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Some Problems in Measuring Tread Wear of Tires

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Contents

Some Problems in Measuring Tread Wear of Tires

S. Spinner* and F. W. Barton

Some problems in tread wear testing of tires are discussed and methods for dealing with these problems are presented. Experimental data are shown to illustrate these methods. Finally some recommendations are made, based primarily on this information, in order to achieve greater uniformity and a statistically valid approach to tread wear testing.

Key words: Tires; tread wear testing; statistics.

1. Background

The purpose of a Uniform Quality Grading System (UQGS) for tires has been described as one which will enable the potential consumer to make "an informed choice" in purchasing. It seems reasonable, then, that whatever other criteria are to be included in a UQGS, that an estimate of the "life" or expected mileage of a tire in normal use must be included. This is usually one of the first questions which the prospective buyer asks--and justifiably so. This does not mean that he will always choose the tire having the highest estimate of expected mileage; but he should if possible, be informed to what degree this particular characteristic was balanced against other qualities of tires also to be included in a UQGS. It has frequently been pointed out that the design of tires is a series of compromises in which optimum performance in a given category must sometimes be sacrificed to obtain acceptable performance in another category.

The present report deals with some of the problems involved in analyzing tread wear, presents some data based on this analysis, and makes some tentative recommendations based primarily on this analysis.

One of the arguments frequently used by those claiming that a standard for tread wear is not possible (either not possible at all or not possible at the present state of knowledge) is that the rate at which

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tires wear varies so widely with the nature of the roads, driving habits of individual drivers, the cars, loading of the tires, etc., that such a standard cannot be set.

While it is undoubtedly true (and well-known) that the rate at which tires wear will vary widely under different conditions, such an argument tends to obscure rather than clarify the essential problem, which is to obtain a reasonably accurate estimate of the relative rates of wear of different tires under a normal range of variation of environmental conditions. We hope to demonstrate, by using an appropriate experimental procedure, that although the problems involved in achieving such a goal are not too simple, neither are they insurmountable. For this purpose, we rely heavily on a series of papers [1, 2, 3, 4]* produced at NBS about 15 to 20 years ago. We find it necessary to recall these papers because, although the procedures described therein have been followed in a superficial way, the full value of their approach has apparently not been realized by those engaged in tread wear testing from the time since the appearance of these papers to the present.

Indeed it is most unfortunate that often considerable skill in measuring tread depth and other dimensional changes taking place as the tire wears down (which from the nature of the material being measured is not a routine task but a skill which can only be acquired after considerable experience) is not matched by a corresponding understanding of how to properly utilize these measurements in a statistically valid approach in both experimental design and subsequent analysis of the data.

We begin by distinguishing between the two classes of parameters which can affect the tread wear of tires [5]. The first of these classes are called external, or those parameters which will cause the same (or identical) tires to wear at different rates. These include the conditions mentioned previously and which we now list in a more complete form:

1. Road conditions--the texture and composition of the road, its nominal coefficient of friction, the size and distribution of asperities, the curvature and "hilliness" of the road.

2. Weather conditions--temperature, humidity, amount of rainfall, snow, etc.

3. Nature of driving conditions--average speed, variation about this average, amount of "stop and start" driving and open road driving.

4. Car characteristics and wheel position of tire on car, loading, and inflation pressure.

5. Individual driver characteristics.

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*Figures in brackets indicate literature references at the end of this paper.

The second class of parameters may be called intrinsic or internal. These are the factors which would cause two intrinsically different tires to wear at different rates if all the external parameters (such as those listed above) were held constant; and conversely, which would cause two intrinsically identical tires (with respect to tread wear) to wear at the same rate under identical external conditions. Such parameters would include the compounding and design of the tread, construction and composition of the carcass, and processing variables during manufacture.

It is these relative intrinsic wear rates of the tires which we hope to distinguish and evaluate; and the whole purpose of the experimental procedure to be described is to minimize any differential effect of the external parameters in order that the effect of the intrinsic parameters on tread wear can be realized. Also, although such procedures can (and have) been used to differentiate the effects of intrinsic factors on tread wear [1], our purpose here is only to evaluate their combined effect on this property. The effect of such internal parameters on tread wear are of the greatest concern to tire designers and engineers but not of direct interest in attempting to arrive at a basis for setting a standard for tread wear.

It is also possible that these intrinsic factors may interact with the external ones, so that one type of construction, for instance, may wear better under one set of external conditions, while another construction of tire may give superior tread wear performance under a different set of external conditions. If this interaction is significant, it probably poses the most serious barrier to establishing a reliable tread wear standard. However, we believe that even this problem is amenable to, at least, a workable solution. We shall return to this subject later.

2. Experimental Design

Returning now to the design of the experiment to cancel out as far as possible the effect of variations in the external parameters, it is clear that if the test tires are used on vehicles traveling in convoy, then variations in external factors 1, 2, and 3 can have little or no effect in changing the relative intrinsic wear rates of the tires; since all the tires will have been subjected to these same conditions at the same time. Concerning condition 3, there is actually no compelling reason for maintaining the speed at a rigorously constant value throughout the test. The essential requirement is that the speeds of all the cars in a convoy vary in the same way and that the speed pattern be consistent from period to period. Then one can accommodate the speeds to traffic and weather conditions without invalidating the test procedure. The customary procedure seems to be based on the tacit assumption that accuracy in maintaining a constant speed is somehow equivalent to accuracy of experimental design in evaluating tread wear. (This, of course, is not the first time that investigators have attempted to disguise--to themselves and to others--a lack of accuracy in conception by emphasizing accuracy--and quantity--of measurement.)

The maintenance of a constant load on a particular wheel position throughout the test is essential. However, small variations in load from one wheel position to another are compensated by the statistical design. To accelerate the test, the load is usually maintained at the maximum rated load for the inflation pressure used.

Since there is no way that all the test tires can run on the same wheel position of the same car at the same time, variations in condition 4 can be dealt with by an appropriate statistical design, generally of a Latin Square type. The basic principle underlying such a design is to have each tire on each wheel position of each test vehicle for equal numbers of measuring periods so that at the conclusion of the test any external variation of tread wear due to variations in car or wheel position will have been minimized. Furthermore, if measurements of tread depth are made after each period between tire rotations, it is possible not only to evaluate the relative intrinsic wear rates but also to determine which wheel position, car, and measuring period cause the fastest (and slowest) wear rates for all the tires--aside from any intrinsic variation in the tires themselves [2].

Let us suppose, for instance, that the test requires the relative intrinsic tread wear rates of 16 tires. This would involve 4 cars, and for each tire to have occupied each wheel position of each car once would require 16 sets of changes. If one chose 500 mile runs between tire changes (a reasonable figure since it corresponds to a normal day's run), then the test would be completed in 500x16=8000 miles per tire, excluding break-in.*

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*The advantage of such relatively short term tests is that, properly designed, they can give as reliable an estimate of tread wear, as when the tires are run to completion, and at significantly less time and expense [4]. It also seems relevant to point out here that the running of tread wear tests is not cheap. Even a relatively short term test such as the one described here costs about $10,000; so that if the tests are not properly designed and the results not properly arrived at, then this money will have been wasted. Even worse, such inadequate tests may lead to erroneous results. Very often, when results of such tests are questioned, the questioner is overwhelmed by being told that they were obtained by so many and so many miles of testing of so many and so many tires. (The larger the figure that can be used for "so many," the more impressive the answer.) If the questioner senses that something may be wrong but cannot put his finger on it, he is again overpowered by being told that "tires were changed from wheel to wheel and car to car in a forward X pattern" and that speeds were maintained at "exactly 70 mph" at exactly 100 percent load, and tachometer readouts and other charts are triumphantly shown to prove this.

If this report accomplishes nothing else, it will have attained some useful purpose if it can succeed in making the reader aware of the problems involved in tire testing, indicate a rational approach to dealing with these problems, and also to become aware when certain commonly used irrational procedures are followed! And these irrational procedures are <u>not canceled out but multiplied</u> by following them in testing many tires for many miles.

If there were reasonable assurance that the conditions were such that the tires could run 16,000 miles without failure or wearing out, then the measuring period could be doubled (to 1000 miles), or the 500 mile measuring period could be retained and the pattern of tire rotations repeated. Then each tire would have been on each wheel position of each car twice instead of once. Such a procedure could be used to determine the degree of correlation between the first and second 8000 mile runs; inasmuch as the schedule of tire rotations in the first and second 8000 mile runs would have been identical.

A common practice in changing tires from wheel position to wheel position and car to car is to follow some preset pattern such as "forward X." It is preferable to randomize the schedule of tire rotations so that no possible cyclic variation in other external conditions, such as temperature, can affect the relative intrinsic wear rates in an unforeseen way. Also if measurement of tread wear are not made before each period of tire changes, then a great deal of the advantage in making these changes will have been lost.

The effect of differences between drivers should also be taken into account. If the driver is retained with the same car throughout the test, then "differences between cars" actually becomes "differences between cars plus drivers [5]." To change drivers from car to car would introduce an unnecessary complication into the analysis of the data. (In a recent tread wear test that came to the authors' attention, the investigators announced that they had rotated drivers from car to car. This appears to be an example of changing merely for the sake of changing with no logical reason for this procedure. Nowhere did they indicate what the purpose of these changes was or what advantage in analyzing tread wear or any other relevant parameter was gained from it.)

3. Measurement of Tread Wear

In the NBS papers previously mentioned considerable attention was given to the best method for measuring tread wear. They favored measuring the progressive loss in tread rubber by means of weight loss rather than by decrease in tread (or groove) depth; and successfully used this method in their investigations. However, the measurement of groove depth as the indicator of tread wear is almost universally used today and was used in the investigations to be described here. This brings up the further question of how to average the various readings of tread depth in order to obtain uniform results for comparison of tires.

Not all facilities use the same procedure for obtaining the overall average tread depth for tires having the same or similar designs, and the problem is further complicated by the different types of tread designs, each requiring a slightly different procedure. For radial ply and snow tires, the tread designs depart even further from "normal" with attendant complications in measuring. These variations in tread design indeed were among the principal reasons for the NBS group favoring the weight loss method which is free of this complication. (Other variations such as changes in tread profile during test, which can also vary differently for different types of tires, can also contribute to different estimates of tread loss.)

The problem is not hopeless, for as long as the various methods are reasonable and self-consistent, a satisfactory relative measure of tread wear can be obtained, even though the absolute values of tread depth of one facility might not agree with those of another. It would be most desirable, however, to have a consistent standard technique for measuring tread depth so that values obtained by different facilities could be compared.

Measurement of the rate of tread wear, r, for a given measuring period, usually given in mils per 1000 miles, is obtained from

$$r = \frac{\Delta D}{m} \times 1000$$

where ΔD is the difference in mils for a measuring period of m miles; ΔD may be the difference in the average of several readings for a single groove or the difference in "overall average" using any consistent method of obtaining this overall average as mentioned above.

Two additional points concerning tread wear measurements are mentioned, because although they appear obvious, they have often been overlooked.

1. Tread wear rates are usually given to two (and even three) significant figures (1 part in 100). The tread depths themselves are usually recorded to 3 significant figures (in mils) and averages of several readings for a single groove as well as overall averages are also given to 3 significant figures. However, the tread loss, ΔD, for a typical period may be less than 10 mils. Consequently, in such cases the calculated tread wear rate is justified to only two or sometimes only one significant figure (about 1 part in 10). It follows then that if tread wear ratings are to be properly given to 3 significant figures, then a minimum of 4 significant figures is required to indicate tread depths. If the number of measurements comprising the average is large enough (6 to 10 for a single groove and 25 to 50 per tire) and the variation in individual measurements is not too large (±2 mils for a single groove), then one may give the average depth to 4 significant figures and then the tread wear rate to 2 significant figures is justified. (Tread wear rates

are sometimes given to 3 significant figures but this is mainly to avoid rounding errors in subsequent calculations.) Of course, if Δ D has 3 significant figures, then r may also have 3.

2. The second point to note is that precision of results does not increase linearly with the number of measurements but with the square root of the number of measurements. Thus, if the number of measurements entering into the average were doubled, the precision of the average would not be doubled, but would increase by about 1.4; and for the precision to be doubled, four times as many measurements would be required. This is an important economic consideration in attempting to estimate the number of measurements needed in arriving at reliable results.

Another frequent practice is to give tread wear data on a cumulative or incremental basis, rather than on the basis of individual measuring periods. Such a cumulative presentation appears to be preferred because one can easily see by following the data as the test proceeds that the tread is wearing down (as it should be doing) whereas a rate of wear measurement based on individual measuring periods appears to have no pattern but jumps up and down in an apparently erratic manner. This is disconcerting to an unsophisticated observer. This impression is reinforced when the data are plotted on the usual sclae, which shows a fairly smooth descent for the cumulative data, and fairly large apparently random variations for the individual measurements. However, although cumulative data can have auxiliary value, they cannot be as revealing as tread wear loss from individual measurements. It is the very smoothness of the cumulative presentation that tends to obscure rather than point up differences in tread wear during individual measuring periods. In a sense, it defeats the purpose of tire rotations and other external variations during individual measuring periods to "smooth over" these variations. Figure 1 illustrates the difference in these two ways of presenting the data. The upper curve gives the percentage loss in a tire as a function of measuring period. Its departure from smoothness seem to be small in comparison with the lower curve which gives the rate of tread loss for individual measuring periods. Actually, the lower curve is the graphical derivative of the upper one. The apparently erratic departure from smoothness can be related to wheel position, car, weather, or other changes in environmental conditions previously listed. This is not apparent in the upper curve. Mandel [6] has also pointed out that the nature of cumulative data is such that illusory effects can be obtained by making it appear that successive measured quantities are quite different while the actual variations in these measured quantities are insignificant.

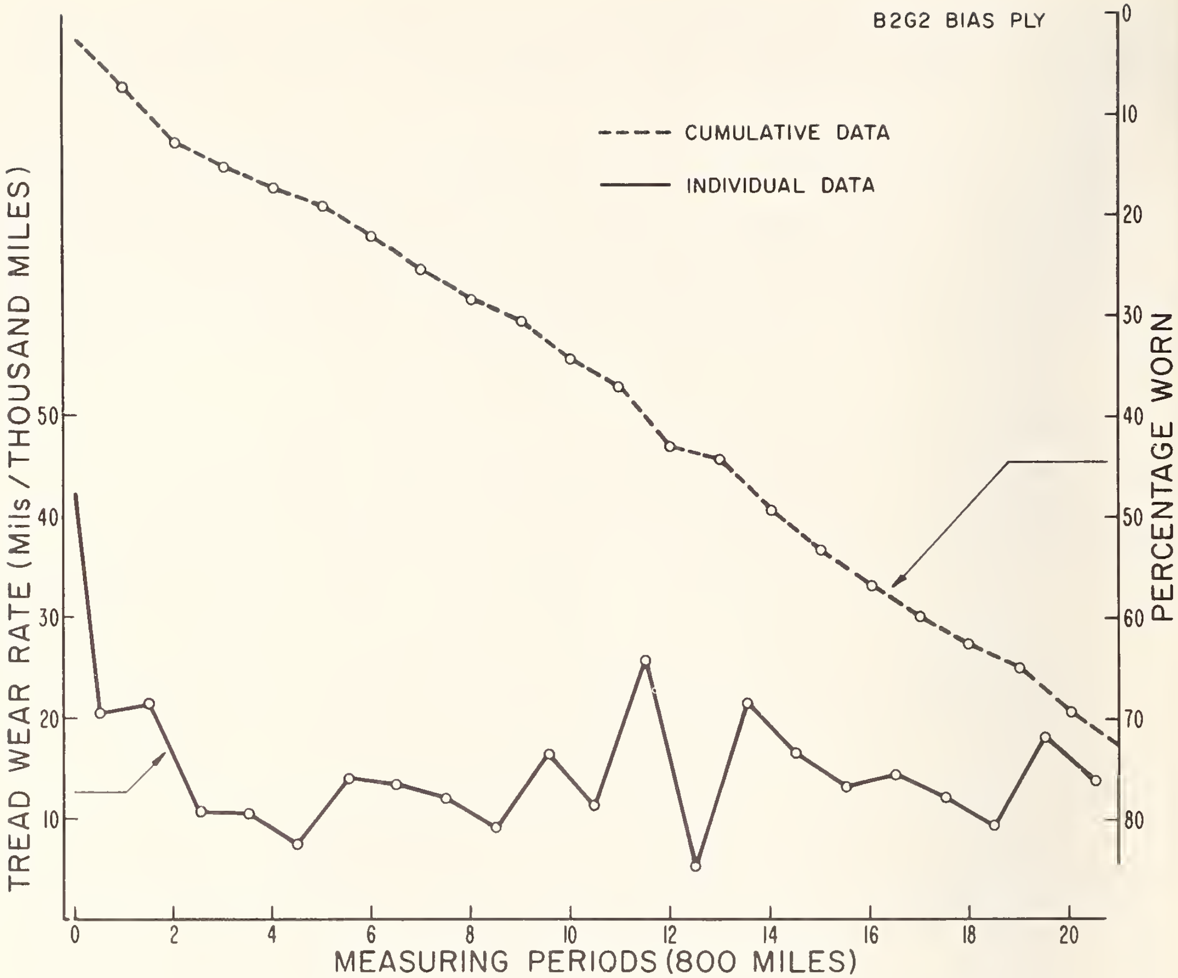

Figure 1. Tread wear data for the same tire presented on an individual and a cumulative basis.

4. Break-in Period

The apparently high tread wear rates seen in the initial portion of the lower curve in figure 1 are typical when groove depth measurements are used as indicators of tread wear; and are of considerable importance in attempting to arrive at an accurate measure of tread wear. The NBS group noted that when the weight loss method is used to indicate loss in tread rubber, then this large initial wear rate did not appear.

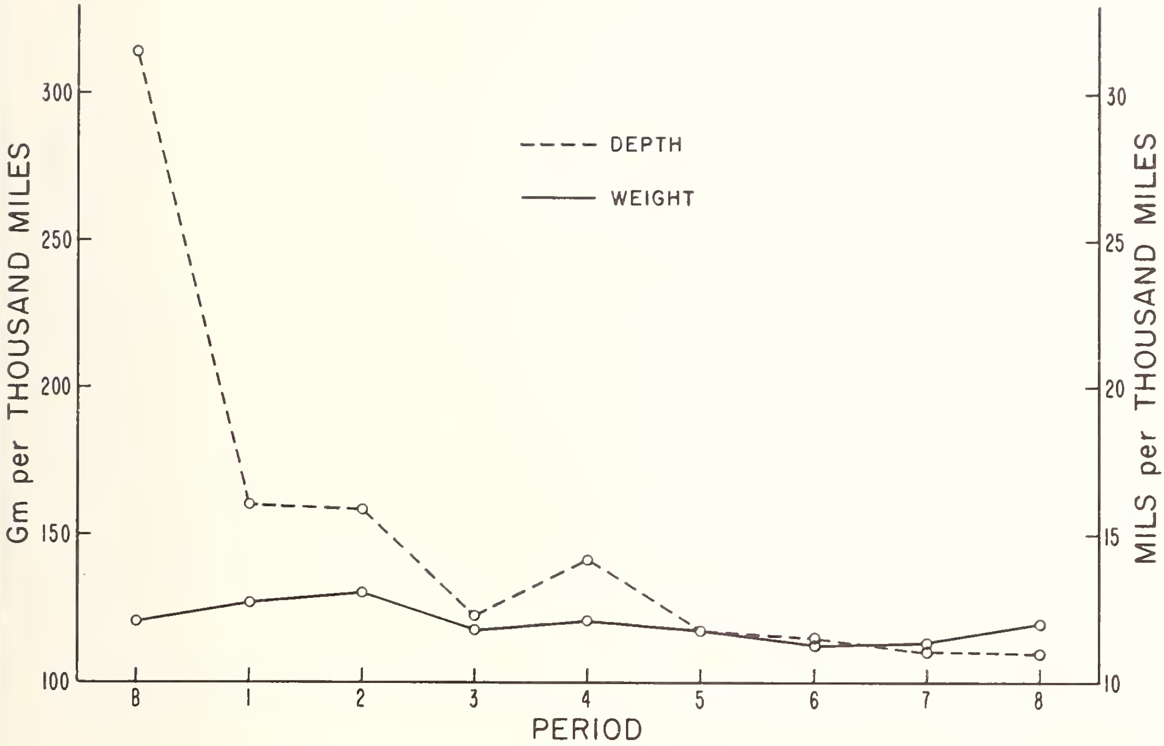

Figure 2. Comparative rates of wear for the same tire by groove depth and weight loss method.

Figure 2 from one of their papers [2] demonstrates this difference in apparent tread wear rates as measured by the two methods. Apparently, whatever changes in tread design, rubber compounding, and other design features that have taken place in tires since the time of the measurements shown in figure 2, this apparent initial tread loss when measured by the groove depth method still exists. It also seems clear that since this apparent loss (using groove depth) is not matched by a corresponding high loss as indicated by weight measurement, that the groove depth measurement in this initial stage is not a true indication of tread loss. This was another reason for the NBS group's preference for the weight loss method. However, since we are, for the present, committed to the tread depth measurement (which does offer certain advantages [2] in addition to its prevalence), this problem must be resolved.

Inspection of the lower curve in figure 1 shows that once the initial high value of tread wear rate has been traversed, the "baseline" about which the fluctuations in tread wear rates during successive measuring periods take place is fairly flat. Apparently there is some dimensional change, not associated with actual loss in rubber in the early stages of wear, that is superposed on the actual tread loss. Since there is no way at the present time for separating these two effects by groove depth measurements alone, the problem can be resolved by making the break-in period long enough for this initial effect to have ceased or become negligible. From this point on, the fluctuations in tread wear rates (about the flat baseline) should indicate true losses in tread rubber.

This would indicate that the break-in period should be longer than the 100 or 200 miles usually used. Since the initial (apparent) loss varies with tread design, tire construction, and compounding, the break-in should be long enough to insure that all the tires in a given test should have passed through this initial period. A break-in of at least 500 miles would appear to be indicated from figure 1. Another advantage of this longer break-in period would be that if a tire requires replacement by its duplicate during the course of the test for any reason (to be discussed later), then the longer break-in would remove the possibility of the apparent high initial loss biasing the computation of the average tread loss for that tire for all the measuring periods.

In the two tests to be described, we followed the usual practice of only 100 and 200 mile break-in periods. However, in future work we intend to use the longer break-in period.

5. Basis of Comparison of Tread Wear of Tires

We shall now discuss in some detail the basis on which the tires in the tests to be described were compared. (Another way of stating the problem is "what is a reliable criterion for assigning a tread wear rating to tires?") The method of computing the tread wear rate of a tire for a given measuring period has already been shown. It would appear that the arithmetic average of the tread wear rates for all the measuring periods of the test should provide the proper indication of the tread wear rate for each tire of the entire test. This is not so, however. Stiehler, Richey, and Mandel [3] have demonstrated very clearly that if the arithmetic average of the tread wear rates for all the measuring periods are used, then the influence of certain external parameters (such as those arising from wheel position, and measuring period) is not removed, so that one does not obtain a true measure of the relative intrinsic wear rates of the tires. However, if the geometric average for all the measuring periods is used, then the effect of these external factors is largely removed and one does obtain essentially a true measure of these intrinsic relative wear rates. Thus the best designed test for determining tread wear rates may be vitiated if the arithmetic rather than the geometric averages of the wear rates were used. The process of obtaining the geometric average is quite simple since all that is required is to take the arithmetic average of the logarithms of the wear rates and then take the antilogarithm of the answer thus obtained, and with modern electronic desk calculators the procedure for obtaining the logarithms and antilogarithms of a number is no more difficult than pressing an appropriate button.

It can also easily be demonstrated that if only arithmetic averages of tread wear rates are used and if only tires are compared (effect of wheel position and measuring period ignored), then the arithmetic average of the tread wear rates for the individual periods would be equal to that which could be obtained from only 2 depth measurements; the first before the first period of tire rotations and the second at the end of the final period of tire rotations. The argument applies equally well if weight measurements are used. The only advantage to be gained from depth (or weight) measurements during intermediate periods would be to provide some indication of the variability of the tread wear rates for the individual periods about the (arithmetic) average of the tread wear rates for all the periods.

Consequently, when tires are compared only on the basis of arithmetic averages, it is meaningless and wasteful to take groove depth measurements either after each period of tire rotations or after a sequence of periods (usually after a tire has been on each wheel of a car in a forward X pattern). Such intermediate measurements add very little to what may be learned from an initial and a final measurement alone.

Either one takes measurements after each period of tire rotations and draws appropriate conclusions from them (i.e., evaluates the effect of wheel position, measuring period, and the wear rates of the tires themselves, which can properly be done only on the basis of the geometric averages of the tread wear rates for individual periods), or one need take no intermediate measurements at all. Furthermore, there is no point in using geometric averages of measurements taken after a sequence of tire rotation periods since such measurements implicitly assume an arithmetic average of the tread wear rates during the sequence. The result would be a melange of geometric and arithmetic averages from which no legitimate conclusion could be drawn.

The geometric average of the wear rates for all the measuring periods would be a sound method for comparing the tread wear of different tires in a given test were it not for the fact that tires do not generally have equal tread depths at the start of the test. Clearly if two tires had equal rates of tread wear, but unequal initial tread depths, the tire with the greater initial tread depth would have the longer expected mileage. It seems clear that this should be taken into account in comparing the two tires. In order to assign a tread wear rating to the tires to be compared, then, we divide the average initial tread depth by the geometric average of the tread wear rates over all the measuring periods for each tire. The "geometric projection " (GP in miles) thus obtained, then, is the basis for comparing tires in the data to be shown.

The geometric projection is used only for comparing the tires themselves. To evaluate the effect of wheel position, car, or measuring period on the relative rates of tread wear, obviously, only the geometric average of the tread wear rates of the tires should be used.

Although the geometric projection appears to provide a valid basis for comparing tires, it does not necessarily follow that this GP is an accurate estimate of the "life expectancy" or the number of miles the tire will actually run in use. There are three reasons for this. First, the external conditions under which the tire would continue to run after the test would in all probability be quite different from those during the test, with attendant differences in the rate of tread wear. If the tires were to continue to run under test conditions on the same road and with the same schedule of tire rotations, then the agreement between the period to establish the GP and subsequent tire wear would probably be much better, but even here differences in other external conditions (such as weather) between the initial and later periods could cause differences between the GP and actual mileage.

The second reason for not expecting agreement between GP and actual mileage is that a tire is considered to be worn smooth when any portion of the tire reaches smoothness (shown by the wear bar indicators). Generally there is enough tread depth in the remainder of the tire so that, based on "overall average," the tread depth of the tire at this point is usually only from about 70 to 90 percent worn. This non-uniform wear does not necessarily arise from misalignment of the wheels or incorrect inflation pressure. During the tests these two factors were regularly checked and properly maintained--but some uneven wear still resulted. (It would perhaps be over optimistic to expect tires to always wear down so that the tread would be 100 percent worn when replacement becomes necessary.) Uneven wear may result from lack of uniformity in construction or some other design feature of the tire, or to the interaction of the tire with the suspension system of the car.

Since the initial tread depth used in the calculation of GP is the overall average and since the computation of GP then assumes 100 percent worn tires at removal, the GP would be higher than the actual mileage except in the rare case of a tire replaced when actually 100 percent worn. If, instead of using the initial overall average tread depth to compute GP, one were to use the initial average tread depth of the fastest wearing grooves (whether at the shoulders or center), one could obtain a much better agreement between GP and actual mileage; and, indeed, there was some question of whether this might not be a better way to compute GP. However, it seemed preferable in comparing tires to use the initial overall average tread depth since then a uniform procedure could be followed; i.e., one that would not vary according to which grooves of a particular tire happened to wear faster.

The third reason for lack of agreement is that the point at which tires are removed as worn in actual use is often quite arbitrary. The more cautious (or wealthier) driver may decide that a tire needs replacement a few thousand miles before his more careless (or poorer) counterpart. Between a driver who says, "The tires still look good, but I am going on a trip so I'll buy new ones," and the driver who says, "The tires look shot but I'm going to trade the car in shortly, so why should I spend money for new tires now?;" there may be some 5000 miles of tire use--if the second driver survives, that is! It would be most unlikely to obtain good agreement between GP and actual mileage when the actual mileage of a tire can vary by such wide amounts.

Even if the tires were continued to be run under the same test conditions, the person supervising the test must decide whether a given (worn) tire will survive the next measuring period. If he is cautious, he may remove a tire as smooth even though it might have survived the next measuring period. On the other hand, if he decides to let the tire continue, it may wear down to the fabric in some portion and (barring failure) the tire will have a longer measure of tread life than had the tire been removed at the proper time. In any case, the actual point at which tires are removed under test is usually at discrete intervals of mileage (depending on the measuring period) whereas the GP is not subject to this restriction.

6. Description of Tread Wear Tests

A full description and analysis of these tests will appear in a subsequent publication. We shall confine ourselves here mainly to those aspects of these tests that are relevant to the present discussion.

Two sets of tests were conducted. One involved only bias ply tires and the other used radial ply tires along with some bias plies for comparison.

We shall describe the tests with the bias ply tires first. These tests had a twofold purpose. The first was to obtain a measure of the tread wear characteristics of as large a sampling of the population of bias ply tires used at the present time as possible (within the limits imposed by time and available facilities) in order to provide a defensible experimental basis for a grading system for this property. The second purpose was an attempt to answer the question raised earlier--whether, recognizing that tires wear at different rates under different conditions, they would still rank in the same or comparable order, i.e., whether the tires having the lowest tread wear rates under one set of external or environmental conditions would be the tires having the lowest tread wear rates under a different set of external conditions.

It was in order to achieve the first purpose that the large sampling was selected. The number of sizes and designations of bias ply tires used in this country is so large that even a large sampling can constitute only a small percentage of the total population. Nevertheless every attempt was made to choose as representative a sampling as possible.

For any particular test three commonly used sizes were selected; 6.50-13, 7.75-14, and 8.45-15. Each size consisted of 32 tires or 16 pairs (a "pair" consisting of two tires from the same manufacturer and designation). Thus 96 tires (48 pairs) were used in any one test. In order to attain as wide a sampling as possible, the tires in the three sizes were usually not from the same manufacturer and designation. Tires from smaller as well as larger manufacturers were included. A range of "quality" tires according to manufacturers' classification and list price were included (Premium; 110 level; original equipment, or 100 level; 90 and 80 level). To run 96 tires at one time would require 24 cars which would make for an unwieldly and perhaps illegally long convoy. Therefore, the number of cars used was halved (12 cars--4 cars for each of the three sizes). The tires were divided into 4 groups, A, B, C, and D. For each test period, 2 of these 4 groups were run while the other 2 groups remained idle. Each of the combinations AB, CD, AC, and BD were run for the same number of periods, but the order of the periods and the allocation of tires to groups were randomized. Such a chain block design is an established statistical procedure for compensating for the fact that all the tires do not run during the same measuring period. Each tire ran 8000 miles during the test after a 100 mile break-in, and each car ran 16,000 miles. All tires ran in "matched pairs" (i.e., tires of one designation from one manufacturer ran on opposite sides of the same axle). Although the order of tire rotations (as well as the storage periods) was randomized, yet the schedule was so arranged that at the end of the test each tire had been on every wheel position of each car for its size once and only once. The usual speed was 70 mph and the load on each tire was 100 percent of the T&RA rating for 24 psi, the inflation pressure used. (See comments in Section 2, page 3.)

If any tire failed or wore out during the test, the matched pair was replaced by a nominally identical matched pair which had already been broken-in in the same way as the tires replaced in order for the subsequent statistical analysis of the data to remain valid.

One pair of "standard" SAE traction tires was included among the largest and smallest size tires, and two pairs of these standard tires were included in the intermediate size, to determine the feasibility of using such a standard tire as a basis for comparison in grading tires.

In order to fulfill the second purpose of these tests, the pattern of tire rotations with "identical" tires (same manufacturer designation and size) was repeated on three different road surfaces. The first was a "low wear," relatively flat asphalt road, the second was a concrete road, and the third a "high wear," or mountainous road--having more and sharper turns--the pavement being approximately of the same composition as the low wear road. Thus the entire test consisted of 96x3 = 288 tires, each tire traveling 8000 miles and a total of 576,000 vehicle miles, not including break-in. (It is seen that even a short term 8000 mile test can become quite lengthy if enough tires are included!)

All tests were conducted on public roads in Texas, the low and high wear tests were conducted by Southwest Research Institute, San Antonio; and the concrete test by Automotive Research Associates, San Antonio.

7. Results and Discussion

One of the first observations of the tread wear data from the three tests was that the differences between most of the matched pairs in any one test was so small in comparison with the overall variation of all the tires in that test, that the average GP of the pair could be taken as representative of that particular designation of tire. Consequently, in the data to be shown each unit represents a pair (48 for each of the three tests and 16 of each of the three sizes comprising the 48).

In table 1 we show the ranges in GP for the three sizes used in each of the three tests.

The GPs for the low wear course were distinctly higher (by a factor from about 3 to 4) than for the high wear course; and the GPs for the low wear course were somewhat higher (by about 7 to 25 percent) than for the concrete course. Also the three ranges of GP values for the high wear course are lower than for the other two. However, this is only so on an absolute basis. On a relative basis--dividing the range by the median value for that range--the relative ranges for all three courses are of the same order of magnitude.

Table 1. Ranges of geometric projections in miles for bias ply tires* in three tread wear tests

Test	Size		
	6.50-13	7.75-14	8.45-15
Low Wear	19,300 - 62,950**	21,800 - 54,000	26,650 - 48,300
Concrete	17,850 - 42,100	17,350 - 47,350	24,500 - 51,200
High Wear	7,200 - 19,250	5,300 - 14,350	5,180 - 12,700

*Total number of tires, 288 or 144 pairs; number of tires in each test, 96 or 48 pairs; number of tires of each size in each test, 32 or 16 pairs.

**This value is anomalous. The next highest value in the group was 49,850.

We now come to the critical question of the degree of rank correlation, ρ, between similar tires on the three different courses. The rank correlation is obtained from

$$\rho = 1 - \frac{6\Sigma d^2}{n^3-n}$$

where d is the difference in rank between 2 pairs of similar tires and n is the number of specimens involved (16 in this case). For this purpose we have compared the tires not only on the basis of GP, but also on the basis of AA, the arithmetic average of the tread wear rates; GA, the geometric average; and AP, the arithmetic projection computed in the same way as GP, except AA is divided into the initial tread depth rather than GA (used to obtain GP). The results are shown in table 2.

Table 2. Rank correlation of all pairs of tires in 3 tests based on Arithmetic Average (AA), Geometric Average (GA), Arithmetic Projection (AP)* and Geometric Projection (GP)*

	Comparison	Rank Correlation, ρ 6.50-13	7.75-14	8.45-15	Avg ρ	Overall Avg ρ
AA	Low Wear/High Wear	.76	.66	.11	.51	
	Low Wear/Concrete	.64	.88	.52	.68	.51
	High Wear/Concrete	.48	.56	0	.35	
	Avg ρ	.63	.70	.21		
GA	Low Wear/High Wear	.88	.57	.26	.57	
	Low Wear/Concrete	.72	.86	.47	.68	.56
	High Wear/Concrete	.69	.57	0	.42	
	Avg ρ	.76	.67	.24		
AP	Low Wear/High Wear	.88	.72	.34	.65	
	Low Wear/Concrete	.77	.89	.70	.79	.62
	High Wear/Concrete	.56	.52	.22	.43	
	Avg ρ	.74	.71	.42		
GP	Low Wear/High Wear	.90	.70	.45	.68	
	Low Wear/Concrete	.75	.87	.73	.78	.65
	High Wear/Concrete	.64	.51	.29	.48	
	Avg ρ	.76	.69	.49		

*AP = $\frac{D_o}{AA}$; GP = $\frac{D_o}{GA}$; where D_o is the initial overall average tread depth

We see from the overall averages of the ρ's for the same tests, but based on various methods of rating the tires for tread wear, that the GP gives the best correlation; the order being GP>AP>GA>AA. This gives weight to the argument for using GP as the best indicator of tread wear rating for comparing tires. It is also seen that the best correlations are obtained with the smallest size tire and the worst correlation is with the largest size tire. However, even under the best conditions for ranking (using GP) the overall average of the correlations between similar pairs of tires in the three sets of comparisons (high wear vs. low wear, high wear vs. concrete, low wear vs. concrete) is not high enough to permit a reasonably accurate prediction of how a tire would rank in one test as a result of its ranking in another test.

Two possible reasons or a combination of them suggest themselves for not having a higher overall average value of ρ. The first is that the interaction between external and internal conditions mentioned earlier exists, so that tires will not rank in the same order (or at least better correlated order than has been found) under different external conditions. If this is true, then a possible method for arriving at a reasonable tread wear rating is to have the tires run over roads having different characteristics in a single test. These roads could combine the characteristics of the three courses used here. Thus the integrated effect of these roads would affect the tires in a similar manner and no tire would be unduly punished for having somewhat poorer tread wear rates on a given type of road and no tire would benefit unfairly from having a superior (lower) tread wear rate on another surface.

A reasonable suggestion would be to build a track of about 5 or 10 miles composed of different kinds of typical road surfaces. This track should also have right and left turns and "straights" so that the tires would have to run at a variety of speeds which (as previously indicated) is a more realistic situation, than a constant 70 mph. On such a track, indeed, tires could run for stretches at speeds higher than 70 mph which again approximates more nearly normal use. Also such a track would not interfere with the normal flow of traffic and would permit greater freedom for varying and improving experimental procedures as more knowledge is gained in the course of tread wear testing and as technology in tires improves.

The other possible reason for the correlations not being higher is that the tires themselves (of the same nominal kind) are not so uniform that a higher correlation between these tires in different tests should be expected. This possibility does not at first seem very likely in view of the agreement between the pairs of tires of the same type which, it is recalled, was close enough to permit the average GP of both tires to be used as representative of that type (or designation). However, it is very possible that the standard experimental procedure of always running these two similar tires as a matched pair, predisposes the experimental conditions in such a way that these tires seem more nearly alike than had they been rotated on an individual basis. It was first thought to check this possibility by repeating any one portion of these tests on the same road (using, for instance, only the 8.45-15 size which gave the lowest values of ρ) and then to see whether the "pairs" in the second test agreed both in rank and in GP with the corresponding pairs of the first test. This procedure seemed reasonable at first but was rejected because if the external weather conditions were different between the first and second tests and if the interaction between external and internal parameters held, then, even if all other experimental conditions during the second test were identical with the first, lack of agreement in corresponding pairs in both tests would not resolve the question of whether the variability of the tires or variability in external conditions was responsible for possible lack of uniformity of the ranking of the tires.

We propose, then, to adopt the following procedure to check the variability of tires with respect to tread wear. The specimens will consist of 16 tires divided into 4 nominally identical sets. These sets may be from the same or different manufacturers. The 16 tires will be run in an 8000 mile test with 500 mile measuring periods, or 16 measuring periods. The conditions of the test will follow the same pattern as previously described but with this additional condition: The four similar tires (or sets) will be divided into two matched pairs (as usual) but each pair will be treated separately and randomized in the order of tire rotations with no relation to the other pair of the same set or to other sets. Thus, although we know from previous data that the two tires of the same pair will agree with each other, we expect to determine the variability within each set, in comparison with the variability from set to set or the intrinsic error in the test itself.

In figure 3 the GPs of all the tires on all three courses are compared according to the manufacturer's designation of quality. The letter A represents a premium tire; B, a 110 level tire; C, a 100 level or original equipment tire; D, a 90 level; and E, an 80 level tire. The list prices of these tires are in the same order for any one manufacturer, A being the highest in price and E the lowest. S represents the standard SAE tire. The abcissas of the figures give the quality designations of the tires, and the ordinates give the GPs on a logarithmic scale. The logarithmic scale is chosen in order that the spread in values about the average for each group should be on an equivalent relative basis. This spread about the averages indicated in the figures by the lines above and below the average value is the 50 percent tolerance interval. This interval, which is estimated to include approximately 50 percent of the population of tires in that group, is often used in analysis of this type. Since the averages are taken for the logarithms of the GPs, they are actually the geometric average of the GPs themselves.

A major inference to be drawn from an inspection of the figures is that the spread in GP for any group (where a measure of this spread is given) is such that clear distinctions between the different categories

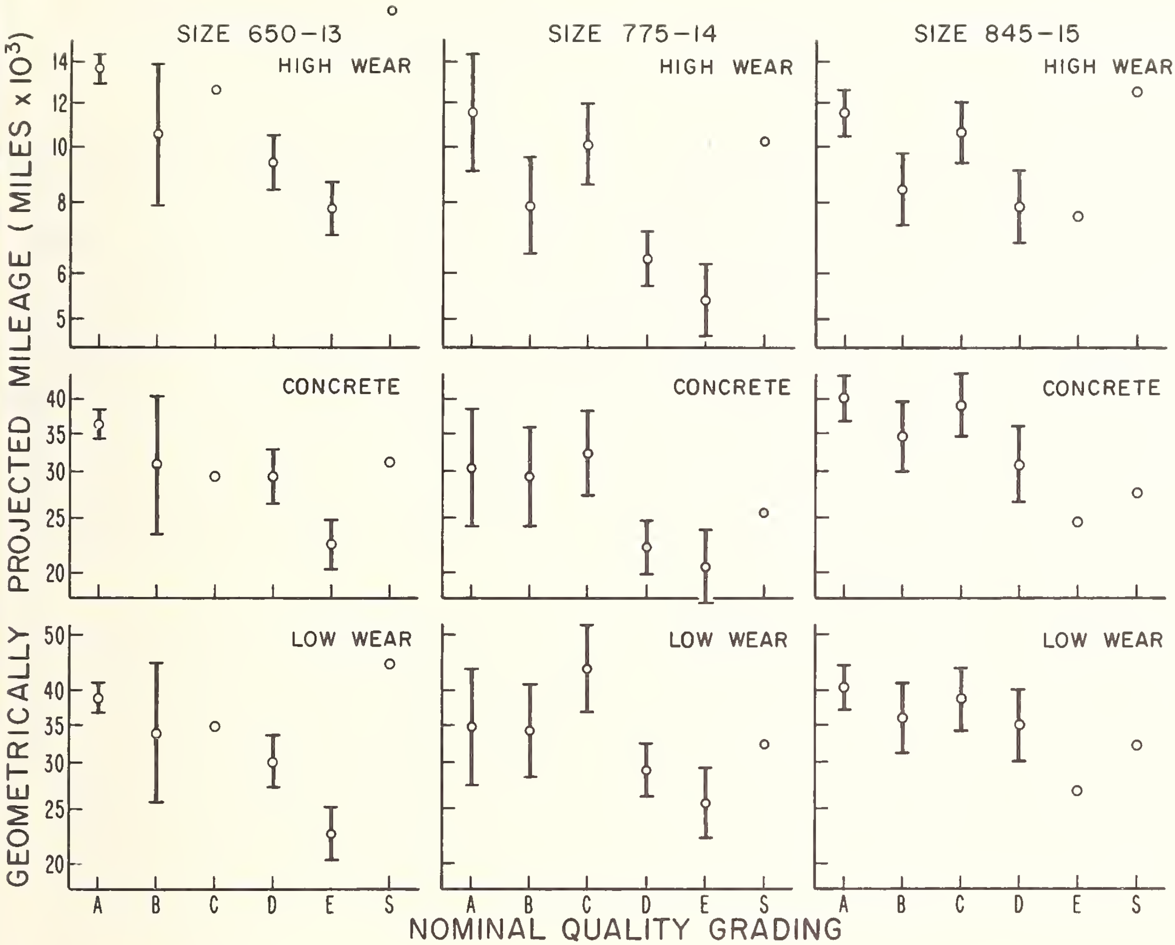

Figure 3. Geometric projection in miles for various nominal quality gradings. Line segments represent approximate 50 percent tolerance intervals. A, B, C, D, E, and S represent premium, 110 level, 100 level or OE, 90 level, 80 level, and standard SAE tires, respectively.

can be made only in a few cases. For instance, the tires designated as A, B, and C show considerable overlap in their 50 percent tolerance intervals so that no distinctions of practical consequence can generally be made between these categories. The tires rated E do appear to be lowest in GP while tires classified as D appear generally to occupy an intermediate position between the A, B, and C tires on the one hand and the E tires on the other.

From this it would appear that if one purchases the more expensive types of tires (A, B, or C), the mileage will not necessarily be in proportion to the price; however, if one purchases one of the less expensive types he will probably get somewhat poorer mileage. This is not unexpected since (as indicated earlier) long mileage is not the only criterion considered in purchasing. Other features of higher priced tires may be lower noise levels or esthetic factors such as white sidewalls.

The fairly large dispersions about the average values for the various groups (with attendant uncertainty in determining significant differences between groups) are also to be expected if one recalls that in order to obtain as large a sampling of the tire population as possible, the number as well as the names of manufacturers in the various quality groups in the three sizes was not the same, and in a number of quality categories many manufacturers could not be included. In those cases (in addition to the S tires) where no indication of dispersion is given, not enough specimens were available to provide such a measure. It is also recognized that at the present time, no clear cut, industry wide accepted standards exist for making such quality distinctions in tires. A statement to this effect will often be found in tire advertisements. Indeed, it is the purpose of a Uniform Quality Grading System, mentioned at the beginning of this report, to provide such standards.

A significant piece of information to be gained from the figures is that the ranking of the standard SAE tire is so different in the three tests in the three sizes. In the high wear test it ranks highest (over the average of the other grades) but ranks lower with increasing size in the low wear and concrete tests. This indicates quite clearly that the tread wear characteristics of the SAE tires are significantly different from conventional ones and, therefore, it would not be feasible to use the SAE tire as a standard of comparison for tread wear. (This is no reflection on the SAE tire, which was designed as a standard for skid and traction measurements.)

8. Tread Wear Test with Radial Ply Tires

The total mileage of test was 19,400 miles per tire, consisting of 19,200 miles of test + 200 miles of break-in; 6 cars, 24 tires consisting of 8 pairs of radials and 4 pairs of bias plies (a "pair" consisting of 2 nominally identical tires); 24 measuring periods of 800 miles each. The bias plies were all 7.75-14 in size and the radials were the equivalent size, 195R14. The size selected was such that all the different types of radials could be included. The test tires are listed in the left-hand column of table 3. One pair of SAE standard tires was included among the bias plies. The other conditions of the test, speed, load, and inflation pressure, were the same as in the previously described bias ply tests.

The 8 radials and 4 bias plies were run in matched pairs as before, but in accordance with manufacturer's recommendations, the cars were always run with 4 radials and 4 bias plies on the same car at all times (no mixing of radials and bias plies on the same car). Yet in accordance with previous practice, the schedule of tire changes was so arranged that at the conclusion of the test each tire had been on each wheel position of each car once (and only once). As previously, tires failing to complete the test were replaced with duplicates of the same nominal type. The tests were carried out by Uniroyal, Inc., at their Laredo, Texas, facility. As with bias ply tests, however, the schedule of tire rotations and procedure for obtaining and processing the data was planned and directed by this Office.

9. Results of Tread Wear Tests with Radial and Bias Ply Tires

Inasmuch as all the bias plies and three of the radials failed to complete the test, it is convenient in this case to present the results of these tests in terms of percentage worn at completion and the corresponding mileage. This is given in table 3.

Table 3. Mileage run by tires in Laredo test

	Tire	Miles*	Percent Worn
Radial	P2F1	19,400	30.1
	P2F2		30.1
	F2F1	19,400	37.8
	F2F2		37.9
	C2F1	19,400	50.6
	C2F2		50.6
	A2F1	19,400	51.4
	A2F2		56.6
	B2F1	19,400	60.9
	B2F2		49.3
	K2F3	16,200	45.6
	K2F4		45.3
	D2F3	16,200	51.1
	D2F4		52.2
	O2F1	11,400	45.3
	O2F2		46.9
Bias Ply	B2G1	17,800	71.9
	B2G2		71.8
	S2-21	17,800	83.7
	S2-22		84.3
	A2G1	12,200	83.0
	A2G2		75.0
	R2E1	9,400	90.0
	R2E2		95.0

*Test was 19,400 miles. Tires with lower mileage had to be removed before completion of the test.

The following observations concerning the results presented in the table are worthy of note.

1. As in the previous tests, all of the matched pairs performed so nearly alike that the average of the two could be taken as representative of that type. Thus, P2F1 and P2F2 (in which the final number distinguishes the two specimens of the same type of tire) could be treated as "P2F"--a given make and type of tire with no significant difference between the two specimens comprising this type. The only exception to this is B2F1 and B2F2 in which the percentage worn at the completion of the test differed by about 10 percent.

2. Three of the eight pairs of radials did not complete the test even though they were only about 50 percent worn at the time of removal. This points up even more sharply than for the bias plies, that tires are removed as worn when any portion reaches smoothness. For the radials, the shoulders and outside grooves were worn to such a degree that the cords of the belt were almost exposed. Thus even though the wear as indicated by overall average tread depth was still low, these radials had to be replaced. It is very possible that had these tires run on cars having suspensions better matched to their characteristics, or had higher inflation pressures been used, their obvious potential for longer tread wear mileage would have been better realized.

3. Conversely, it is noted that because all of the bias plies wore to a greater extent as indicated by the percentage worn than the radials at the time of removal, some of them (bias plies) wore to longer mileage before removal than some of the radials. Thus the more even, even though more rapid overall rate of tread wear of the bias plies worked to their advantage. However, it is also noted that five of the radials completed the test whereas none of the bias plies did.

4. It is also interesting to note that the tire removed earliest (the cheapest tire in the lot), R2E at 9,400 miles, had the most even rate of tread wear being worn to 90-95 percent before removal.

5. The standard SAE tire was the only one from the previous tests included in these Laredo tests. The GP for these tires from the previous tests was 32,250 miles for the low wear, 24,600 miles for the concrete, and 10,200 miles for the high wear test. (The road conditions for the Laredo test were probably more severe than the low wear on concrete roads used in the bias ply tests.) However even without this condition, the difference between the GP for this type of tire in the previous tests and the actual mileage when replaced at Laredo (17,500 miles) is not surprising for the reasons previously given. It is interesting to note, however, that had bias ply tires with the highest GP ratings from the tests described previously been used in the Laredo test, that even with the low rank correlations given in table 2, these bias plies would probably have been able to complete the test as did five of the radials.

10. Recommendations

The following recommendations are made in order to achieve greater uniformity and a statistically valid approach to tread wear testing.

1. Tread depths to be given for each groove measured in mils. The average for each groove measured to be based on at least six measurements equally spaced around the circumference of the tire in regions other than the wear bar indicators. Successive readings after each period of tire rotations to be taken at the same places in each groove measured.

2. Average of each groove measured and overall average to be given to four significant figures (tenths of mils). Also the individual values of depth for each groove upon which these averages are based should be available so that an estimate can be formed of the spread of these individual values about the average.

3. Rates of tread wear for each groove measured and for the overall average of all the grooves to be given in mils per 1000 miles, to one decimal place.

4. Tires (ordinarily) to be run in matched pairs. Schedule of tire rotations from wheel to wheel and car to car should be such that on completion of the test, each tire will have been on each wheel position of each car the same number of times. This is of fundamental importance in arriving at a statistically valid analysis of the data.

It is recommended that once a statistical pattern has been prepared, randomization within this pattern be carried out to avoid any possible systematic bias.

5. Measurements of tread depth to be made at the start and between each period of tire rotations. Thus "number of tire rotations" and "number of measuring periods" will be the same. The actual number of averages of tread depth measurements, then, will be one more than the number of measuring periods. Also, all measuring periods should be for the same number of miles.

6. An appropriate break-in of at least 500 miles for each tire is recommended. Tread depth measurements to be made before and after break-in and the tread wear rate for the break-in period to be computed in the same manner as for the measuring periods in the tread wear test proper. The average tread depth after break-in for each groove measured and for the "overall average" to serve as the starting value of tread depth, in subsequent calculations.

7. Tread wear rate of tires for entire test to be computed from the geometric average of the tread wear rates for all the measuring periods.

8. Tire to be compared with each other on the basis of the "geometric projection" computed from the equation,

$$GP = \frac{D_o}{GA},$$

where GP is the geometric projection in miles; D_o is the initial overall average tread depth in mils after break-in (assuming that the initial portion of the wear curve is comparable for all tires under test); GA is the geometric average of the tread wear rates for all the measuring periods of a tire.

$$GA = \sqrt[n]{r_1 r_2 \cdot \cdots \cdot r_n}$$

where n is the number of measuring periods and $r = \frac{\Delta D}{m} \times 1000$, where r is the tread wear rate for any measuring period in mils per 1000 miles, ΔD is the difference between successive values of the average tread depth for any measuring period of m miles.

9. Any tire requiring removal before the completion of the test, either as worn smooth (as defined below) or for any other reason, should be replaced along with its mate by a nominally identical pair.

10. A tire shall be considered to be worn smooth when any portion of the tread reaches smoothness or reaches the level of the wear bar indicators. Also, if a region of the tread outside the end grooves (near the shoulders), attains a degree of wear such that the cords beneath the rubber are near exposure, then the tire should also be removed as smooth even if the shoulder grooves are still at a safe level.

11. The present practice of making measurements of various changes that take place as the tire wears down should be retained. These include changes in o.d., in cross-section, shoulder drop tread, hardness, and hot inflation pressure. While such measurements are not necessarily directly related to tread wear, they do provide valuable information on important changes in tires during wear.

11. References

[1] John Mandel, Mary N. Steel, and Robert D. Stiehler, "Tread wear of tires influence of type of rubber and black," Ind. & Engr. Chem. 43, 2901 (1951).

[2] R. D. Stiehler, M. N. Steel, and J. Mandel, "Factors influencing the road wear of tyres," Trans. Inst. Rubber Industry 27, 298 (1951).

[3] R. D. Stiehler, R. G. Richey, and J. Mandel, "Measurement of tread wear of commercial tires," Rubber Age 73 (No. 2), (1953).

[4] J. Mandel and R. D. Stiehler, "Statistics--a tool in testing rubber," ASTM Bul. No. 204, 44 (1955).

[5] A similar distinction was made by DeVinney in his paper, "Factors affecting tire traction," SAE Paper 670461, presented at the SAE Mid-Year Meeting, Chicago, Ill., May 15-19, 1967.

[6] John Mandel, "Fitting a straight line to obtain types of cumulative data," J. Am. Statistical Assoc. 52, 552-566 (1952).

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