Triaxial Acceleration Analysis Applied to Evaluation of Pavement Riding Qualities

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Traditionally the riding qualities of a pavement are expressed as some function of localized irregularities in the contour of the pavement surface. This is predicated on the fact that the portion of passenger comfort or discomfort imparted by all features of the pavement surface can not be isolated and determined separately from other influences such as vehicle characteristics or psychological and physiological aspects of the passenger himself.

Measurements of riding qualities have dealt almost exclusively with vehicle displacements in the vertical direction only, these having been and still being the most prominent and most amenable to measurement. By this procedure displacements in other directions have been ignored, although their relative influence on riding comfort as determined by comfort research is known to be great.

During the past few years certain features of highway construction and use have emphasized surface iregularities that cause significant amounts of combined transverse and longitudinal motion. In response to this developing need for determination of riding qualities on the basis of component motions, an instrument for measuring and recording induced accelerations in the three principal directions was developed and adapted to a passenger vehicle. This paper describes the equipment and its use in evaluating riding qualities of various pavements in Kentucky.

● THE riding quality of a pavement, in contrast with several other highly regarded qualities such as strength, stability, or durability, is not in itself a physical characteristic of the pavement alone. Like skid resistance or night visibility, it depends upon interrelationships of vehicle, pavement, and driver or passenger. Analogous to failure in a pavement lacking stability or durability, passenger discomfort is the most tangible result of poor riding quality—although safety in driving or even deterioration of the vehicle and the pavement itself may be involved.

As a consequence of this relationship between passenger and pavement, the most fundamental measurements and expressions of pavement riding quality would be in terms of human comfort. However, such an approach is complicated in that it involves difficulties of separating pavement features (which are within the province of the highway engineer) from other influences such as properties of the vehicle, speed of travel, or changing psychological and physiological aspects of the passenger.

Because of these complexities, riding qualities have been traditionally expressed as some function of localized irregularities in the contour of the pavement surface. Emphasis has been placed on vehicle displacements in the vertical direction since those are the most prominent effects of pavement irregularities. So far as measurements are concerned, vehicle motions in other directions have been ignored, although their importance has been recognized. As indicated by comfort research (*1*), relatively minor motions in the transverse and longitudinal directions can contribute as much to discomfort as major displacements in the vertical direction.

Within the past decade the need for including all component motions in riding quality analysis has become increasingly prominent. Distortion of road surfaces by sustained heavy traffic, exceptionally rapid rates of construction, reduced standards of workmanship, shortages of highway personnel, and other factors combined have introduced elements of roughness that were unimportant in former years. Then, too, a much higher level of riding comfort along with all the other improved features of highways is expected by the driving public. To some extent, this is reflected in the prominence given riding comfort in practically all methods of sufficiency rating.

In response to this need, the Research Division of the Kentucky Department of Highways initiated riding quality research in 1949 (*6*). For several years the effort was confined to studies of construction control, construction methods (*7*), and specification tolerances. After experience had provided sufficient understanding of causes and effects of various components of road roughness, the project was directed toward the design of equipment to measure simultaneously the displacements or tendencies for displacements in the three principal directions. This resulted in a combination of instruments for sensing and recording triaxial accelerations of a passenger in a standard vehicle, and analysis of the records in terms related to human comfort. After an integrated device was built and proved feasible, it was applied to a wide variety of roads in Kentucky so that the pavements could be rated numerically from the standpoint of relative riding quality.

EQUIPMENT INSTRUMENTATION

The instruments for measuring and recording acceleration were first adapted to a 1953 Chevrolet 4-door sedan, shown in Fig. 1. Preliminary tests were made with the accelerometers mounted at several places on the vehicle or on rigid attachments within it. This approach was abandoned because vibrations of the car could not be eliminated from the records without damping or reducing the sensitivity of the instruments to the point where the records were impaired.

After consideration was given to mounting the accelerometers on various objects carried in the car, a method was devised for measuring vibrations of a test passenger by strapping the accelerometers to a person sitting beside the driver (See Fig. 2). With this realistic procedure the influence of the vehicle was resolved to a constant value in the acceleration records and consequently in the relative pavement roughness data, as long as significant features of the vehicle were controlled. Frequent maintenance inspections and adjustments, frequent lubrication, constant attention to minor variables such as tire pressure, and use of the vehicle only for riding quality tests provided the desired control.

Figure 1. Test vehicle.

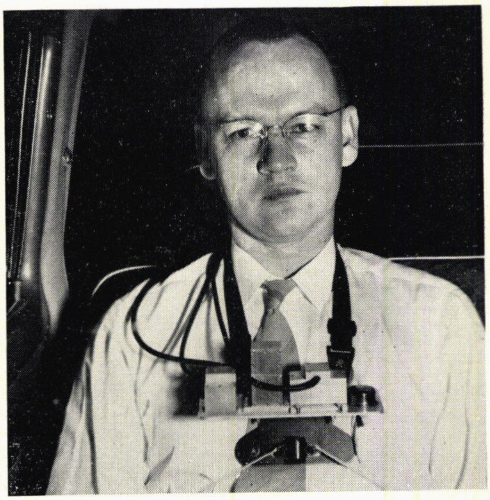

Figure 2. Test passenger, with sensing mechanism strapped in place.

Re-evaluation or recalibration of the vehicle on a test strip was made periodically, although there has been no evidence of appreciable change. Because of this uniformity, the original vehicle has been retained for all measurements to date, and it is considered reliable for use on several hundred additional miles of evaluation entailing several thousand miles of travel. When a new vehicle replaces the one now used, complete recalibration will be necessary, and probably a conversion factor will be required for comparisons of old and new records.

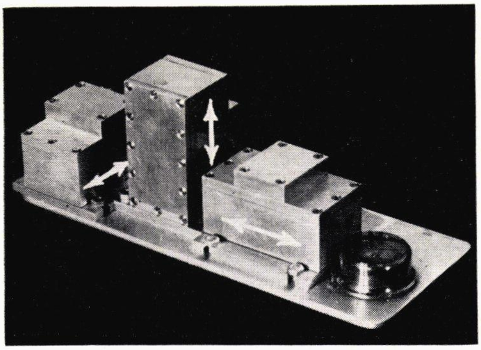

Figure 3. Sensing mechanism, consisting of accelerometers and level attachment. Triaxial orientation of accelerometers is indicated by arrows.

Sensing Mechanism

As illustrated in Fig. 3, three resistance type accelerometers and a bubble level comprised the sensing mechanism. The accelerometers were identical in character and use, with the exception of an allowance for the influence of gravity on the unit oriented in the vertical direction. Specification tolerances on the accelerometers were as follows:

Range	± 2 g.
Natural frequency	
(Undamped)	100 cycles per sec.
(Damped)	40 cycles per sec.
Accuracy and linearity	1 percent of full scale or better
Resolution	1 percent of full scale or better
Response to transverse direction	2 percent maximum
Damping (silicon fluid)	0.6 to 0.7 of critical (at room temperature)
Temperature variation (per °F)	
Sensitivity or span	+0.03 percent
Shift in zero	+0.02 to 0.05 percent

The accelerometers were rigidly fixed to an aluminum plate which in turn was strapped about the shoulders and chest of the test passenger. A cable connected each unit with the recording equipment.

Essentially each accelerometer acted as an element in a Wheatstone Bridge circuit, with a bridge balance providing the complementary elements and secondary resistors for adjusting all recording units to zero when the accelerometers were at rest. As noted later, the balance is also useful in comparative calibration of the accelerometers.

Recording Mechanism

Impulses created by changes in resistance of the accelerometers with induced motion were recorded on a 9-channel recording oscillograph. This instrument, with attendant devices, was mounted on the floor immediately in front of the rear seat of the vehicle, as shown in Fig. 4. Each channel contains a galvanometer to which is attached a small mirror rotating with changes in the voltage. A beam of light from a single source is projected onto each mirror, and reflected to a roll of photographic chart paper in the detachable chart magazine. Thus, when the galvanometers were excited by impulses from accelerations of the sensing units, the mirrors were rotated in proportion to the accelerations, and the responses were recorded as three traces on the photographic paper.

Additional channels were utilized for the following purposes: three were locked in place to mark the zero position of each accelerometer trace; and one each was used to monitor the voltage applied to the sensing units, to serve as an event marker, and to record the tachometer operating in conjunction with the speedometer of the car. The event marker was provided as a means for the driver to record the location of extraneous influences such as bridges, passing trucks, or other events having no bearing on the riding quality of the pavement. Constant speed and constant voltage imposed on the accelerometers were, of course, highly important to the validity of the records.

All nine traces are also reflected to a viewing screen located at the top of the recorder (above the magazine) in Fig. 4. By this means the results can be viewed during adjustment and calibration of the instruments, and also it provides for check observations during test runs.

The chart magazine, easily detachable from the recorder unit, accommodates 125-ft. rolls of photographic paper 5-in. wide. Exposed chart is passed over a rubber metering roller driven by a drive mechanism with interchangeable gears. Ten chart speeds ranging from ¼ in. per sec. to 100 in. per sec. can be achieved, thus permitting selection of chart speeds most suitable for analysis with variable speeds of travel or variable pavement roughness features.

A shutter or light seal, automatically actuated as the magazine is removed or attached, permits removal of the magazine without exposing the chart paper regardless of light conditions. Although darkened con-

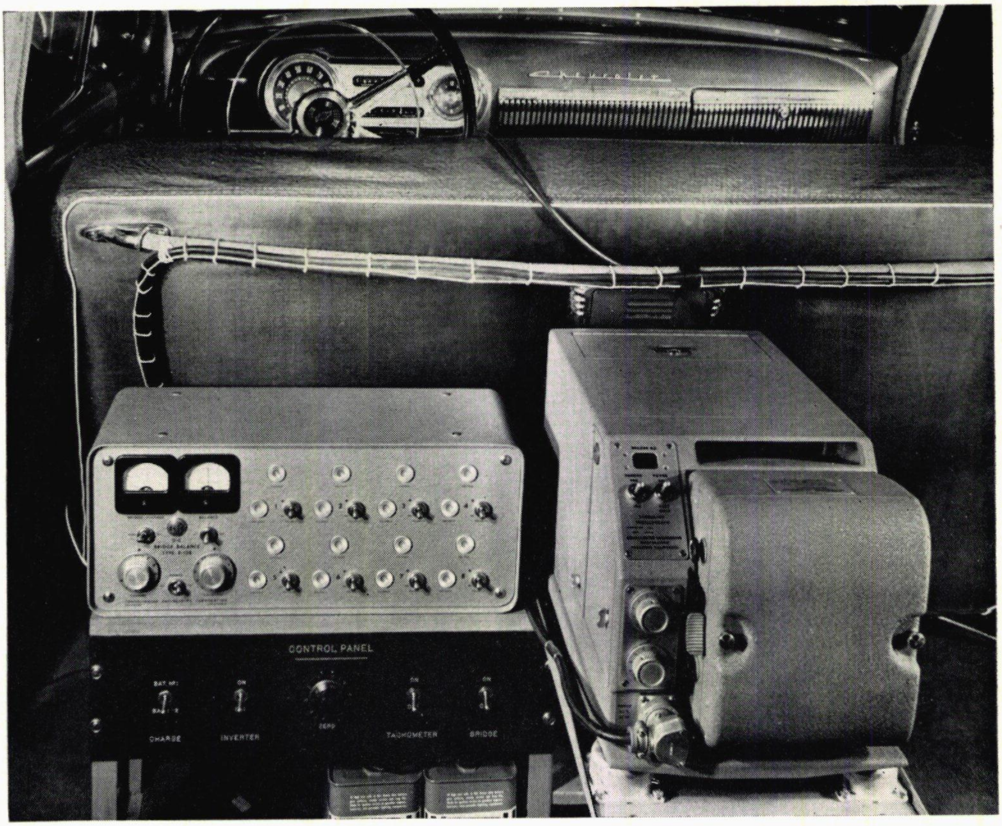

Figure 4. Recording mechanism mounted in rear seat of test vehicle. Control panel and bridge balance are on the left, and recording oscillograph with the chart magazine attached is on the right.

ditions are preferred when the magazine itself is loaded with photographic paper, this can be done under subdued light. If no darkroom is available, charts can be changed under an opaque cloth, or even a bundled overcoat has been used successfully with the sleeves turned inside out and the operator's hands inserted through these openings. Thus, on extended trips away from the laboratory the changing of charts presents no problem.

Beginning and ending portions of a representative chart exposed in a test run are shown in Fig. 5. At the extreme top edge of the chart (see arrow) there is a straight line trace representing voltage on the accelerometers. Any deviation of the line from the edge of the chart would represent a change in voltage hence a change in the sensitivity of the units.

Other straight-line traces from top to bottom of the chart represent:

1. Events—with the beginning and end of the actual test run marked by offsets.
2. Zero transverse acceleration.
3. Zero vertical acceleration.
4. Zero longitudinal acceleration.
5. Tachometer speed—a straight horizontal line if the speed of the vehicle is constant (no vehicle acceleration).

Of course, the three irregular traces represent the transverse, vertical, and longitudinal accelerations respectively, as determined by the accelerometers.

Settings of the galvanometers were made such that zero lines and the neutral position of the event marker are equally spaced 1 in. apart on the chart, and through adjustment of the voltage applied to the bridge this distance has been made to represent ½ g acceleration of the sensing units. Although they are not evident in Fig. 5, faint vertical lines mark time

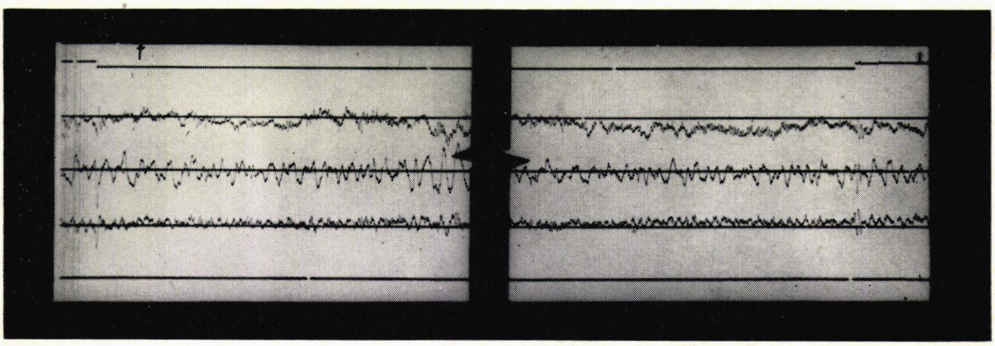

Figure 5. Representative oscillograph chart.

intervals on the chart. This is accomplished with a timing device in the recorder, which is driven by a synchronous motor and projects light onto the photographic paper to form distinctive lines at intervals of $1/100$ sec. and $1/10$ sec. while the chart is in motion. Time intervals are important not only in the sence that they define rates of acceleration on the chart itself, but also in their use for locating roughness characteristics and events when the record is correlated with vehicle speed.

Power Supply

Two sources of power are required for operation of the instruments. The bridge circuits—accelerometers, galvanometers, and bridge balance—requiring a stable D.C. voltage, are energized by two 9-volt dry cell batteries connected in parallel. These are visible at the bottom of Fig. 4. The dry cells are capable of operating the bridge circuits for several months of normal use, with only periodic adjustment of the bridge voltage rheostats required.

The light sources, paper drive, and timing mechanism in the recording unit require 115 volts, which is supplied through a converter powered by 12 volts from two automobile batteries. For this purpose a second battery was mounted on brackets under the hood of the car, and the two were connected such that they were in series when the recorder was operating. When records were not being made, the circuit could be switched to parallel. This permitted normal operation of the vehicle, and charging of both batteries from the standard 6-volt generator. All the power circuits could be operated from the control panel on the lower left in Fig. 4.

OPERATION OF THE EQUIPMENT

Because of the natural or resonant frequencies of vibration of vehicles and occupants in relation to the frequency with which pavement deformations are encountered, riding quality depends considerably upon the speed at which the pavement is traversed. It is often observed without the aid of instruments that one pavement has poorer riding quality at 60 mi. per hr. than at 40 mi. per hr., and with another pavement the reverse is true. To some extent this fact vitiates comparison among pavements tested at a common speed, but practical considerations require that this be done.

In view of the fact that the average speed of travel on rural highways had reached 51 mi. per hr. in 1952 (*10*) and was increasing, a test speed in that vicinity was considered typical of the condition under which pavement roughness would be experienced. Inasmuch as this was close to 80 ft. per sec. (54.5 mi. per hr.) that value was adopted as a standard. Calibration of the automobile speedometer provided an indicated driving speed of 57.5 mi. per hr. which the driver carefully adhered to. Some tests have been made at lower speeds for comparative purposes, and of course a much slower rate will be necessary and appropriate when tests are made in urban or rural congested areas.

Adjustments of Instruments

Before starting a test run, several inspections and precautions were made. Instruments were briefly checked for operational features such as battery voltage, paper supply, and light source. The vehicle was then driven

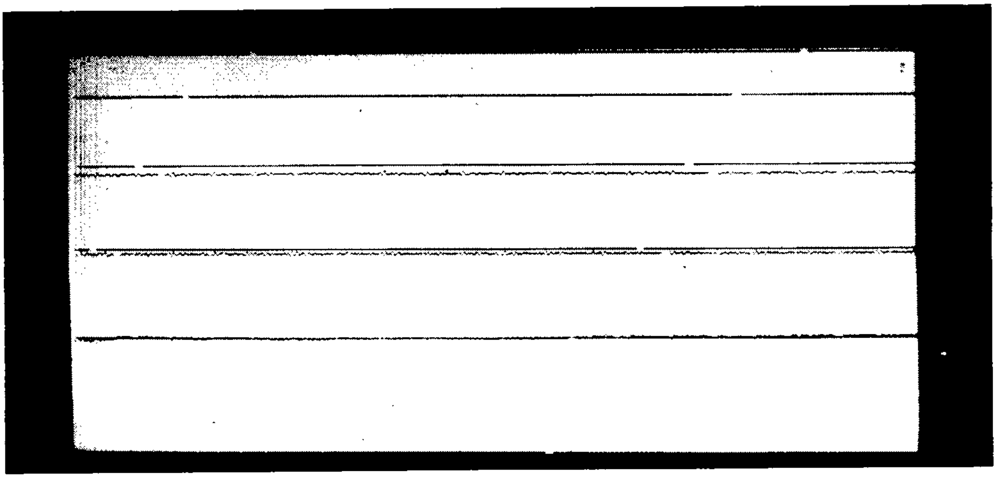

Figure 6. Oscillograph chart of vibrations inherent in a test passenger at rest.

several miles to allow tire pressures, shock absorbers and similar features to become stable.

Tire pressures were thoroughly checked and adjusted to 25 lb. per sq. in. before each test run since variations in pressure could be quite influential on vibrations above the fundamental frequency of the tires. At 25 lb. per sq. in. this fundamental frequency is 10 to 12 cycles per sec., which is within range of many vibrations caused by surface irregularities.

Power switches were turned on several minutes before a test was started to energize and bring to proper temperature all the instruments except the chart drive, timing mechanism, and light source which were free from the influence of temperature. After considerable use had demonstrated the consistency of the equipment, checks for accelerometer voltage were made only at convenient times, and the bridge balanced if necessary. Similarly, the zero positioning of the accelerometer traces was found to be so constant that an occasional check and readjustment was sufficient.

The sensing mechanism was strapped firmly onto the test passenger, and leveled through observation of the bubble level attachment. In doing this the passenger assumed an erect but relaxed position, his feet being flat on the floor and his hands at his sides or folded in his lap. It was important that this position be maintained throughout each test run, and that there be no undue resistance to motion. Since a test run normally varied from a fraction of a minute to no more than a few minutes depending upon the length of pavement being tested, possibilities for varying the reaction during a test were slight.

Probably variations among tests were more difficult to control, particularly when several tests were made in a single day. The best precaution against this influence was the use of one person for as many tests as possible, with frequent opportunities given for exercise outside the car especially late in the day when fatigue increases rapidly.

The influence of vibrations inherent in typical passengers was investigated with the vehicle idle and the passenger sitting in the normal position supporting the sensing mechanism. Results of one test of this type are recorded on the chart in Fig. 6. Small disturbances caused by breathing and heartbeat are apparent, but they are of no consequence in the pavement analysis. Hardly any difference in this respect is displayed by persons of different size and weight, but these factors are appreciable in their effects when vibrations induced by the pavement and vehicle are transmitted through the passenger to the accelerometers. There appeared to be negligible differences among muscular individuals weighing from about 130 to 160 lb., which was the range represented in most of the tests. Greater but still limited differences exist in the fundamental frequency and hence the reaction of much heavier and fleshy persons as compared with those that are slender and light in weight.

According to Jacklin and Liddell (*1*) this varies from about 2.80 to 2.65 cycles per sec. when the weight of a passenger on a car seat increases from 120 to 200 lb. Probably a greater influence on the accelerometers mounted in this way would come from secondary vibrations introduced by extremely fleshy supporting bodies as compared with those that are more rigid.

Test Procedure

Usually, for a given section of road to be analyzed, representative portions were selected as samples unless the project was less than a mile or two in length, in which case the entire project would be tested. In most instances the test run was intentionally made one mile, because this minimized the effort of the driver and test passenger and provided a chart of convenient length for analysis. Coverage of the project, with respect to geometric features such as divided lanes, curves, directions of traffic of different classes, and the like depended upon the objectives of the test, although these features were seldom taken into account during the preliminary phases of development and use that are being reported.

A starting point was selected and carefully referenced to some permanent landmark. This was entered in the log of tests along with other pertinent data. Then, the test run was started a sufficient distance in advance of the starting point for the driver to reach a constant speed. All the instruments, including the light source, paper drive, and timing device were set in operation as the car approached the starting point so that records were being made as the test strip was entered.

By means of a remote control switch held in his hand, the test passenger recorded the starting point with the event marker. As noted before, he also recorded any events extraneous to pavement riding qualities during the test run. The end point was recorded in the same manner.

Throughout the period of test the driver concentrated his effort on maintaining a constant speed and keeping the vehicle in the normal wheel tracks established by predominant traffic. This required a great deal of judgment on the part of the driver, although on most pavements having considerable age these tracks are readily apparent. Whenever traffic using the road became a potential influence it was incumbent upon the driver to select an adequate opening before starting the test run in order to avoid changes in speed and any turning or passing movements.

Following a variety of tests at different chart speeds, a speed of ½ in. per sec. was selected as the one most appropriate for tests at the standard vehicle speed. With this combination, one longitudinal inch of the chart represented 160 ft. of pavement, or the prominent $\frac{1}{10}$ sec. lines marked on the chart represented 8 ft. of pavement. This, of course, made the least time interval of $\frac{1}{100}$ sec. marked on the chart equivalent to a very limited distance of travel on the pavement.

A generalized correlation of accelerometer records with pavement surface relationships is given in Fig. 7. The upper irregular line in each of the three sections of the illustration represents an accelerometer trace. Since the accelerometer in each case was sensing impulses caused by differences occurring with respect to four points of vehicle-to-pavement contact simultaneously, and the relationships were constantly changing, there is no absolute basis for relating differences in wheel positions in one direction with the induced acceleration in that direction.

For the purpose of generalized correlation, a pavement section of recent construction was selected, and elevations were taken with a level and rod in the wheel tracks at 2-ft. intervals longitudinally. Theoretical calculations of the plan grades at these points were made using the design profiles, and the two sets of data were reduced to a common datum. From this the differences in measured and calculated grade were obtained, and the magnitude of deformities shown.

Interpretations of the effects caused by these deformities were plotted in conjunction with the accelerometer traces as follows:

Vertical acceleration versus the average difference between actual and calculated grade in both wheel tracks (related to up and down motions or bounce).

Transverse acceleration versus the average difference in elevation of the left and right wheel tracks, or in effect the changes in crown (related to rolling motions or yaw).

Longitudinal acceleration versus the average differences in elevation of the front and rear wheels of the vehicle (related to forward and backward oscillations or pitch).

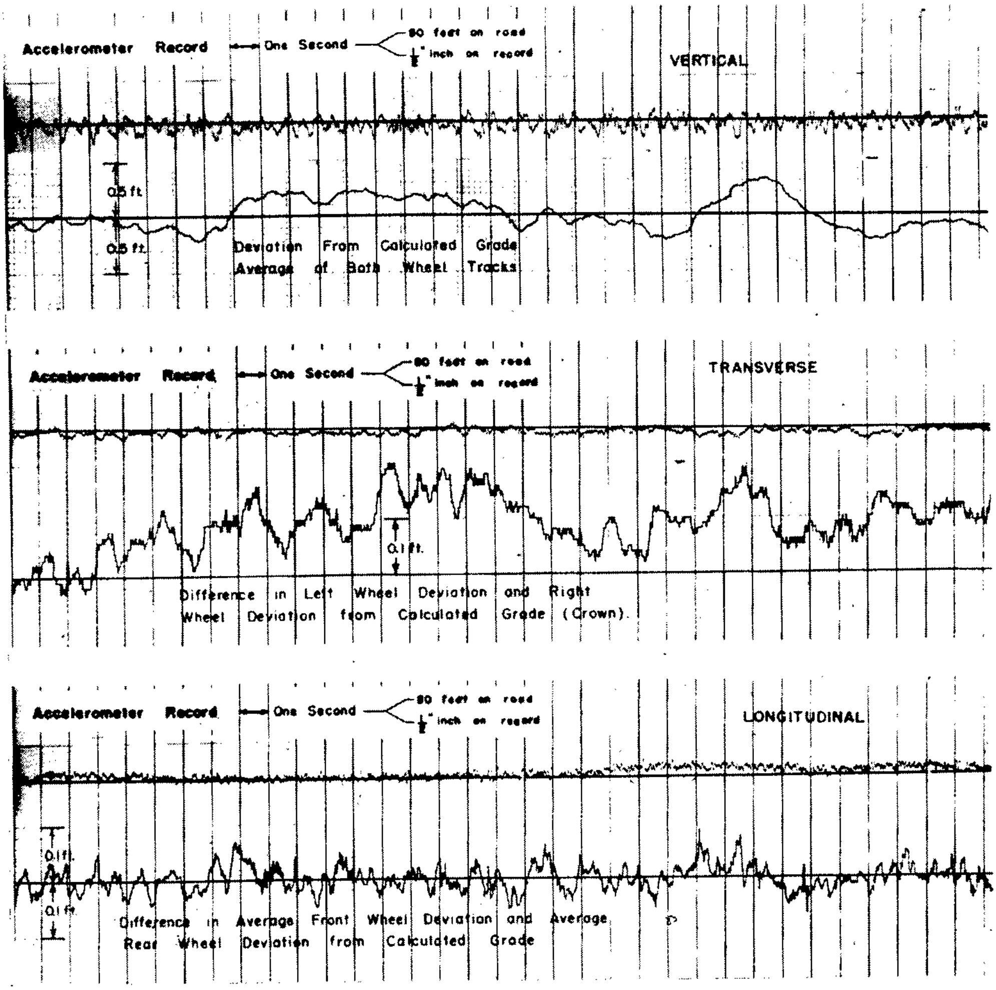

Figure 7. Generalized correlation of accelerometer records with pavement surface relationships.

Since the distances over which the plotted deformities occur are rather large, and the factors of pavement elevation do not take into account relations among the four wheels as such, comparability of the pairs of curves is fairly remote. Even so the relationships tend to confirm what judgment implies, that passenger discomfort is not directly proportional to localized changes in contour of the pavement. The compounding of motions and the response of various elements between the road and the passenger are of primary importance. For example, motions may be sustained or even amplified by relatively small deformities encountered immediately after one of greater magnitude, and the net effect can be related to the local irregularities only in a general way.

ANALYSIS OF RECORDS

Several possibilities for analyzing the charts and determining relative roughness values of the pavements are inherent in the type of record obtained through this test procedure. A frequency distribution of accelerations above a certain magnitude, the amount of work in foot pounds of effort sustained or expended by the passenger, and several others are apparent at a glance. Only one approach has been used thus far, mainly because the authors preferred pavement riding quality factors as closely associated with passenger comfort as possible.

Theory of Discomfort

During motion at a constant velocity unchanging in direction, a person is not subjected to any forces other than gravity and therefore he feels no discomfort from external influences. Although he is moving, he is unable to perceive the motion except through auditory or visual observations.

With changes in velocity or acceleration, the force required to produce acceleration is dependent upon the mass of the person. Or conversely, a person of given mass is subjected to constant force whenever he is undergoing uniform acceleration. Under this circumstance the person is subjected to gravity and another constant force. As a passenger in a vehicle being accelerated, the person must resist this force but with an unchanging effort so long as the acceleration continues. Actually, the effort does not entail discomfort once it is established, although it will cause fatigue if it is maintained for an appreciable period of time. Inasmuch as accelerations impressed upon a passenger in an automobile are varying and of limited duration, the essence of vehicle passenger discomfort lies in changes of acceleration. This distinguishing feature of human discomfort has been demonstrated by controlled investigations (*12*), particularly in situations such as passenger elevators where the motions are direct and relatively simple.

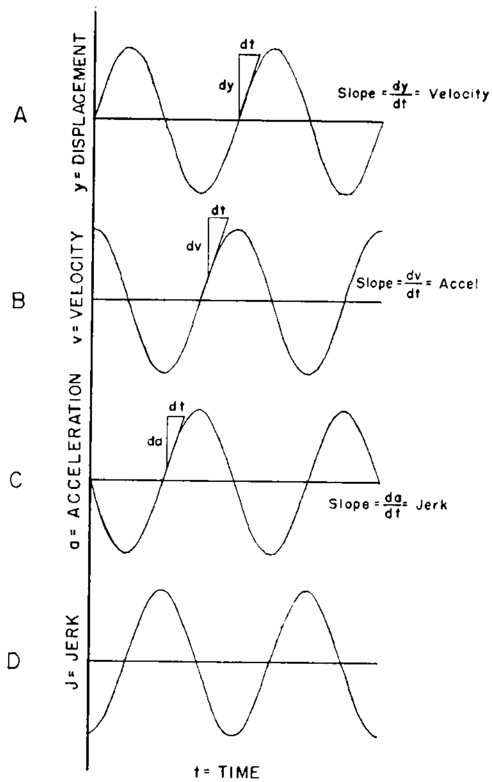

Figure 8. Fundamental relationships of motion represented in harmonic vibrations.

On the basis of these observations, an additional concept of motion which involves change in acceleration has been derived from comfort research. This feature is commonly termed "jerk" and from the standpoint of a person subjected to it the requirement is a varying effort to resist the varying forces causing changes in acceleration. Physiologically the flexing of resisting muscles results in discomfort and sometimes sickness—the latter probably being a completely separate aspect of the response.

Basic relationships involved in the various concepts of motion are illustrated by curves of harmonic vibration drawn in Fig. 8. Each succeeding curve from A to D is defined by the slope of the function plotted immediately above it. Hence, in a realistic situation of accelerations imposed on a passenger riding in a vehicle, a measure of the discomfort experienced by that individual is expressed in the slopes of acceleration curves representative of his body responses.

Application to Riding Quality

Although, as noted previously, a direct conversion from passenger acceleration to pavement irregularities is not possible, discomfort of the passenger as represented in the jerk values is an authentic and realistic measure of pavement riding quality. Consistency of this approach, and particularly comparisons among different pavements, is dependent upon the elimination of variable effects such as those that could come with changes in the vehicle.

When a consistency regarded as more than equal to the requirements was demonstrated in preliminary tests, summation of significant jerk values was adopted as the basis for expressing relative pavement riding qualities. Actually the level at which jerk becomes uncomfortable varies with individuals, and even varies for a given individual from time to time. In addition, it is known to vary with the frequency of vibrations, and with the direction in which the acceleration is applied.

Evaluation of comfort levels by Janeway (*2*) indicated that frequencies in the order of those resulting from pavement irregularities (about 1 to 10 cycles per sec.) were within the range where change in acceleration was the determining factor of comfort, and that the comfortable lower limit of vertical disturbance was about 41 ft. per sec.^{3} at frequencies of 1 to 6 cycles per sec. Essentially this value should apply with negligible error throughout the range from 1 to 10 cycles per sec., but probably a lower limit is appropriate for records taken with the accelerometer strapped to the test passenger instead of being mounted in the mechanism transmitting vibrations to the passenger. This is so, since the passenger supporting the sensing device dampens the vibrations considerably.

In lieu of more authoritative data, an arbitrary limit of 32 ft. per sec.^{3} (or one g per sec.) was assumed as the maximum comfort level for analysis of the records. Thus, in the evaluation of the vertical accelerometer trace, only those slopes representing more than 32 ft. per sec.^{3} were of interest since jerks of lesser magnitude were not discomforting to the passenger, and it was immaterial whether they occurred or not.

The longitudinal and transverse traces presented a greater problem since research on vibrations in those directions—particularly with respect to the discomfort threshold—is more limited. Jacklin and Liddell (*1*), using an uncushioned seat vibrating at frequencies up to 2 cycles per sec. and practically 3000 individual readings in a laboratory study of human response, concluded that for the average subject the discomfort caused by transverse vibrations may be equal to the discomfort caused by vertical vibrations 13 times more severe. Similarly, the discomfort from longitudinal vibrations may be equal to vertical vibrations 7.5 times more severe. Both relationships depended on the degree of discomfort experienced and other variable features of the test.

Several factors such as the relatively low frequencies, the uncushioned seat, and the linear motion used in those tests were not comparable with conditions created by a moving automobile. Then, too, the vibrations were measured on the moving seat or platform rather than on the person activated by that apparatus, and the records were not amenable to determination of jerk values. Until relationships among the component motions can be determined using the test vehicle and equipment for artificially inducing controlled vibrations, arbitrary relationships and comfort limits must be assumed. Research of this nature is planned, but in the meantime the assumed upper limit of comfort relating to the transverse and longitudinal traces has been set at 16 ft. per sec.^{3} ($\frac{1}{2}$ g per sec.). Thus, in the analysis of records, minimum slopes of the longitudinal and transverse acceleration traces considered significant to riding quality are half as great as the minimum considered for the vertical trace.

To facilitate measurement of jerk values from the accelerometer charts, the device shown in Fig. 9 was constructed. A chart is placed under the transparent indicator and retained in the proper position by a straightedge under each of the lower metal projections. The pivoted indicator and the chart are simultaneously adjusted until the indicator line coincides with the maximum slope on a definite vibration phase of the acceleration trace being analyzed. Then the jerk value corresponding to that change in acceleration is read directly from the inscribed scale divided in g's per sec. at the top of the device. Both sides of each vibration are analyzed, and jerk values greater than the ascribed minimum are totaled for each trace. Indicated riding quality of the pavement is expressed in the total g's per sec. per mi. of pavement.

RESULTS AND OBSERVATIONS

Although the comparative riding qualities of pavements can be realistically expressed in total jerk values, these overall summations will have limited meaning until the basic relationships of comfort pertaining to accelerations in the three directions are established under the sensing conditions that are used. For the present, comparisons are best obtained with separate expressions of vertical, transverse, and longitudinal jerks. This is so, since a large part of the roughness of some pavements comes from the induced transverse accelerations, whereas others display prac-

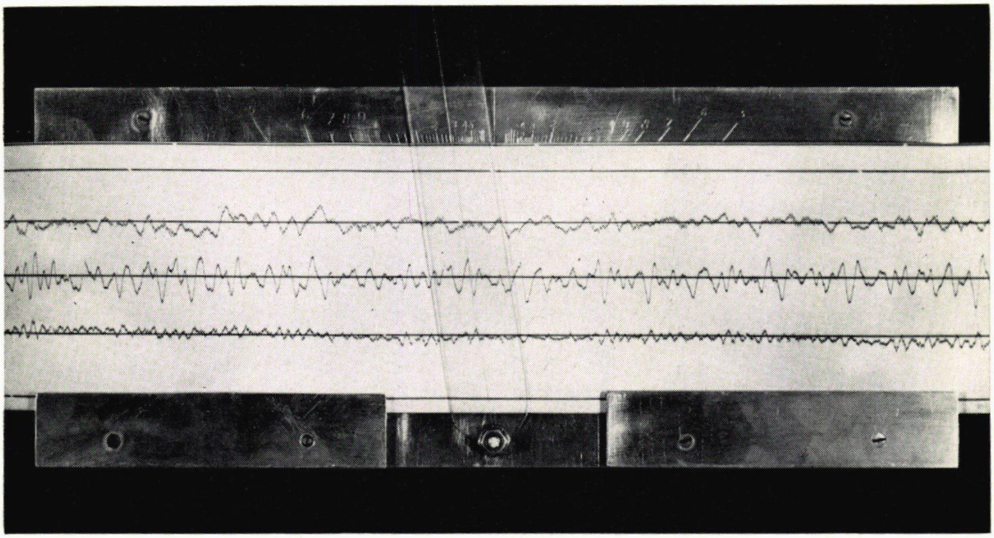

Figure 9. Device for measuring individual jerk values.

tically negligible transverse and longitudinal jerk values but major roughness in the vertical direction.

The relatively limited data obtained under so-called standard and well-controlled conditions of the test procedure, which totals approximately 150 mi. of test runs to date, hardly provides a basis for estimating the ranges of values that can be considered representative of different riding quality classifications. However, under the system of record analysis that has been described, the indications are that pavements with jerk values below 300, 150 and 250 per mi. in the vertical, transverse, and longitudinal directions respectively, will be definitely classed as smooth, and probably extreme roughness will be certain when these values exceed 800 for the vertical and 500 for the other two directions. These, of course, are based on observation and opinion of individuals making the test runs, and they are subject to much more investigation and change.

The records have much more value for the present, in their portrayal of the specific roughness features of a pavement section. For example, the road represented by the chart in the upper part of Fig. 10, was resurfaced in 1953, because of the surface deterioration and structural deficiencies. Undoubtedly riding quality was improved, but much greater improvement could have been achieved if distribution of the bituminous mix had been directed more toward uniformity in crown. Had riding quality records for the full length of the project been available to design and construction personnel in 1953, possibilities for overcoming a part of the roughness, both for the project in its entirety and for sections in greatest need of restitution, would have been apparent at a glance. This particular sample of pavement had riding quality indications of 887-vertical, 178-transverse, and 266-longitudinal, in contrast with comparable values of 292, 125, and 299 for the particular section of another road represented by the chart in the lower portion of Fig. 10.

Another contrasting situation is evident in the two charts shown in Fig. 11. For the bottom chart, pronounced vertical vibrations, with respect to both amplitude and slope of the traces, were caused by a general warping and distortion of the pavement, and broken slabs at relatively frequent intervals. Offsetting of the transverse and longitudinal traces from their respective zero lines in the upper chart was caused by the failure of the passenger to level the sensing mechanism.

The indicated discrepancy for the transverse (upper) trace is approximately 0.1 g, which represents no more than 0.5 percent error in the results since the component of ac

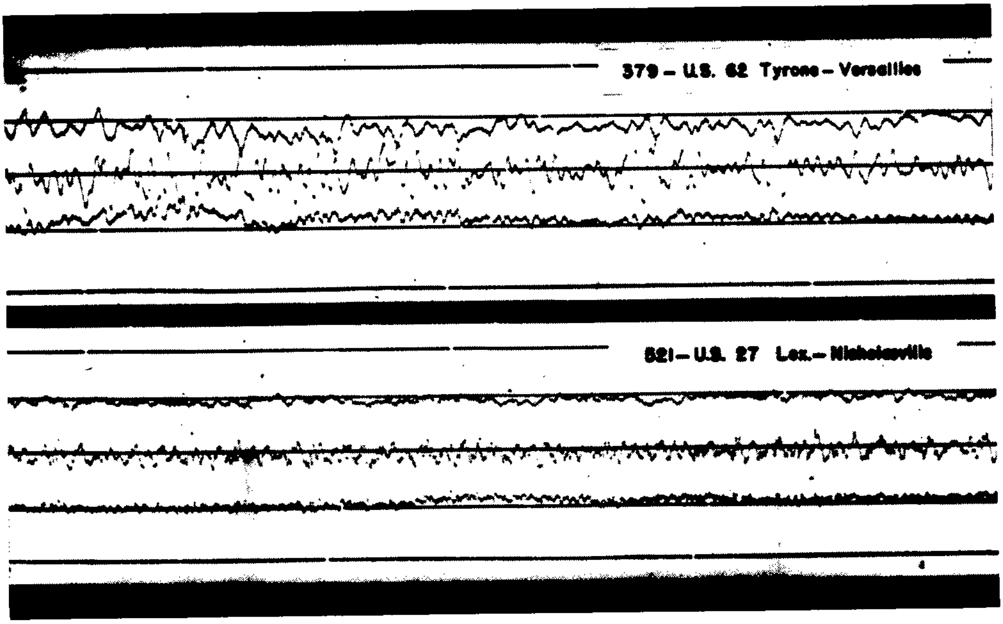

Figure 10. Charts of combined riding qualities of two flexible pavements measured at a vehicle speed of 80 ft. per sec. and a chart speed of ½ in. per sec. No. 379. Pavement width: 18 ft.; initial construction: 1933; resurfaced (bit. conc): 1953. No. 521. Pavement width: 22 ft.; initial construction: 1949; resurfaced (rock asph): 1954.

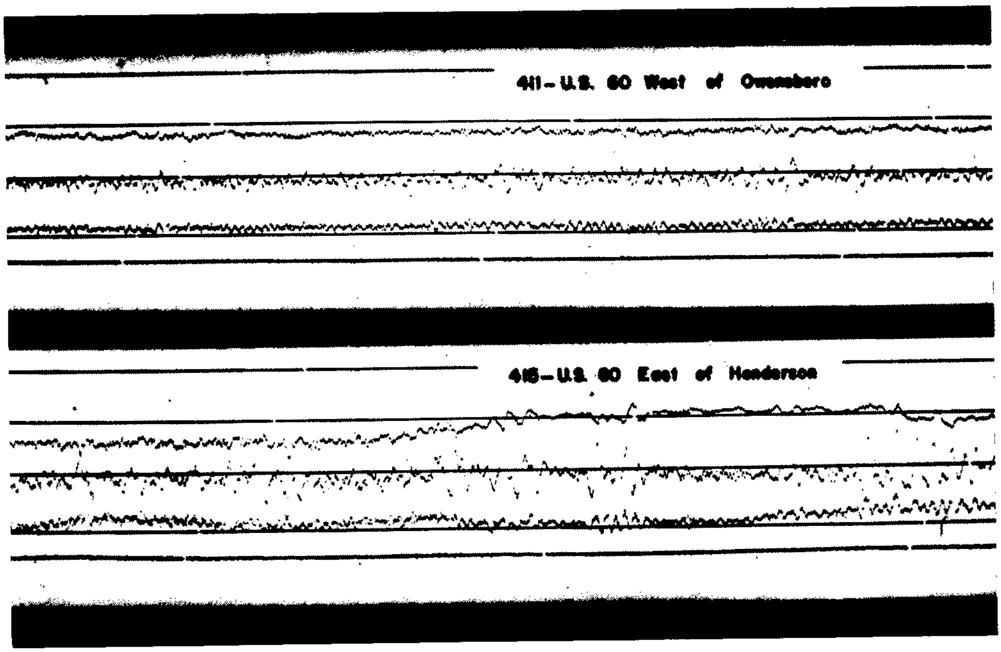

Figure 11. Charts of combined riding qualities of two rigid pavements measured at a vehicle speed of 80 ft. per sec. and a chart speed of ½ in. per sec. No. 411. Pavement width: 18 ft.; initial construction: 1926. No. 415. Pavement width: 18 ft.; initial construction: 1932.

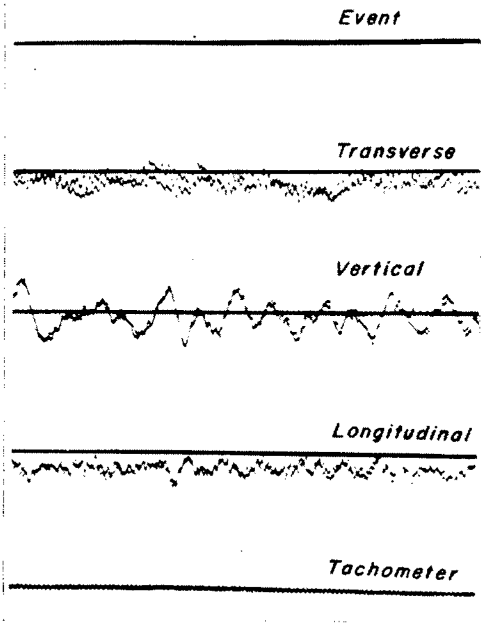

Figure 12. Superimposed charts obtained from separate tests on a section of pavement.

celeration that was measured differed from the actual acceleration in the transverse direction by a factor related to the versine (1 − cos.) of the angle formed by the correct plane and the actual plane in which the sensing mechanism was held. This amounts to a very small error in acceleration, even though the offset distance on the chart appeared large, since that discrepancy is related to the sine function of the angle—a value which increases rapidly with relatively small increases in small angles.

The deviation of the transverse trace in the lower chart represents a sustained acceleration exerted on the passenger as the car rounded a horizontal curve. This, of course, produced no jerk values to influence the comfort of the passenger.

Reproducibility of results was checked on several occasions, particularly when the car was passed over the calibration test pavement. Results of two such duplicate tests, made approximately two weeks apart, are illustrated in Fig. 12. Although this represents about the best reproducibility achieved, no difficulty has been experienced on any attempts to check for reproducibility, and for practical purposes calculated jerk values have been identical. Because of the fact that the riding qualities of pavements are subject to change with use, it is recognized that a calibration strip on a pavement in service is not desirable. Thus far a satisfactory alternate has not been arranged, but certain portions of airport pavements are considered promising for this purpose.

Several possibilities for improvement in the technique and analysis of records are recognized, some of which have been discussed. For example, individual slope determinations, even with the device constructed for measurement of jerk values, is a tedious and time-consuming procedure. On the average an experienced operator can analyze in approximately one hour a 33-in. chart representing a mile of single-lane pavement. This makes analysis of records a retarding feature unless several individuals are assigned to the task, since useable charts can be accumulated at a much greater rate.

One possibility for overcoming this, which has not been investigated for fesaibility, is the use of integrating galvanometers in conjunction with the three differentiating galvanometers marking the accelerometer traces. Assuming their use is feasible, the integrating galvanometers could replace those recording on the channels now locked rigidly in place. Thus, with each test run the chart would record all the individual accelerations and also the summation of those accelerations in each of the three directions. However, the summations could be converted to riding quality values only if a statistical analysis of results from many tests showed that typical ranges of total acceleration (perhaps in combination with certain patterns of the traces) were indicative of jerk values within reasonable limits. If this type system were perfected, the advantages of both rapid evaluation of riding quality and the distribution of all components of roughness throughout the length of the test pavement would be achieved.

This and other possibilities that have been mentioned for improvement in the technique are considered urgent items for additional research. In the meantime, the triaxial acceleration method offers a realistic approach to the evaluation of overall pavement riding quality, and it provides data useable in several phases of highway planning, design and construction.

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