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Effect of Testing Conditions on Rolling Resistance of Automobile Tires

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The effects of some test condition variables on tire rolling resistance results are presented and discussed from the viewpoint of establishing good testing practice. A designed experiment study was made on simultaneous effects of changes in load, speed, and inflation pressure on a radial and bias tire. All main and interaction effects were significant except for speed-load interaction on the radial tire and load-load interaction (curvature effect) on each tire. Quantitative effects of unit changes in each variable at any level of the other variables showed that load control is the most critical. Rolling resistance was shown to be significantly higher on a Safety Walk test wheel surface than on bare steel. No significant difference in scatter of results was found, however. Rolling resistance of a set of light truck tires was esentially the same on worn as on new Safety Walk. Results on sets of replicate tires suggested that four tires in each set are enough to characterize the set. A warm-up time of 20-25 minutes was shown to be sufficient to develop equilibrium air pressure. Data are presented to show how a safe upper limit to the test speed for a given tire can be determined, and how a safe service speed could be estimated without requiring that the tire be run to failure.

Background

The SAE Subcommittee on Rolling Resistance of Tires has developed Standards SAE J1269 and J1270 for automobile tires and J1379 and J1380 for truck and bus tires. A current review of J1269 has stimulated several investigations into the relevance, adequacy, and proper limits for the specified controls on testing conditions. Since so many variables are involved, many of which are interactive, we have used statistical approaches wherever possible in the present study.

Scope

The principal variables are load, speed, and inflation pressure, which are interactive in tests at thermal equilibrium. We have used a designed experiment to demonstrate the main effects, curvature, and interaction of these variables over a range of factor levels for each. Calculated coefficients in a response equation are used to characterize tires for sensitivity to these variables.

How much refinement in test control is justifiable in view of the variability in nominally replicate tires? We again took the statistical approach by comparing the standard deviation on a group of replicate tires with that on repeat testing of a single tire.

The SAE has favored testing on a wheel covered by Safety Walk. The International Organization for Standardization (ISO) favors a bare steel surface. We have investigated

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the levels and repeatability of rolling resistance values on each surface. The relative values on new and worn Safety Walk were determined in a separate test.

What speed range should be covered in routine tests? Plots of rolling resistance as a function of speed are nonlinear below about 5 MPH (8 km/h) and above the speed at which traction waves dominate the force. The upper limit is also critical for safety of personnel and apparatus. The limit is illustrated by test results on tires having high speed ratings.

The running time used to warm up is a good candidate for study as a means for reducing the total time required for rolling resistance tests. We have measured the time required to reach equilibrium for automobile tires running under regulated pressure and under capped pressure.

Apparatus and Normal Practice

Standards Testing Laboratories measures rolling resistance by a spindle force method on a 67.277-in. (170.8 cm) diameter test wheel. This apparatus, which is shown in Fig. 1, is designed to test tires for automobiles and light trucks. The apparatus and operating procedure conform to SAE J1269 and have been shown by interlaboratory tests to give results which are near the median of all the participating laboratories. Safety Walk coating is normally used on the test wheel.

The average force required to run a tire forward and reverse on the test wheel is used as its rolling resistance value. This eliminates cross-talk in the load cell as well as those machine and rim effects that are directional.

Results are not normalized to those that would be expected on flat surface operation. No corrections are made for ambient temperature changes since the test room is kept within the specified tolerances for temperature. The actual load on the tire is recorded at the time a reading is taken, both to confirm that it is within tolerance and so that the true values could be used for calculations such as that for rolling resistance coefficient.

Skim tests are not used to evaluate bearing friction because results are too dependent on the contract force between tire and test wheel. Furthermore, such tests determine only the unloaded bearing friction, which may have an undetermined relation to the loaded friction. A better practice is to minimize this input by bearing selection, alignment, and proper lubrication.

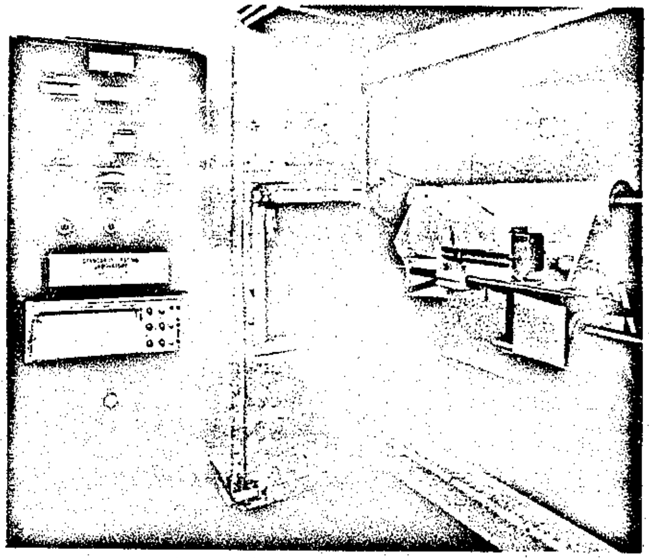

FIG. 1 — SPINDLE FORCE APPARATUS FOR MEASURING ROLLING RESISTANCE

EFFECT OF INFLATION PRESSURE, SPEED & LOAD

The pertinent test conditions that can be controlled at any desired level within normal operating ranges of tires are inflation pressure, speed and load. Each of these factors has a non-linear effect on rolling resistance and the effect of an incremental change in one may depend upon the level of each of the other two, which means that there are interaction effects. Furthermore, the quantitative effects assignable to each factor are usually not the same for one type of tire as for another. An equation can be obtained for a particular tire, however, in which the coefficient of each factor level represents the effect of that factor on the rolling resistance. Separate terms within such a mathematical model give main effects, curvature effects, and interaction effects. Schuring (1) in his summary of the literature on effect of operational variables points out the need for such a study of interaction effects by use of designed experiments.

Test Design

The test design chosen was one described by Claxton and Conant (2); a three-factor, three-level factorial (0:3-27) that is a patched orthogonal pattern of zero qualitative factors and requires 27 tests (trials) to complete. The ten a-coefficients in the following second-order response equation were calculated.

$$Y = a_o + a_1x_1 + a_2x_2 + a_3x_3 + a_{11}x_1x_1^2 + a_{22}x_2^2 + a_{33}x_3^2 + a_{12}x_1x_2 + a_{13}x_1x_3 + a_{23}x_2x_3$$

Where Y is the rolling resistance at any chosen combination of factor levels x_1, x_2, and x_3

x_1 is the inflation pressure in experimental units (e.u.)
x_2 is the speed in e.u.
x_3 is the load in e.u.
a_o is the rolling resistance at the center of the design where $x_1=x_2=x_3=0$
a_1, a_2, and a_3 are the main effects of pressure, speed, and load respectively
a_{11}, a_{22}, and a_{33} are the curvature effects of pressure, speed and load respectively
a_{12}, a_{13}, and a_{23} are the interaction effects of pressure-speed, pressure-load, and speed-load, respectively

Factor Level Assignments

Ranges for the factor levels were chosen so that any combination which could occur in service such as that of the highest load with the lowest pressure were considered. These considerations led to the assignment of experi--mental units shown in Table 1.

TABLE 1 — Factor Level Assignments

x_1 pressure			x_2 speed			x_3 load		
e.u.	psi	kPa	e.u.	mph	km/h	e.u.	lbf	kN
-1	30	207	-1	20	32	-1	895	3.98
0	35	241	0	40	64	0	1087	4.83
+1	40	276	+1	60	97	+1	1279	5.69

The loads represent 70%, 85% and 100%, respectively, of rated load as given in the 1983 Tire and Rim Association Manual for the P195/75R14 and P195/75D14, tires tested, so each e.u. represents 15% of the rated load, or 192 lbf (0.85kN).

The design table used for data analysis is shown in Table 2 where factor levels are given in experimental units. Rolling resistance values found for each combination of factor levels are also shown.

TABLE 2 — Design Table and Rolling Resistance Data

Trial No.	Press[1]	Speed	Load		Rolling Resistance, y_i: Radial lbf	Radial N	Bias lbf	Bias N
1	-1	-1	-1		9.47	42.1	12.87	57.2
2	0	-1	-1		8.72	38.8	11.71	52.1
3	1	-1	-1		8.18	36.4	10.89	48.4
4	-1	0	-1		10.41	46.3	14.11	62.8
5	0	0	-1		9.40	41.8	12.60	56.0
6	1	0	-1		8.79	39.1	11.57	51.5
7	-1	1	-1		11.29	50.2	15.41	68.5
8	0	1	-1		10.28	45.7	13.76	61.2
9	1	1	-1		9.60	42.7	12.67	56.4
10	-1	-1	0		11.97	53.2	16.57	73.7
11	0	-1	0		10.82	48.1	14.86	66.1
12	1	-1	0		9.94	44.2	13.42	59.7
13	-1	0	0		12.58	56.0	17.53	78.0
14	0	0	0		11.56	51.4	15.82	70.4
15	1	0	0		10.75	47.8	14.11	62.8
16	-1	1	0		13.93	62.0	19.38	86.2
17	0	1	0		12.65	56.3	17.48	77.7
18	1	1	0		11.77	52.4	16.02	71.3
19	-1	-1	1		14.13	62.9	19.72	87.7
20	0	-1	1		12.85	57.2	17.87	79.5
21	1	-1	1		11.97	53.2	16.5	73.4
22	-1	0	1		15.28	68.0	21.5	95.6
23	0	0	1		13.73	61.1	19.31	85.9
24	1	0	1		12.58	56.0	17.40	77.4
25	-1	1	1		16.43	73.1	23.56	104.8
26	0	1	1		14.68	65.3	20.75	92.3
27	1	1	1		13.53	60.2	18.97	84.4
				$\bar{y}$	11.75	52.3	16.16	71.9

[1] Regulated Pressure

Test Procedure

Two tires were run through each of the 27 trials, a P195/75R14 radial, shown in Fig. 2 and a P195/75D14 bias ply shown in Fig. 3. The face of the test wheel was covered with a #80 medium grit 3M Safety Walk. Ambient temperature was 75 $\pm$ 5°F (24 $\pm$ 3°C) throughout the experiment, which was completed in a single test session. After an initial 20 minute warm-up and break-in under the most severe conditions (trial 25), the other tests were made in the general order of decreasing severity. Rolling resistance for each trial was recorded when it had stabilized. Pressure was regulated to the designated value by means of a rotary union.

FIG. 2 — RADIAL TIRE

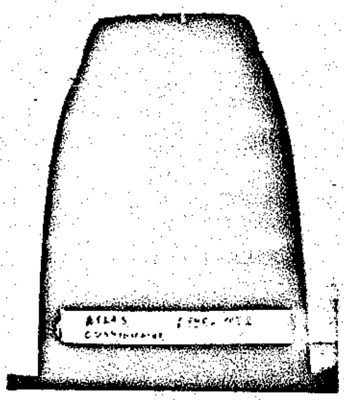

FIG. 3 — BIAS PLY TIRE

Results

Table 3 shows the calculated a-coefficients for the response equation. Since only 10 coefficients were determined from 27 trials, there were 17 degrees of freedom. This is enough for a good estimation of the degree of confidence in the significance of each coefficient. Only a_{23} for the radial tire did not have a significant effect on the calculated response, at a greater than 99% confidence level. The value of Y_i was calculated for each trial in determining the significance, as was the amount by which it differed from the corresponding measured value of Y_i. The standard deviation of these differences was only 0.092 lbf (0.409N) for the radial tire and 0.131 lbf (0.584N) for the bias tire. The low values of these indices demonstrate the repeatability of the test as well as the sufficiency of the quadratic model on which the response equation is based.

TABLE 3 — a-Coefficients

Coeff.	Radial		Bias		
	lbf	N	lbf	N	
a_0	11.486	51.09	15.818	70.36	Value at design center ($x_1 = x_2 = x_3 = 0$)
a_1	-1.021	-4.54	-1.617	-7.19	Main effect for pressure
a_2	0.896	3.99	1.309	5.82	Main effect for speed
a_3	2.169	9.67	3.332	14.82	Main effect for load
a_{11}	0.178	0.79	0.217	0.97	Curvature for pressure
a_{22}	0.249	1.11	0.251	1.117	Curvature for speed
a_{33}	-0.036*	-0.016*	0.046*	0.20*	Curvature for load
a_{12}	-0.106	-0.47	0.195	-0.87	Interaction: press.-speed
a_{13}	-0.263	-1.17	-0.388	-1.73	Interaction: press.-load
a_{23}	0.074*	0.33*	0.235	1.05	Interaction: speed-load

*Not significant at 99% confidence level. All others were significant.

The principal value of data such as those in Table 3, is the quantitative relative importance of the various influences on rolling resistance for these two tires. A load change of one experimental unit (192 lbf) for example, had more than twice the effect of either pressure or speed change of one experimental unit (5 psi, 20 mph). The negative value for a_1 shows how much the main effect of pressure acted to decrease rolling resistance as pressure was increased by one experimental unit.

The increase in Y per unit increase in e.u. is greater at high than at low factor levels for both pressure and speed as shown by positive values for a_{11} and a_{22}. The low significance for a_{33} means that Y increases very nearly linearly with increase in load.

Negative values for a_{12} and a_{13} show that the effect of higher speeds or loads decreases as the pressure is increased and that the effect of an increase in pressure is less at high than at low loads or speeds. Since a_{23} is positive, the effect of speed change is greater at high than at low load, and the effect of load change is greater at high than at low speed, at least for the bias tire.

The values given in Table 3 can be used to plot the effect of pressure, speed or load at constant values of the other two factors. Fig. 4 and 5, for the radial and bias tire respectively, show rolling resistance as a function of speed at three of the pressure-load combinations used in the experiment. Plots of rolling resistance as a function of load at assigned values of pressure and speed or of pressure at assigned values of load and speed could also be made. Values of Y at factor levels not included in the experiment can be obtained from such plots by interpolation or extrapolation. The figures show extrapolation of half an e.u. at each end of the experimental range, but care is needed so that this does not extend into factor levels that would produce aberrant responses. Speeds below about 5 mph (8 km/h) or above the onset of wave formation, for example, should not be included. Pressure, speed and load are controllable variables in laboratory testing for tire rolling resistance. Their resultant effect on the tire temperature is the actual operating variable. Tire temperature is also affected by ambient temperature (3,4) and other conditions such as road surface and tire shear in cornering, traction, or braking (5).

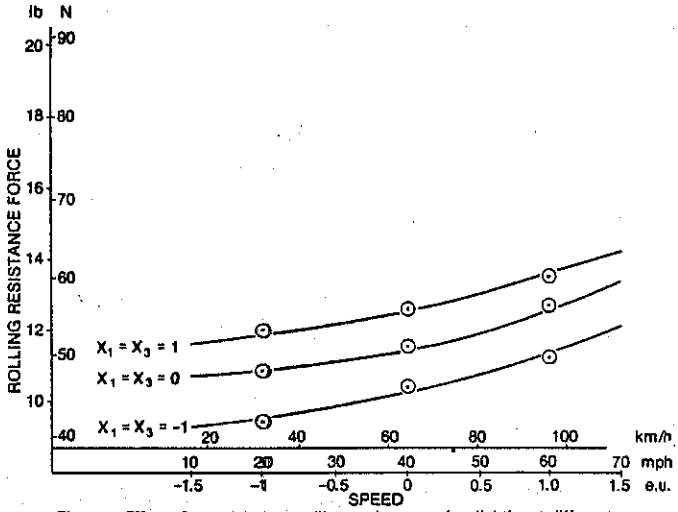

Fig. 4 — Effect of speed (x_2) on rolling resistance of radial tire at different pressure-load combinations. Lines are calculated from response equation; circles are measured values.

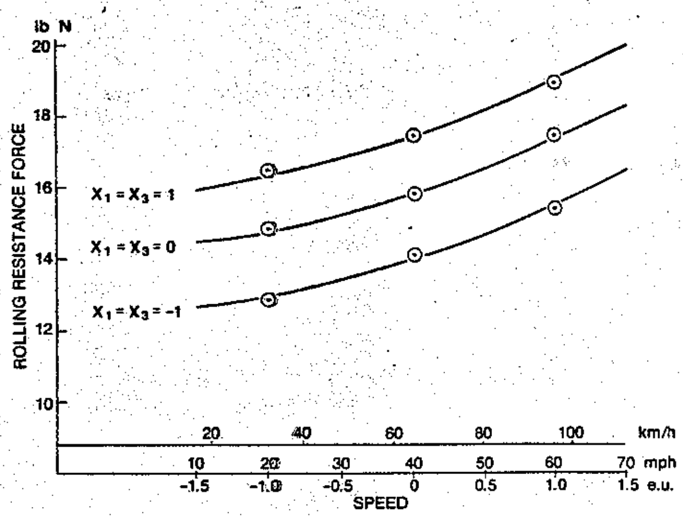

FIG. 5 — Effect of speed (x_2) on rolling resistance of bias ply tire at different pressure-load combinations. Lines are calculated from response equation; circles are measured values.

RESULTS ON REPLICATE TIRES

A recent study that STL made for the Dunlop Corporation involved four sets of P195/75R14 tires. Each set contained four nominally replicate tires. Rolling resistance was measured at each of four speeds on a bare steel test wheel. This surface is shown in Fig. 6. The test was repeated at each of the three lower speeds on the same wheel when covered with Safety Walk. This surface is shown in Fig. 7.

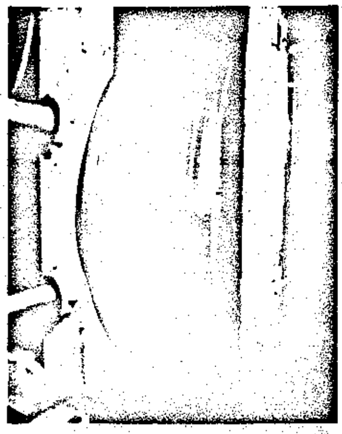

FIG. 6 — TEST WHEEL WITH BARE STEEL SURFACE

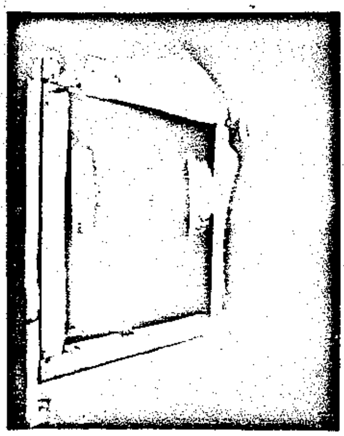

FIG. 7 — TEST WHEEL WITH SAFETY WALK SURFACE

The load was always 1190 lb. (540 kg), and the contained air pressure was regulated to 26.1 psi (180 kPa) at the time the rolling resistance was read. Each tire was first warmed up at 50 mph (80 km/h) for one hour and the rolling resistance recorded after it had stabilized. The same procedure was then followed at other speeds except that the time required for stabilization was 15 minutes or less. All tests were made within a three week period.

Analyses of the data included:

1. The scatter of results that is attributable to a combination of tire differences and test repeatability.
2. Significance of differences among different sets of tires at different test speeds and on different surfaces.

The means and standard deviations of rolling resistance are summarized in Table 4. Several conclusions relative to the effect of testing conditions can be drawn from these indices.

1. Rolling resistance forces were consistently higher on Safety Walk than on bare steel. The t-test shows this to be true at greater than 95% confidence level for all groups and speeds. Fig. 8 is a graphic comparison of surface effect.

2. Rolling resistance forces were consistently higher at higher speeds on either surface, as shown in Fig. 8 where the averages from all four groups are plotted.

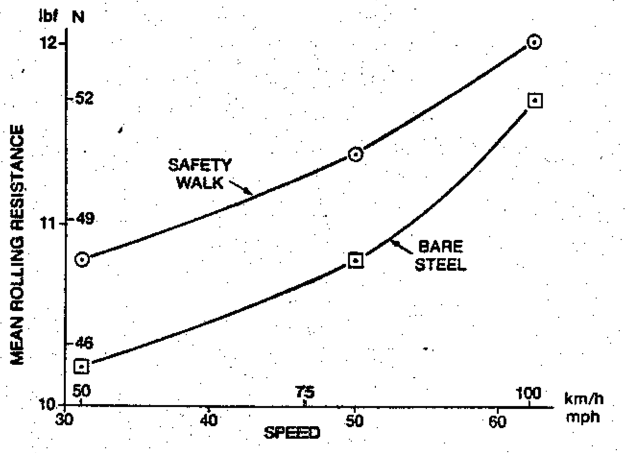

FIG. 8 — Effect of speed on rolling resistance forces — different surfaces on test wheel.

3. Standard deviations of rolling resistance forces on Safety Walk averaged about the same as those on bare steel. The slight advantage for Safety Walk, shown in Table 4, is not significant in view of the inconsistent values at different speeds and for different groups. Better distinction might have been shown had there been more tires in each group. The final line in the table, however, where all four groups at each speed were considered as a single unit for determining standard deviations, again shows little difference in scatter between the two surfaces.

4. Set A was slightly less sensitive to speed than was the average of Sets B, C, and D over the range from 31.2 to 62.5 mph (50.2 to 100.6 km/h). The respective rolling resistance coefficients were 0.035 and 0.043 lbf/mph (0.096 and 0.119 N/km/h); these co-

efficients are obtained by dividing the rolling resistance by the load.

Reproducibility of Results on Replicate Tires

Some relatively large differences among supposedly replicate tires were observed in the footnoted entries in Table 4. These could be traced to aberrant readings on a single run. Since a given tire was neither consistently high nor consistently low, the discrepancy is attributable to test operation. Such instances were very rare, however, so the same ratings for the different sets would have been obtained had there been more than four tires in each. If aberrant results are replaced by results of immediate reruns, four tires can be used to represent the average performance of a given design, assuming the samples are normally distributed within the total design population. The standard deviation of rolling resistance results on a set of tires is unlikely to be reduced to less than 0.05 lbs. (0.22N) by increasing the number of tires in a set. The significance of a given difference in the means of two sets might thereby be increased however.

TABLE 4 — Rolling resistance indices on four sets of P195/75R14 tires. Each set contained four tires.

	Mean Forces, lbf						
	On 3M Safety Walk			On bare steel			
Set / mph	31.2	50	62.5	31.2	50	62.5	93
A	10.7	11.2	11.8	10.1	10.6	11.2	16.1
B	10.7	11.4	12.1	10.2	10.9	11.6	17.6
C	10.9	11.4	12.2	10.2	10.9	11.5	17.7
D	10.8	11.5	12.2	10.3	10.9	11.6	17.8
Av	10.8	11.4	12.1	10.2	10.8	11.5	17.2
	Standard deviations, lbf						
A	0.12[1]	0.05	0.07	0.14[1]	0.08	0.06	0.37[1]
B	0.04	0.08	0.03	0.08	0.12	0.06	0.08
C	0.07	0.06	0.06	0.03	0.03	0.06	0.06
D	0.07	0.07	0.08	0.06	0.09	0.09	0.07
Av	0.08	0.06	0.06	0.08	0.07	0.06	0.14
Total[2]	0.13	0.10	0.16	0.13	0.11	0.18	0.68

[1] Data cells contained aberrant values

[2] Calculated on all 16 tires as a unit

Multiply table entries by 4.448 to get values in newtons

Multiply mph values by 1.609 to get km/h

Luchini (6) found rolling resistance to be a little higher and somewhat more reproducible on test wheels covered with a Safety Walk textured surface than on a smooth steel surface. Velinski and White (7) had previously shown that road roughness significantly increased vehicle rolling losses due to energy dissipation in tires and suspension. Such results favor the use of Safety Walk in laboratory tests so as to more nearly duplicate pavement surfaces; results should also be more valid because surface asperities produce greater energy loss in high hysteresis treads than in low hysteresis treads, so the effect of tread compounding can be more truly evaluated. The International Standards Organization, however, favors bare steel surfaces, partly because they want to test for rolling resistance at speeds high enough to destroy a Safety Walk surface. A further argument against Safety Walk is that results on a particular surface may change as it becomes worn. As described in the following section, we have analyzed some pre-existent data for answers to the latter possibility.

Effect of Worn Safety Walk Surface

Not enough has been known about the contribution of surface interactions to rolling resistance to justify any predictions about relative results on worn and new Safety Walk on the test wheel surface, Standards Testing Laboratories obtained some pertinent experimental data as part of an interlaboratory test sponsored by the Rolling Resistance Sub-Committee of the SAE Highway Tire Committee. Five current production light truck tires in sizes P215/85R16 to 9.50R-16.5 LT were tested. Each tire was run under twelve load-pressure combinations: four loads at a low pressure, three loads at a medium pressure, and five loads at a high pressure. Within this framework the actual loads and pressure chosen were such as to be reasonable for each tire size.

The complete set was first tested in November 1, 1982 (Run 1), at which time the test wheel was covered with Safety Walk that had been used for about 150 test runs. The surface particles were no longer sharp, but there were no bare spots. After the tires had been tested by other laboratories they were returned to STL for retest to evaluate repeatability. This retest was made in June

1983, on Safety Walk that had not been previously used (Run 2).

Table 5 shows the results obtained by subtracting the values obtained in Run 2 from the corresponding ones in Run 1. Test wheel surface was, of course, not the only variance between Run 1 and Run 2. The tires had been aged and exercised, and a systematic drift in testing accuracy might have occurred. Nevertheless, the following conclusions are justifiable:

1. Except for the bias tire (No. 4), the average of the entries for each tire was less than 0.2 lbf (0.9N). Therefore, neither the test surface accumulated run or aging effect was significant for the radial tires tested.

2. The significant decrease in rolling resistance for the bias tire must be attributable to factors such as break-in, wear, or change in tread surface. In view of the previous results on Safety Walk relative to bare steel, it is unlikely that a sharp Safety Walk surface would favor lower values than would a dull surface.

3. The averages on Run 2 were consistently slightly lower than those on Run 1; possible because of cumulative effect of exercise on the tires. This point should have further study.

4. The entries in Table 5 generally decreased with increased load, especially at low or medium pressures.

5. The entries in Table 5 generally increased with increased pressure at all loads.

Conclusions 3, 4, and 5 have no obvious relationship to the test wheel surface.

TABLE 5 — Difference between rolling resistance forces (lbf) measured on a worn Safety Walk Surface and those measured on a new surface.

(Run 1 — Run 2)

Test No.	Load	Pressure	Tire No. 1 P215/85R16	2 P235/85R16	3 9.50R-16.5	4 7.50-16	5 7.50R-16	Av.
1	low	low	0.28	0.43	0.12	0.52	0.14	0.30
2			-0.01	0.07	-0.01	0.29	-0.08	0.05
	to							
3			-0.02	-0.38	-0.59	0.32	0.28	-0.08
4	high		-0.15	0.63	0.67	-0.77	0.06	-0.18
5	low	medium	0.06	0.42	0.13	0.93	*	0.38
6	to		0.20	0.63	0.18	1.49	0.43	0.59
7	high		0.07	-0.68	0.17	1.07	0.26	0.18
8	low	high	0.27	-0.23	-0.01	0.94	0.06	0.21
9			0.27	0.43	0.42	1.01	0.29	0.48
10	to		0.13	0.13	0.04	1.21	0.32	0.37
11			-0.09	0.19	-0.04	1.42	0.05	0.31
12	high		0.40	-0.08	0.38	1.55	0.33	0.52
Av			0.12	0.13	0.12	0.83	0.19	0.26

*Bad reading; not used in average

Multiply table entries by 4.448 to get forces in newtons

SPEED RANGE

The equilibrium rolling resistance coefficient of a tire that has regulated inflation pressure increases with increasing speed. An example is shown in Fig. 9 from some data obtained for the Chrysler Corp. The tire had a European speed rating of H (130 mph - 209 km/h). The rate of increase also became progressively higher at higher speeds, which suggests a speed-dependent mechanism increasingly dominant. This mechanism is the formation of a traction wave is sometimes called a traveling wave (8) because it traverses the tire circumference, and sometimes is called a standing wave because the peaks and troughs have fixed positions relative to the footprint when the tire is run at a steady speed. A tire will usually fail within a short time when a traction wave is visible (5), so the speed at which the wave appears is too high for safe operation.

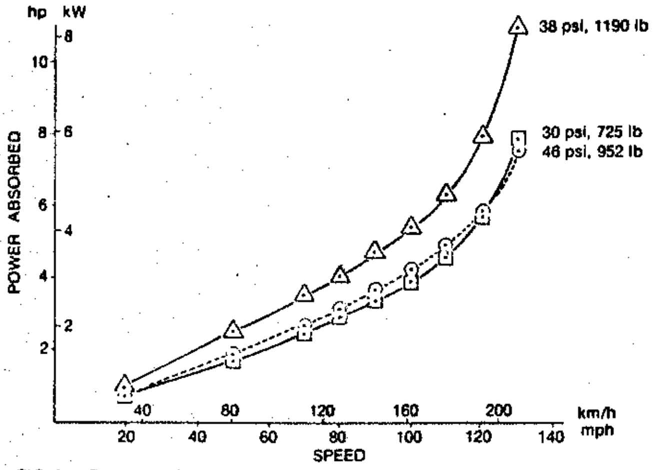

FIG. 9 — Power required by P185/70HR14 Goodyear Eagle GT Tire under different load-inflation combinations. European speed rating 130 mph (209 km/h).

Traction waves influence rolling resistance, and therefore heat generation, at far lower speeds than those at which they become visible. A measure of such heat generation therefore provides a good index for determining the maximum safe speed at which the tire can be tested at a given inflation pressure and given load. Fig. 9 is a plot of power absorbed as a function of speed for the same tire as that in Fig. 10. High usage of power produces high temperature. The curves in Fig. 9 turn upward sharply at about 120 mph (193 km/h), which suggests this as a limiting speed for rolling resistance testing. However, less heat would be developed on a flat road surface than on a curved test wheel. On the road heat would be dissipated by the rapid air flow around the tire and continually changing road surface. The 130 mph (209 km/h) rating is therefore justified.

Tires should not be run to failure in rolling resistance tests, because no purpose is served and there are risks of injury to personnel and damage to expensive equipment such as load cells. Tires for special uses, such as racing or pursuit cars, could be evaluated for high speed safety without producing tire failure by obtaining traces such as those in Fig. 9 and noting the speed at which the traces turn sharply upward.

Use of rolling resistance coefficient as the dependent variable, as in Fig. 10, demonstrates the contribution of high inflation pressure to maintenance of low rolling resistance. Such normalization of the data, however, can mask the strong effect of load on heat generation. Fig. 9 shows that power absorbed by a tire operating high under a high load and high pressure had a somewhat different speed dependence than when operating under low load and low pressure. The high load-high pressure conditions produced higher energy absorption over most of the speed range, and can be attributable to the tire's deflection which was 0.03 inches (0.8mm) greater than the deflection obtained at low load, low pressure test conditions. At 130 mph (209 km/h), however, low load-low pressure conditions started to produce higher losses. This was attributed to the better development of the traction wave at low pressure.

Power loss extrapolates to near zero speed (Fig. 9), but rolling resistance does not. Curves such as those in Fig. 10, change direction abruptly somewhere below 5 mph (8 km/h) so they reach zero force at zero speed. Results in this region are difficult to reproduce and have little meaning, so tests should not be made at speeds below 5 mph.

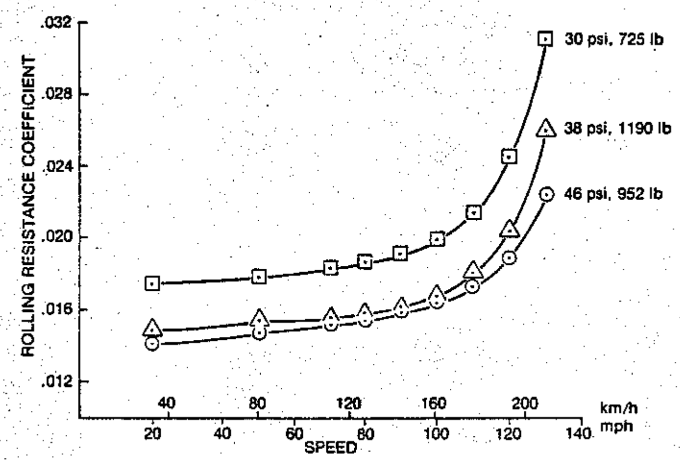

FIG. 10 — Effect of speed on rolling resistance coefficient under different load-inflation combinations. P185/70HR14 Goodyear Eagle GT. • European speed rating 130 mph (209 km/h).

EFFECT OF BREAK-IN AND WARM-UP TIME

A new tire requires no more running time before recording its rolling resistance than does a previously tested tire. Enough break-in is acquired during the warm-up. Warm-up is necessary, however, before recording values that are to be considered as equilibrium.

A true equilibrium requires that temperature values and distribution in the test tire be stabilized and that the contained air pressure is also stabilized. The latter requires an equilibrium contained air temperature in capped air tests, but not necessarily in tests where the air pressure is regulated. As previously stated, our rolling resistance results on replicate tires had stabilized within 15 minutes. This happened because the tire body temperatures reach equilibrium before the contained air does, and the air pressure was regulated in these tests. In a recent test for the Environmental Protection Agency, STL measured the running time at 50 mph (80 km/h) for some tires to reach a contained air pressure that thereafter remained stable for the next ten minutes of running. The results are given in Table 6. These tires were tested at 80% of the maximum load marked on the sidewall. The initial (capped) pressure was 35 psi (241 kPa) for p-metric and 32 psi (221 kPa) for alpha-numeric tires.

Except for the diagonal ply p-metric tire, an average warm-up time of 20 minutes was deemed to be sufficient. Shorter warm-up times have been used in published investigations (9), longer times would be needed for larger tires.

TABLE 6 — Running time in minutes required to develop equilibrium contained air pressure

		Range	Average
P195/75 R14	(60 tests)	15-28	20.7
E 78-14	(30 tests)	14-28	20.6
ER 78-14	(10 tests)	16-26	20.2
P195/75D14	(9 tests)	22-30	25.5

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SUMMARY

The following conclusions were reached on the basis of the experimental results reported in this paper:

1. A designed experiment showed how individual and interactive contributions to rolling resistance from pressure, speed, and load may be evaluated.

2. Load was the most critical of the three basic variables. Its actual value at the time of test should be used rather than the present value.

3. The combined effect of pressure, speed, and load was closely modeled by a quadratic response equation.

4. Not more than four replicate tires were needed to represent a sample.

5. Bare steel test wheels gave slightly lower rolling resistance than did wheels covered with Safety Walk; precisions were equivalent.

6. Results on well-worn Safety Walk duplicated those on new Safety Walk.

7. Rolling Resistance should not be measured at speeds above that at which it starts to increase rapidly.

8. Warm-up time required for automobile tires to reach equilibrium in the capped pressure mode need not exceed 20 minutes; however, this warm up time can be reduced to 15 minutes by regulating (maintaining) air pressure at a desired level.

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