximately 90,000 miles (145 x 10^3 km).

Each vehicle replacement required a correlation of roughness measurements obtained with the old and replacement vehicles. Test sections, both flexible and rigid pavements, were selected to represent pavements with excellent to poor ride qualities. The correlation in 1963 was primarily conducted on two-lane roadways which exemplified the prevailing routes of travel. By 1968, emphasis in roughness testing was shifted to interstate and parkway projects. Correlation between vehicles, therefore, was conducted on these 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 presented in Figure 2. Separate linear regression equations were warranted for each pavement type. Vehicle correlations yielded highly correlatable data; and, therefore, 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 between automobiles. Thus, all measurements are relative to the original test vehicle.

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-inch (3.2 mm) tread depth and were replaced when flat spots, out-of-roundness or any other defects were detected. Performance of replacement tires were 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, tires, etc. affects test results and may introduce serious errors. Two low traffic roadway sections, a bituminous and a concrete pavement, 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. More often than not, some fault was found with one or several tires due to improper front-end alignment or wheel balance. The defective tire(s), with flat spots or out-of-roundness, were replaced. Sometimes the remedy simply involved rebalancing wheels and aligning the front end. Close attention was always given to regular maintenance of the vehicle.

Measurements on the two reference surfaces were at times supplemented with measurements on other pavements for which previous data were available before final judgement 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 insure 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 as much as most other projects under surveillance. Data revealed a slight trend towards increased RI during a three-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, thus underrating 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. It was somewhat compelling to inspect the measured accelerations in terms of discrete frequency ranges and to note their contribution to the roughness index.

A bituminous 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 utilized.
A roughness index was also obtained for each frequency range. Results of the low-pass filter measurements are presented graphically in Figure 3 in terms of cumulative percentage of the total roughness index. Several observations are noteworthy. First, profile characteristics of the two 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-foot (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 ride quality of vehicles changes with speed, and 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 expressway-type roads.

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 presented in Figure 4. Several pertinent observations are noteworthy:

1. Profile characteristics of the two 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 two speeds were somewhat affected by the roughness level of the road. On rougher pavements, the percentage differences between RI for the two 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 4 portrays the influence of speed on roughness measurements and permit extrapolation of
roughness indexes into 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 two sources of roughness: 1) that which is built or constructed into the pavement, and
2) 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 would settle and the pavement would
heave. Heavy loads, and especially overloading, are damaging to the pavement 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 four-lane
roads have been tested annually; inside lanes of several selected projects have also been tested.

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 presented graphically in Figure 5. 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 between lanes. There were some notable exceptions. The greatest differences between
any two lanes in interstate and parkway construction was 41 percent 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 -- three percent in bituminous construction and one percent
in concrete construction.

Comparisons of roughness indexes for interstate, parkway, and other pavements for each construction year are summarized in Table I. Parkways were found to be somewhat smoother than interstate pavements. Other major construction projects were usually rougher than interstate and parkway roads. 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) of interstate and parkway roads 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 which 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 judgements.

The smoothness of concrete pavements was improved on those projects where slip-form paving (7) was used — with the exception of the first two 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 last 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. The bar graph in Figure 6 presents the average roughness indexes of projects for each construction year on four-lane interstate and parkway highways. The median roughness for all projects was 270 for bituminous pavements and 325 for concrete pavements.

**Bituminous Resurfacing**

In 1957, over 50 bituminous pavements were tested for roughness in connection with a pavement design study (8). These pavements represented high-type 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 summarized in Tables II and III. Cited improvements, however, are not precise since measurements were not made just prior to or shortly after resurfacing. Either the terminal roughness...
of the pavement was not obtained in the year of resurfacing or the pavement was tested a year after
resurfacing. Several pavements were excluded from consideration since the measurements were delayed
by more than a year.

Criterion governing selection of the projects for resurfacing was not documented. Roughness data
do suggest that strong consideration was given to pavement serviceability; and, of course, serviceability
is foremostly related to roughness. The bar graph in Figure 7 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 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, high-type construction on US and state routes; therefore, a reasonably legitimate claim may be
made that ride quality on most two-lane highways in Kentucky has materially improved since 1957.

Roughness Inventory

The latest available test results are summarized for various highways in Table IV. Interstate and
parkways showed 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 road 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 in excess of 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. To quantify this increase and to identify
the contributing influences, roughness was related to service period, cumulative traffic and equivalent
axleloads (EAL's). Cumulative traffic for a given lane was determined from lane distribution factors,
average daily traffic (ADT) and the number of days the pavement was in service. The EAL’s were calculated
according to the modified AASHO procedures and traffic parameters developed by Deacon and Deen
(9).

Roughness data for every interstate and parkway project were plotted versus time in service,
cumulative traffic, and EAL’s. Curves were manually fitted for all projects for which four 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 and (or) subsequent years. A straight line was found to best describe the relationships although there were notable exceptions. Computerized, linear regression analysis provided equations of best-fit straight lines. Graphs of six bituminous pavements are presented in Figure 8 for illustration. Similar procedures and analyses were employed for bituminous concrete, bituminous overlays on bituminous base, and concrete pavements involving other high-type construction projects on US and KY designated 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 found to be different for each pavement type, as shown in Figures 9 through 15, and varied according to the original or as-constructed roughness of the pavement. Concrete pavements on interstate and parkway roads deteriorated at a considerably lower rate than the bituminous pavements on the same type facility. On bituminous pavements, the smoother constructed surfaces deteriorated more rapidly -- with the exception of the four-lane parkway roads. On the other hand, concrete interstate pavements and concrete pavements on US designated roads deteriorated more rapidly on projects where the constructed roughness was the highest. Here again, parkway projects exhibited opposite trends.

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. On US designated roads, 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's 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 were time dependent and correlated well with each other. Further consideration must be given to other unaccounted influences, such as rate of differential settlement, rutting, etc. and the interrelationships between each parameter considered.

In general, pavements involving high-type construction do not exhibit rapid changes in roughness. For example, several bituminous pavements on I 64 and I 75 required resurfacing due to severe cracking in the surface course and significant depth of rutting in the wheel paths. 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 foremostly related to the as-constructed roughness of the pavements.

The pavement serviceability performance concept originated in conjunction with the AASHO Test Road. 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 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 consistently yielded higher indexes. If the PSI is to be used as an expression of pavement condition, the better choice would be to use the equations which incorporate cracking, patching and rutting. While 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 construction. A Purdue University study (10) considered test sections on primary and secondary roads, none of which were comparable to interstate. Surely the pavement rater would apply somewhat different standards for these roads and would, therefore, rate them accordingly.

SUMMARY AND CONCLUSIONS

Accelerometer measurements of a passenger's torso, utilizing the Automatic Roughness Measuring System, has been an invaluable tool in evaluating roughness of road surfaces in terms which 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 distracted from continued data collection. The automobile as a testing device does present inherent deficiencies and limitations; and the measurements, either in the form of 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, were 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 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 since 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 and parkway roads 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, two-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 the type of highway facility involved. Concrete pavements on interstate and parkway roads 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 bituminous interstate pavements, the smoother constructed surfaces deteriorated more rapidly, while on concrete interstate pavements the rougher surfaces deteriorated more rapidly. Completely opposite trends, however, were realized on the parkway projects. 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's were valid. The contribution of traffic or loading to roughness, therefore, could not be isolated from service period. Each of the parameters were time dependent and correlated well. Further consideration must be given to other unaccounted influences, such as rate of differential settlement, rutting, etc. and the interrelationships between each parameter considered. Refined measurement of pavement roughness and
improved information on volume, distribution and composition of traffic may be needed to clearly identify those elements which cause pavements to become rougher.

Pavements involving high-type construction generally do not exhibit rapid changes in roughness. The level of service provided by these highways in regard to roughness, therefore, are foremostly 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, slipperiness, etc. will primarily dictate the need for resurfacing.

ACKNOWLEDGEMENTS

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REFERENCES

Figure 1. Block Diagram of Automatic Roughness-Measuring System and Photograph of the Test Passenger with Accelerometer on His Chest and Instrumentation Installed in the Automobile.
CONCRETE PAVEMENT

\[ Y = 0.935 X + 38 \]
\[ E_S = 14.5 \]
\[ R = 0.993 \]

BITUMINOUS PAVEMENT

\[ Y = 0.959 X + 24 \]
\[ E_S = 16.8 \]
\[ R = 0.983 \]

Figure 2. 1968 Vehicle Correlation.
Figure 3. Cumulative Percentage of the Roughness Index with Increasing Range of Acceleration Frequencies Obtained with a Low-Pass Filter.
Figure 4. Roughness Indexes Obtained at Test Speeds of 51.5 mph and 70 mph on Bituminous and Concrete Pavements.
Figure 5. Distribution of Initial Roughness Values for Newly Constructed Bituminous and Concrete Pavements.
Figure 6. Average Roughness Index for Each Construction Year on Bituminous and Concrete Pavements Involving Four-Lane Interstate and Parkway Projects.
Figure 7. Roughness of Bituminous Pavements Monitored since 1957 (Graph Shows the Average RI of All Pavements, Pavements Selected for Resurfacing, and Remaining Pavements).
Figure 8. Relationships between Roughness and Pavement Age, Cumulative Traffic and EAL's for Six Bituminous Interstate Projects (Shown in Two Graphs To Avoid Confusion of Data Points).
Figure 9. Combined Regression Equations Relating Roughness to Age of Bituminous Pavements on Interstate Highways.
Figure 10. Combined Regression Equations Relating Roughness to Age of Bituminous Pavements on Four-Lane Parkway Highways.
Figure 11. Combined Regression Equations Relating Roughness to Age of Concrete Pavements on Interstate Highways.
Figure 12. Combined Regression Equations Relating Roughness to Age of Concrete Pavements on Parkways.
Figure 13. Combined Regression Equations Relating Roughness to Age of Concrete Pavements on US Designated Roads.
Figure 14. Combined Regression Equations Relating Roughness to Age of Bituminous Pavements on US and KY Designated Roads.
Figure 15. Combined Regression Equations Relating Roughness to Age of Bituminous Resurfacing on US and KY Designated Roads.
**TABLE I**

CONSTRUCTED ROUGHNESS OF PAVEMENTS

<table>
<thead>
<tr>
<th>CONSTRUCTION YEAR</th>
<th>INTERSTATE</th>
<th>PARKWAY</th>
<th>COMBINED</th>
<th>OTHERS</th>
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<tr>
<td></td>
<td>NO. OF PROJECTS</td>
<td>AVG. RI</td>
<td>NO. OF PROJECTS</td>
<td>AVG. RI</td>
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<tr>
<td></td>
<td>RI</td>
<td>RI</td>
<td>RI</td>
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<tr>
<td>CONCRETE (CONVENTIONAL PAVING)</td>
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<td></td>
<td></td>
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<td>Before 1962</td>
<td>10</td>
<td>331</td>
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<td>8</td>
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### TABLE II

**ROUGHNESS OF RESURFACED FLEXIBLE PAVEMENTS**

<table>
<thead>
<tr>
<th>RI RANGE</th>
<th>NO. OF PROJECTS</th>
<th>AVG. YEARS IN SERVICE</th>
<th>AVG. RI</th>
<th>AVG. IMPROVEMENT IN RI</th>
<th>AVG. PERCENT CHANGE PER YEAR IN RI</th>
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### TABLE III

**SUMMARY OF DATA ON RESURFACED PAVEMENTS**

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<th>YEAR RESURFACED</th>
<th>BEFORE RESURFACING</th>
<th>AFTER RESURFACING</th>
<th>SINCE RESURFACING</th>
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TABLE IV
ROUGHNESS OF VARIOUS HIGHWAYS

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<th>HIGHWAY DESIGNATION</th>
<th>NO. OF PROJECTS</th>
<th>ROUGHNESS INDEX</th>
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<td>BITUMINOUS PAVEMENTS</td>
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*Extrapolated from data presented in Figure 4.