Can Dynamic Tire Forces Be Used as A Criterion of Pavement Condition?

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A moving vehicle exerts a fluctuating component of force on the highway due to vertical motion induced in the vehicle by unevenness of the pavement. This force, superimposed on the static wheel load, is frequently called the dynamic wheel force or the dynamic tire force.

This paper includes a brief description of instrumentation used to determine the dynamic tire force by measuring the fluctuation of the air pressure in a tire of a moving vehicle. Actual force records that were taken on several sections of pavement are included. From these records the corresponding root mean squared value of the dynamic force is determined, and the possible use of this quantity as a criterion of pavement condition is suggested. In addition, for certain pavement sections the frequency of occurrence of various magnitudes of the dynamic tire force is determined.

The influence of speed on dynamic force is investigated by operating the test vehicle over the same length of pavement at different velocities. In like manner the influence of tire inflation pressure on dynamic force is studied by conducting tests in which only the inflation pressure was varied.

The significance of these parameters relative to a pavement criterion based on dynamic tire force is discussed.

•A VEHICLE moving over a perfectly smooth pavement will in general exert only the static wheel loadings on the highway. Unevenness in the pavement profile will, however, induce vertical motion in the vehicle and this will produce fluctuating force components that will be superimposed upon the static wheel loads. These fluctuating force components are referred to in this paper as the dynamic tire forces. The question is raised as to whether or not they can serve as a criterion of pavement condition.

It is evident that the dynamic tire force is a criterion of the interaction between a vehicle and the pavement. On a perfectly smooth pavement the dynamic tire force would be zero, whereas on a rough pavement the force would be large. Unfortunately, however, this force is influenced by factors other than pavement roughness. The suspension characteristics of the vehicle are significant as well as the speed of the vehicle. It has been shown (1) that under certain conditions it is possible to induce either large or small dynamic forces by simply varying the speed of the vehicle. Evidently, if a comprehensive study is made of the dynamic tire force, the vehicle characteristics and the vehicle velocity must be considered along with the pavement profile. Conversely, if only the effect of pavement condition on the dynamic tire force is to be studied, then tests must be made with the same vehicle at the same speed over different pavement sections. These factors were investigated in the test reported herein, and the

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results gave rise to the possible use of dynamic force as a criterion of pavement condition.

The question can well be raised as to the effect of the dynamic tire forces on the highway. Under certain conditions these forces may be small relative to the static wheel loads and they are applied for a relatively short period of time at any one location on the highway. The response of the highway to these forces, however, has been a matter of interest to many investigators.

Although only small deformations may occur in the highway at moderate distances from the point of application of a dynamic tire force, this force may not be insignificant as far as damage to the highway is concerned. High forces will result in high contact stresses, and rapid surface deterioration may result even though the interior structure of the highway may not be adversely affected by such a force. Therefore, it is evident that the relationship between dynamic tire force and highway response is an important area for continued study.

In like manner, the question as to the effect of the dynamic tire forces on the vehicle can also be raised. These forces will in general have large vertical components that will give rise to deformations of the tires of the vehicle. Depending on the frequency with which these forces are applied, it is possible to have either large or small motions induced in the sprung mass (body) of the vehicle. If large body motions are induced, the passengers may experience considerable discomfort. If very little body motion is induced, the passengers may be unaware of the fact that large dynamic forces are acting on the tires of the vehicle.

It is evident that passengers, riding in a vehicle, may be unaware of large forces that are generated between the pavement and the vehicle even though these forces may be causing damage to the pavement. These passengers may even be giving an excellent rating to the pavement at the instant that damage is resulting from an unfavorable combination of pavement condition, vehicle velocity and vehicle suspension characteristics.

Is a pavement in satisfactory condition when it will induce large dynamic tire forces? Is a passenger capable of evaluating pavement conditions based solely on the "ride" of the vehicle? Clearly the task of evaluating pavement condition is not an easy one.

In this investigation the dynamic tire force was measured continuously as a test vehicle moved along the pavement, and the resulting force records were analyzed to obtain the root mean square value of the dynamic tire force. In certain cases the frequency of occurrence of certain magnitudes of the force was determined. The effects of vehicle velocity and tire inflation pressure on the dynamic force were briefly investigated.

MEASUREMENT OF TIRE FORCE

The measurement of the dynamic tire forces has been of interest to many investigators. The Bureau of Public Roads conducted an investigation into this problem and described a system for measuring dynamic wheel reactions that utilized the fluctuating air pressure in a tire of a vehicle (2). The technique was further developed by the Michigan State Highway Department Laboratories in Lansing. The force measuring system used to obtain the results described in this paper was virtually identical to that used in Michigan except for minor modifications. An extensive investigation into methods for measuring dynamic wheel forces is at present being conducted in Germany (3).

The relationship between the dynamic tire force and the change in tire pressure is shown in Figure 1. The tire air pressure, p, is actually the change in the inflation pressure due to the motion of the vehicle on the highway. With this change in air pressure is an associated change in the force of the tire on the highway as indicated by F. By monitoring the air pressure in a tire it is possible to measure the dynamic wheel forces that are superimposed on the static wheel load.

In making tire pressure measurements, the valve core was removed from the valve stem of the tire and a short tube was connected from the valve stem to the rotating element of a special seal that was mounted on the wheel of the vehicle. From the stationary element of this seal, a tube was connected to the pressure measuring system

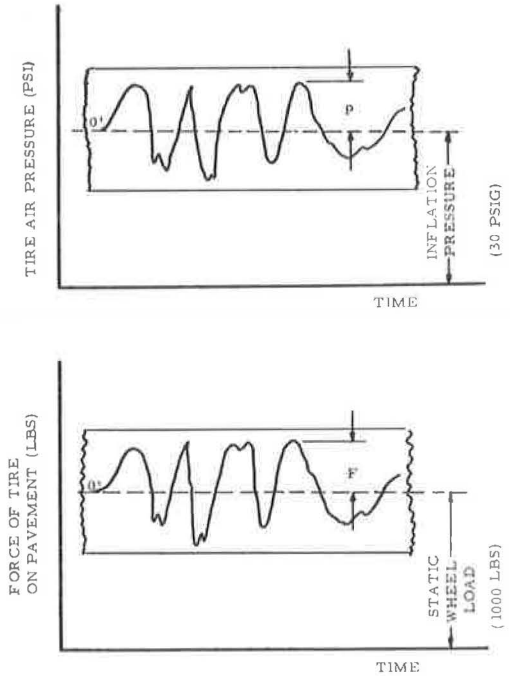


Figure 1. Relationship between tire air pressure and tire force.

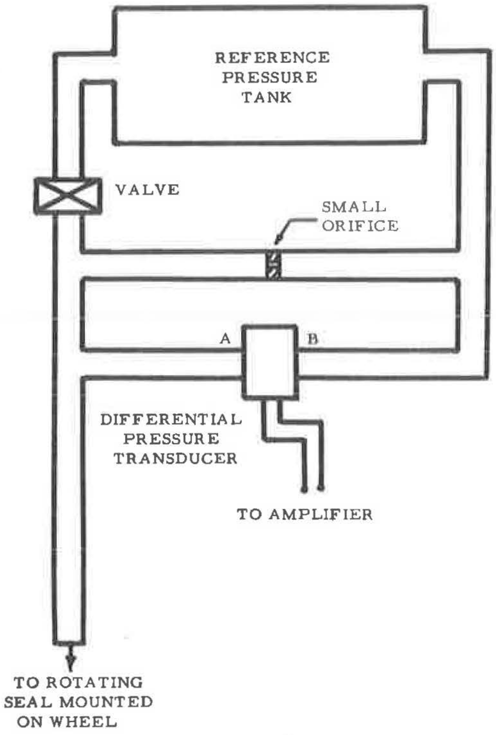


Figure 2. System for measuring change in tire air pressure.

shown schematically in Figure 2. By using this seal, it was possible to monitor the pressure in a rotating tire.

A schematic diagram of the system for measuring the change in the air pressure in the tire is shown in Figure 2. Before making the measurements, the valve to the reference pressure tank was opened, establishing the static tire pressure in all parts of the pressure measuring system. In taking the pressure measurements the valve was closed, thus subjecting side A of the differential pressure transducer to the fluctuating pressure in the tire while at the same time subjecting side B to the original tire pressure established in the reference pressure tank. As the vehicle moved down the highway, the pressure transducer responded to the difference in pressure between these two values and transmitted this information in the form of an electrical signal to an appropriate electronic circuit in which the signal was amplified and recorded with an oscillograph.

Certain difficulties are encountered in making measurements with this system. Air pressure in a tire is sensitive to temperature, and any heating or cooling of the tire will produce a difference in pressure relative to the original tire pressure introduced into the reference tank. In addition, small leaks will also cause a differential pressure to exist even though the vehicle may not be in motion. As a consequence, it is evident that undesirable factors may influence the dynamic tire pressure measurements when using this system.

Relatively slow changes in tire pressure can be eliminated by the introduction of an appropriately selected orifice as shown by the dotted line in Figure 2. With this modification the effect of heating may be minimized, but the selection of the proper orifice requires care so that no appreciable distortion of more rapid pressure changes will result.

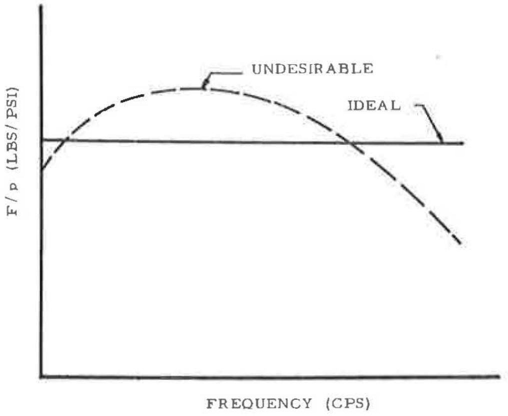


Figure 3. Calibration curves for pressure measuring system.

It is also essential that the proper tube lengths and volumes be selected, otherwise resonances will occur due to the vibration of the air in the system. These vibrations will influence the differential pressure record and produce inaccuracies in the results. The factors that influence the behavior of this system are currently being studied, and detailed information concerning the design and behavior of this equipment will be available in a later report if there is sufficient interest.

Because it is necessary to convert fluctuating air pressure measurements to those of force acting on the tread of the tire, an appropriate calibration relationship must be obtained. If the system is not carefully designed, this relationship will vary considerably with frequency. Relationships between the dynamic tire force acting on the tread of the tire and the change in air pressure as a function of frequency are shown in Figure 3. If inappropriate parameters are selected, an undesirable relationship will be obtained as indicated. This characteristic, shown by the dotted line, indicates that the ratio of tire force to tire pressure varies with frequency. Thus at certain frequencies higher forces will result in the same change of tire pressure. This means that records taken in the time domain cannot easily be interpreted because different frequencies require different calibration factors to convert them to the appropriate value of tire force. The ideal characteristic is shown by the solid line in which the ratio of tire force to tire pressure is the same value at all frequencies. With this characteristic it is possible to take a time domain record, such as that shown in Figure 4, and to determine the force that will exist on the tire at a selected time, regardless of the frequencies that exist in the record. It is evident that a calibration relationship, shown by the solid line, is most desirable, and hence the pressure measuring system shown in Figure 2 should be designed with this objective in mind.

The pressure measuring system was connected to the right front wheel of the test vehicle which was operated at a constant velocity over various sections of pavement. Knowing the velocity of the vehicle, it is possible on the analog record to indicate the position of the vehicle on the highway and to determine the corresponding tire force. In making the actual record, it is necessary to switch on the electronic equipment and to approach the test section with the pressure measuring equipment in operation. To indicate the location on the record of the start of the test section, a special device is placed on the highway at the beginning and at the end of the selected section of pavement. When the tire of the test vehicle strikes this device, a special mark is made on the record establishing the beginning and end of the pressure measurements relative to the highway.

Records obtained on the oscillograph are actually records of fluctuating tire pressure versus time. By using the vehicle velocity it is possible to convert time to position of vehicle on the test section, and by using the calibration curve it is possible to convert tire pressure to tire force. To obtain accurate records it is necessary to calibrate the test vehicle before any change in vehicle characteristics can occur between the time of calibration and the taking of the record.

This system for measuring dynamic tire force must be carefully designed so as to avoid spurious pressure fluctuations and to obtain a constant calibration relationship. When these conditions are realized, this system is very sensitive and will give consistent results.

ANALYSIS OF TIRE FORCE RECORDS

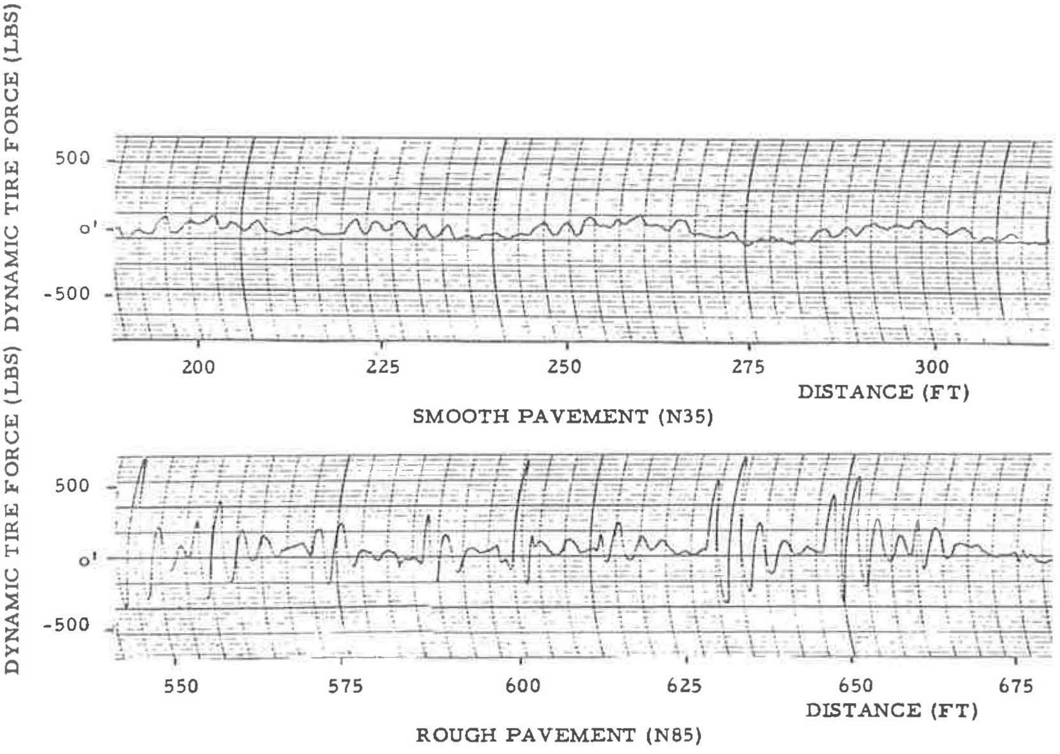
Oscillograph records of tire pressure versus time for two extremes of pavement condition are shown in Figure 4. The number o′ on each record can be used to locate the records relative to the axes shown in Figure 1.

The ordinates representing change in air pressure can be converted to tire force if they are multiplied by the appropriate calibration factor previously mentioned. When this is done the force scale, shown at the left, can be added to each record. It is immediately evident that the difference in the smoothness of the two pavement sections has caused a large difference in the tire forces exerted by the wheel of the test vehicle on the highway. In both cases the same vehicle was operated at the same speed, thus the difference is due to the condition of the pavement.

At the beginning of each test section a special mark was recorded. Knowing the vehicle velocity and the elapsed time, to indicate the distance traveled from the starting point by the distance scale shown on the record, the tire force at any location can be determined.

Although the record for the smooth pavement shown in Figure 4 is useful in making a visual comparison of the two pavements in question, it is virtually useless for further study. It was necessary to obtain an additional record for which greater amplification in the recording equipment was used to obtain measurable results. This, however, changed the calibration factor for this record.

Having these records it is also possible to determine how often certain magnitudes of the dynamic tire force occur when driving over the pavement section. This can be done by first reading values of force from the record at equal intervals of distance. These are then assorted such that the number of values in various ranges of tire force



SMOOTH PAVEMENT (N35)

ROUGH PAVEMENT (N85)

Figure 4. Records of dynamic tire force vs distance for two different pavements.

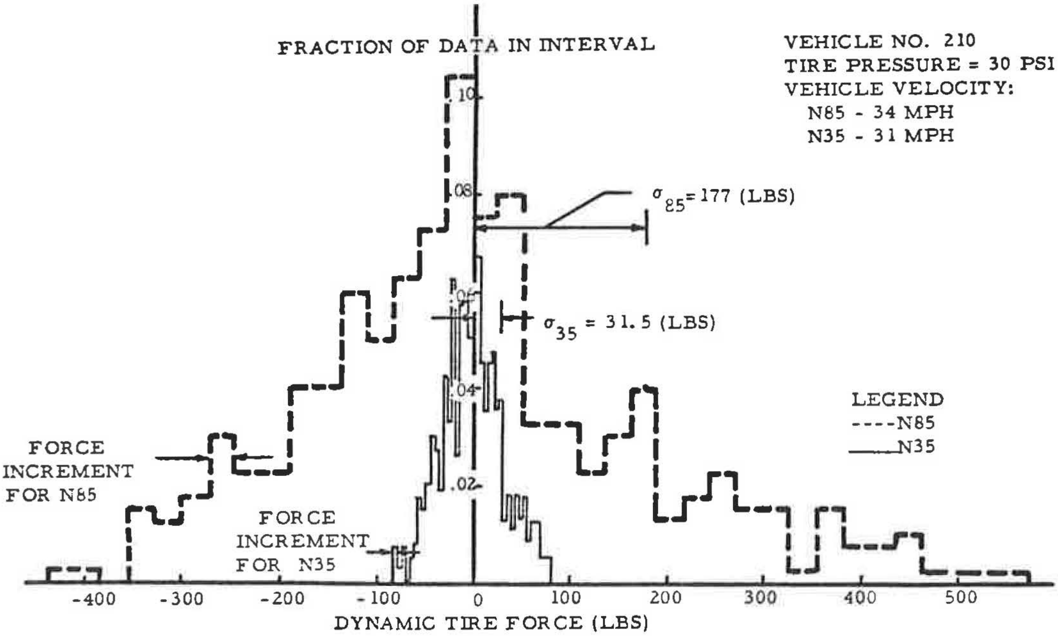


Figure 5. Distribution of dynamic tire forces for pavement sections N35 and N85.

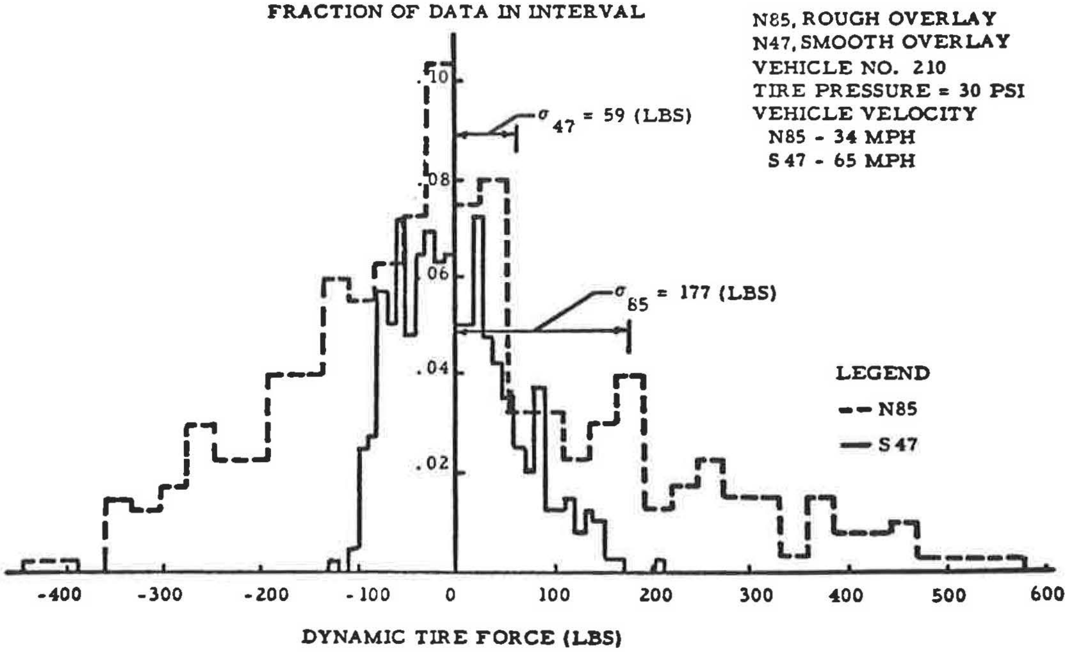


Figure 6. Distribution of dynamic tire forces for pavement section S47 and N85.

is determined. This number is divided by the total number of force readings included in the analysis of the record to obtain the fraction of the values in the force interval under consideration.

Figure 5 indicates results of this procedure when applied to the force records of which small sections are shown in Figure 4; distribution of dynamic forces in both can be compared. A much smaller increment of force must be used to study distribution of forces resulting from the smooth pavement than is used for rough pavement, otherwise no meaningful distribution can be obtained.

Although the pavements compared in Figure 5 are of different types of construction, there is as yet insufficient evidence to associate different force distributions with different types of construction. However, a comparison of pavements of the same type of construction but of different conditions of smoothness is shown in Figure 6, in which less striking differences are indicated.

It is evident from Figures 5 and 6 that the distribution of the dynamic tire force is not symmetrical. Larger positive tire forces are encountered than are those of negative sign. Because the positive values are added to the static wheel load to obtain the total tire force, it is clear that the assumption of a symmetrical distribution will underestimate the maximum forces that act on a highway. This possibility is investigated later in this paper.

It is, however, desirable to obtain a single summarizing statistic that can be used to describe the records in question. Inasmuch as both positive and negative forces are encountered, an average value of force is not significant. A better criterion can be obtained by squaring each force value obtained from the record, obtaining the sum of these values, dividing this sum by the total number of data values and taking the square root of the quotient. This statistic is called the root mean square (RMS) values of the tire force.

This was done for force records taken on several pavements that varied in condition as well as in type of construction. The results of these calculations are shown in Figure 7. The RMS force values for each type of pavement construction are recorded and grouped as shown. In addition, each pavement was assigned one of three subjective ratings (smooth, average, rough) as determined by the individuals who operated the test vehicle. Dynamic forces (RMS) ranging from 32 to 341 lb were obtained, resulting in a large range of values.

Although the subjective estimates of pavement condition are very crude, it is evident that low values of force are related to excellent pavement condition and that large values of force indicate that a considerable amount of roughness is present. Although a more extensive study of the correlation of dynamic tire force with pavement condition is necessary before final conclusions can be reached, it appears that pavement roughness is related to dynamic tire force.

As mentioned previously, the velocity of the test vehicle influences the dynamic tire forces. This was investigated by operating the test vehicle over the same length of pavement at four different velocities. The resulting RMS values of tire force are plotted against vehicle velocity (Fig. 8). Under the conditions encountered in this test, the tire force increases with velocity. This has been predicted theoretically from highway and vehicle characteristics (4, 5).

The distribution of the dynamic tire forces changed with vehicle velocity (Fig. 9). As the speed increased the maximum force increased. In addition, the frequency of occurrence of the larger forces also increased. This was accompanied by a small decrease in the negative forces but with a much larger frequency of occurrence of the negative forces. In other words, the skewness of the distribution increased with vehicle velocity.

The dynamic force distribution shown in Figure 9 by the solid lines (60-mph vehicle speed) was obtained on a pavement typical of many in use today. Likewise, the test vehicle velocity was close to that of many of the vehicles now using this section of pavement. This distribution is therefore not an extreme case such as that shown in Figure 5, but can be considered as representative of frequently encountered conditions.

The distribution is highly skewed, and to compare it with a normal distribution, a histogram was constructed based on a normal distribution having the same mean and the same RMS value as the skewed distribution (Fig. 10).

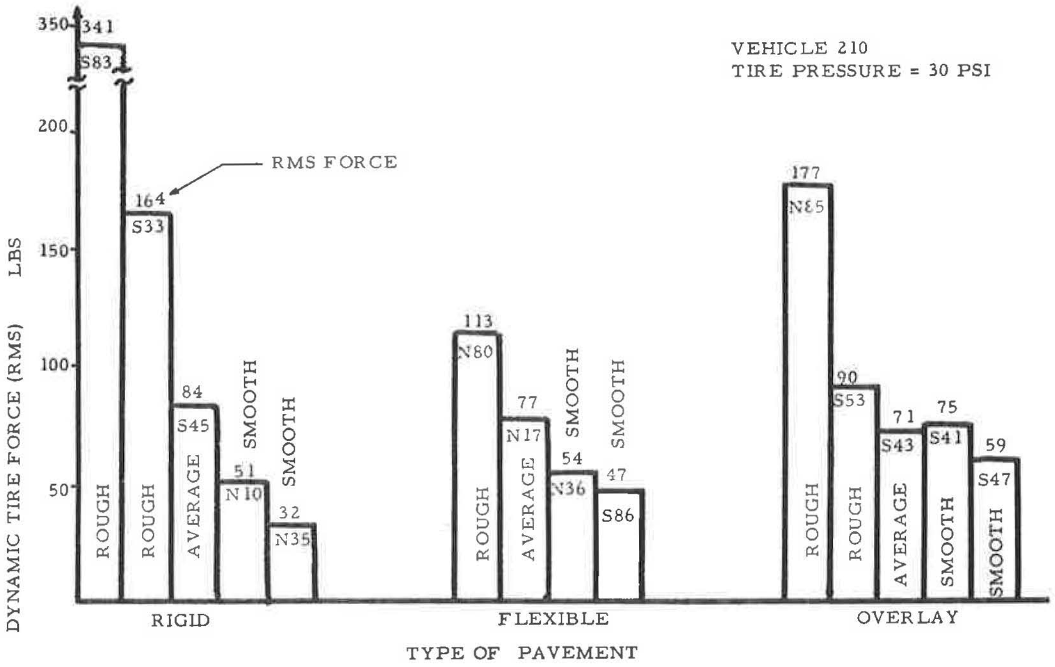


Figure 7. Root mean square value of dynamic tire force for different types of pavements.

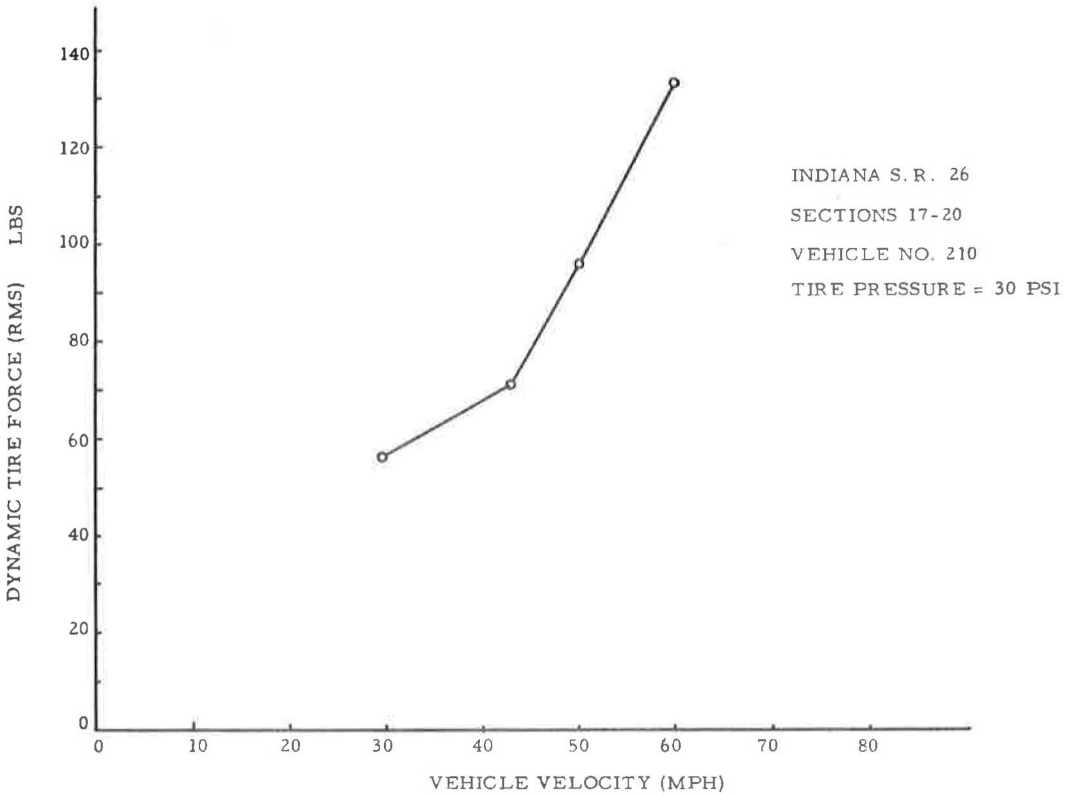


Figure 8. Root mean square value of dynamic tire force vs vehicle velocity.

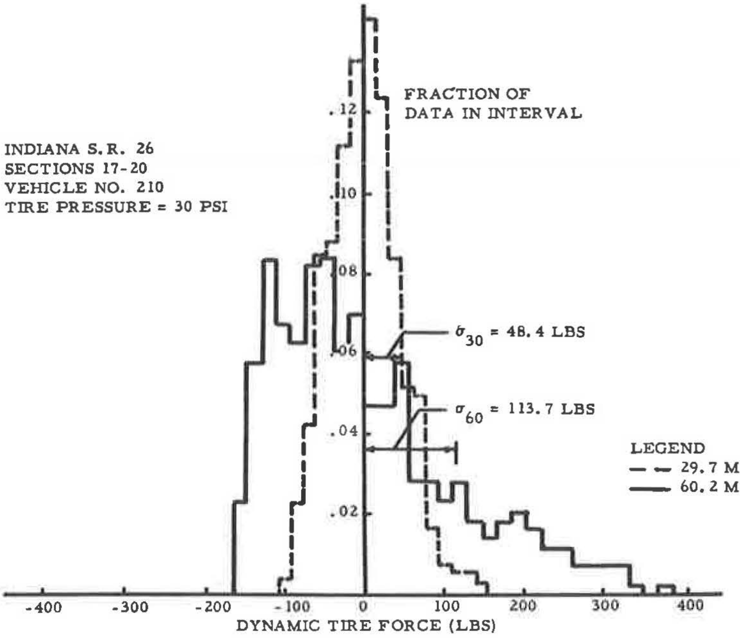


Figure 9. Distribution of dynamic tire forces at different speeds.

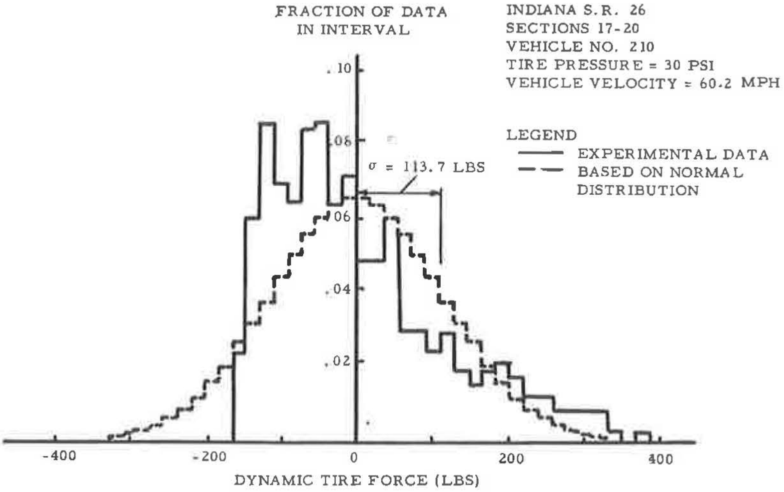


Figure 10. Comparison of dynamic tire force distributions.

Frequency of occurrence of large positive forces is underestimated by the assumption of normality, and the range of the negative forces is overestimated. Depending on the allowable error, the normal curve could be used as a first approximation for the positive forces. Inasmuch as these positive forces are added to the static wheel load to obtain the total force of the tire on the road, the frequency of occurrence of those forces that may be quite significant in the life of a highway will be underestimated. This error appears small, however, for data shown in Figure 10.

Changing the inflation pressure in the tire will influence the dynamic tire forces. This was investigated by operating the test vehicle over the same section of pavement at the same velocity but with different tire inflation pressures. Results are shown in Figure 11, in which the RMS value of the dynamic tire force plotted against tire inflation pressure.

Unfortunately tests were not conducted at relatively low inflation pressures and therefore this series of tests is incomplete. The curve indicates that low inflation pressures will result in lower tire forces, other factors remaining the same. A rapid drop in tire force could be expected for tire inflation pressures less than those recommended by the tire manufacturers (4). No such condition is shown in Figure 11, because all tests were conducted above the recommended pressure.

At high inflation pressures the calibration curve for the pressure measuring system approached that indicated as "undesirable" in Figure 3. A more accurate estimate of the RMS tire force requires a transformation in the frequency domain, and the procedure for determining force scales, described in connection with Figure 4, is no longer valid. An appreciable reduction in force will result from decreased inflation pressures, even though this is not indicated in Figure 11.

Vehicle characteristics influence the dynamic tire force records. The pavement will excite vertical motion in the suspension system of the vehicle that will consist largely of the natural frequencies of this system. This motion will be reflected in the tire pressure measurements.

A study of the frequencies in a tire force record can be made by using a power spectral density analysis (6). This analysis yields a curve, plotted as a function of frequency, the area under which gives the mean square value of the tire force. In addi-

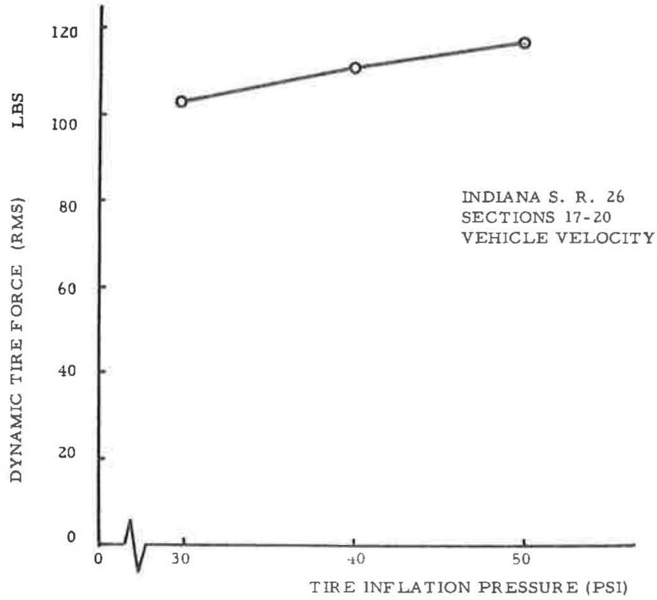


Figure 11. Dynamic tire force vs tire inflation pressure.

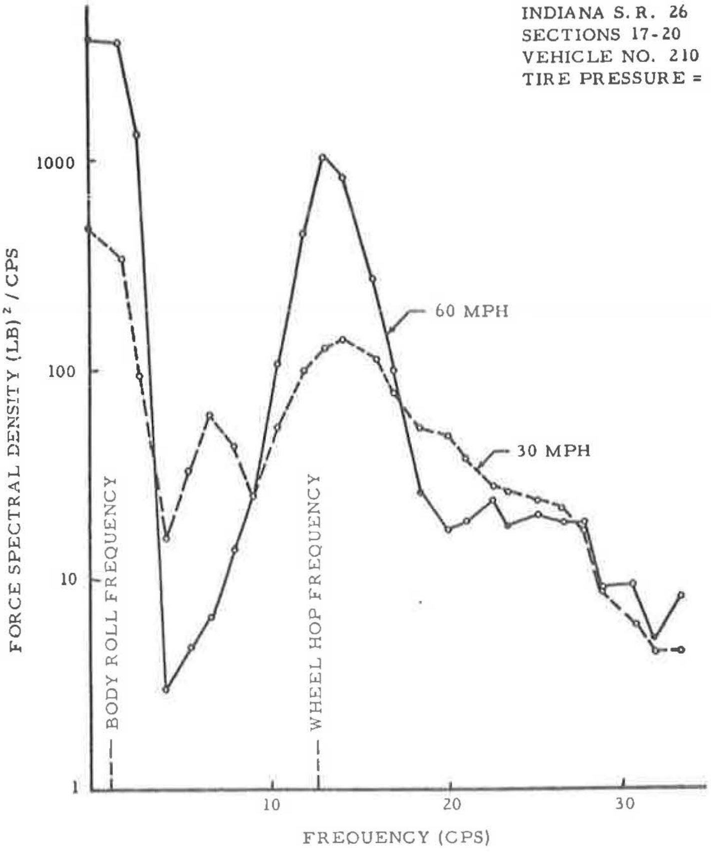


Figure 12. Power spectral density analysis of dynamic tire force records.

tion, the area bounded by any two ordinates gives the contribution to the mean square value that is made by those frequencies lying within the two ordinates.

The analysis can be useful in studying force records used to obtain distributions shown in Figure 9. The dynamic force power spectrum for the test vehicle traveling at 30 mph is shown by the dotted line in Figure 12. Two peaks of appreciable magnitude are indicated by this curve. The first peak, occurring over a range of low frequencies, indicates that the motion of the sprung mass (body roll) of the vehicle makes an appreciable contribution to the total mean square value of the dynamic tire force. A second peak, occurring over a range of higher frequencies, indicates the contribution to this value that results from motion of the unsprung mass of the vehicle (wheel hop).

Power spectral density function of the dynamic tire force for the same vehicle traveling over the same section of pavement at 60 mph is shown by the solid line in Figure 12. The area under this curve is greater, indicating the higher mean square force (Fig. 8).

In the change in the shape of the curve, the peak associated with low frequencies is higher, indicating that the motion of the sprung mass (body roll) changed appreciably. The motion of the unsprung mass (wheel hop) was also increased at the higher vehicle speed as evidenced by the large increase in the ordinates of the curve in the region of the wheel hop frequency.

Another change is in the power spectrum curve for 30 mph, in which a small intermediate peak can be seen approximately midway between the two large peaks. This is due to a large amount of excitation coming from the pavement because no natural frequencies exist in the suspension system of the test vehicle at this frequency. When the vehicle speed is doubled, the frequency of excitation from the highway is doubled. At 60 mph the excitation that caused the small intermediate peak has doubled in frequency, causing an additional excitation at the wheel hop frequency. Inasmuch as the vehicle is very responsive at this frequency, a great increase in tire force is produced.

SUMMARY

From the several techniques discussed, the most useful single statistic is the RMS value of the force. This can be used as a convenient summarization of a record and as a measure of the tire forces encountered for a selected pavement, vehicle and vehicle velocity.

Moreover, this quantity can be used to obtain a first approximation for frequency of occurrence of various magnitudes of total tire force exerted on the pavement. This can be done by using the static wheel load as the mean value of the total force, by assuming a normal distribution of the dynamic tire forces, and by using the RMS value of dynamic tire force as the standard deviation of the distribution curve.

The force power spectrum (Fig. 12) indicates extent to which various frequencies of vibration are present in the tire force records. Of greater importance, however, is the usefulness of this characteristic in performing operations in the frequency domain that cannot be performed readily in the time domain.

CONCLUSIONS

Dynamic tire force is related to pavement condition. Rough pavements cause large forces and smooth pavements cause relatively small forces. If the matter is pursued no further, the use of tire force as a criterion of pavement condition is very simple.

Unfortunately other aspects of the relationship between tire force and pavement condition must be considered. Confusion is introduced when different tire forces can be obtained on the same pavement by simply varying the speed of the vehicle. Can any pavement be rated as either good or bad, depending on the speed selected to take the tire force records? Can the rating of a pavement be changed from bad to good by simply changing the inflation pressure in the tires of the vehicle? Tire force as a pavement condition criterion is susceptible to these manipulations.

Is the actual significance of a pavement condition criterion solely a measure of the geometric properties of a pavement? If so, dynamic tire force measurements are unsatisfactory.

A measurement that is sensitive to the behavior of the vehicle on the highway should be used as a pavement condition criterion. Actually the dynamic tire force is a criterion of a combination of factors that includes pavement condition. Forces that are exerted against the pavement can be influenced by the vehicle suspension system and the speed of the vehicle. Inasmuch as these forces can be decreased, if necessary, by modifying the vehicle and by changing operating conditions, different vehicles, moving with different velocities, will each respond in a different manner to the same highway. The dynamic tire force is a measure of this response and for this purpose it is a valuable criterion.

It should also be pointed out that it is theoretically possible to remove both the vehicle characteristics and the vehicle veolcity from the tire force records, leaving a pavement characteristic that is free of these factors. This procedure is now receiving serious consideration.

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Addendum

The question has been raised as to whether or not it is possible to show a relationship between the values of dynamic tire force shown in Figure 7, and an objective rating of the associated pavement sections.

Fortunately, since the paper was written, it has been possible to obtain BPR roughometer ratings of the pavement sections under consideration.

In Figure 13 the logarithm of the dynamic tire force is plotted against the logarithm of the BPR roughometer rating for the pavement sections shown in Figure 7. Two highway sections have been omitted from this plot due to the lack of valid data. Each type of pavement has been indicated by a special symbol, and it is evident that the number of points for each type of pavement is very small.

Forming conclusions from the small quantity of data shown in the plot is hazardous, but certain trends may be suggested. In general, a large BPR roughometer rating is associated with a large dynamic tire force. Within limits, it may be possible to represent this relationship with a straight line as shown. If this is so, then a simple relationship can be used to predict the dynamic tire force from the BPR roughometer rating or vice versa. Vehicle parameters influencing the dynamic force (such as vehicle velocity, etc.) must not be changed if a relationship between dynamic force and roughometer rating is to be used. In addition, the curve shown in Figure 13 could not be used for heavy vehicles, because it was obtained by using a passenger car. It does suggest, however, that similar relationships may exist for different classes of vehicles. If this is true, then an estimate of the dynamic tire force to which a pavement would be subjected could be determined from the BPR roughometer rating of the pavement together with an appropriate curve of the type shown in Figure 13.

The question arises as to the effects of pavement construction (rigid, flexible or overlay) on the relationship between force and roughometer rating. Unfortunately there is not enough evidence to answer this question, but from the data shown in Figure 13 such an effect would appear to be of a minor nature.

The tests to date indicate that there is a relationship between dynamic tire force and BPR roughometer rating when the vehicle parameters are held constant. However, although a pavement will have only one roughometer rating, it will have different dynamic force values if the vehicle parameters are changed between successive tests of the same pavement.

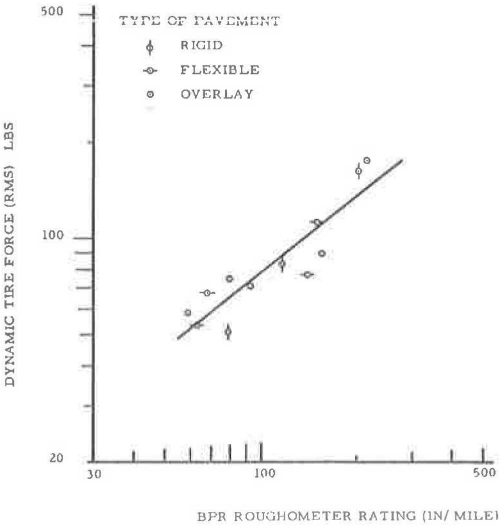

Figure 13. Relationship between dynamic tire force and BPR roughometer rating.