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ROLLING RESISTANCE OF LIGHT TRUCK TIRES

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FINAL REPORT

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16. Abstract

The supplement contains carpet plots of 44 light truck tires giving rolling resistance versus load and reciprocal of inflation pressure. The plots represent measured data. To avoid the expense of taking measurements at all points on the plots, an equation is used which predicts rolling resistance of the tire for loads and inflation values where no measurements were taken.

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PREFACE

This report is a supplement to a report issued in December 1979, entitled "The Rolling Resistance of Pneumatic Tires,"* written by S.K. Clark of the University of Michigan, under sponsorship of the Department of Transportation, Transportation Systems Center with Stephen Bobo acting as Technical Monitor. The report is available through the National Technical Information Service, Springfield VA 22151.

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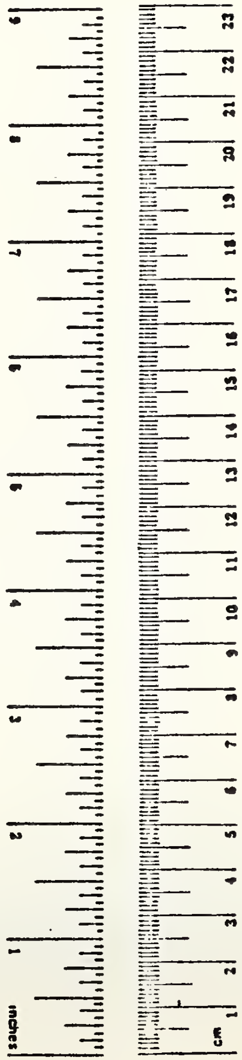
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

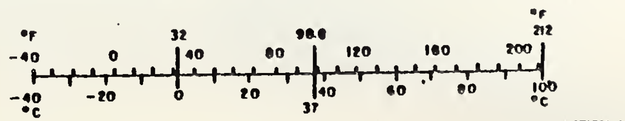
Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
	MASS (weight)			
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
	VOLUME			
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
	AREA			
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
	MASS (weight)			
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
	VOLUME			
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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1. INTRODUCTION

This report represents an addendum to a previous report issued by the University of Michigan entitled, "The Rolling Resistance of Pneumatic Tires," completed under sponsorship of the Department of Transportation, Transportation Systems Center, Cambridge MA.

In that earlier report, it was shown that the rolling resistance of a pneumatic tire was sensitive to load, inflation pressure, construction details, and size. Data representative of the U.S. national population of passenger car tires were presented, and some of the issues concerning measurement of this complex phenomenon were discussed.

The data presented in the previous report were obtained on the basis of capped air tests, that is, tests in which the tire was inflated to its recommended cold inflation pressure and then run until temperature and pressure equilibration were reached under the particular test conditions in question. This is considered a better test than one in which the pressure is regulated at some predetermined value, since it allows the tire pressure to build up in a fashion similar to what would occur in service.

Further reason for the use of capped air tests is that the data obtained from them are well represented by simple analytical relationships for conditions other than those measured by the tests, so that prediction for off-design rolling resistance values can be made with reasonable accuracy. The useful form of predictive equation developed in the earlier report is given as equation (1) below, where F_r, is the tire rolling resistance at the load F_z, with inflation pressure p, while F_{r_o}, F_{z_o} and p_o are rolling resistance, load, and inflation pressure, respectively, at some baseline or standard conditions chosen by the experimenters. The constant c_p is the pressure sensitivity of the tire, which must be determined by at least two tests. The constant c_p is characteristic for each tire, and methods for determining it were discussed in the earlier report.

$$F_r = F_{r_o} \left(\frac{F_z}{F_{z_o}}\right) \left[1 + c_p \left(\frac{p_o}{p} - 1\right)\right] \qquad (1)$$

All measurements were made on a 67-in. diameter indoor test drum, which has become the industry standard for such measurements. A method is presented for converting such values to flat roadway conditions.

2. LIGHT TRUCK TIRE ROLLING RESISTANCE

In the earlier report, light truck tires were not included in the study. Since then, an increasing number of vehicles using light truck tires have appeared on the American market so that their characteristics have become important in assessing national fuel conservation goals.

For the present study, a group of 19 light truck tires was selected based on the following considerations:

(a) Frequency of occurrence of that size in current original equipment production;

(b) Market share of a particular type of construction, i.e., radial vs. bias;

(c) Manufacturer's probable market share.

The tires selected are given in Table 1.

One further complication associated with this type of testing is the fact that for purposes of precision, convenience, and cost it is necessary to conduct these experiments on an indoor test wheel rather than on the highway. This introduces the error of the curved surface upon which the tire runs. Our approach has been to measure the rolling resistance of the tire at its proper load and inflation pressure on the 67-in. drum and then to convert this value of curved surface rolling resistance to a comparable value on the highway using equation (4-29) of the earlier report. Therefore, the data measured on the 67-in. drum was converted to a flat surface equivalent by dividing each of the measured rolling resistance values by the quantity:

$$(1+\frac{r}{R})^{1/2} \qquad (2)$$

where r = tire radius and R = drum radius. This conversion, while approximate, has been subsequently substantiated by a considerable amount of test data and has been accepted, at least for

TABLE 1. TIRE IDENTIFICATION AND TEST DATA LIGHT TRUCK TIRES

Test Number	Tire Number UMLT	Tire Description (All LT Tires)	Construction	Manufacturer	Serial Number	Cold Inflation Press. psi	Equil. Infla. Press. psi	Radial Load lb	Meas.[1] Equil. Rolling Resis. lb	Equivalent[2] Equil. Rolling Resistance on Highway lb	Coeff.[3] of Rolling Resist. lb/1000 lb.
1	1	7.50-16D	6N	Firestone	VAWYCMM309	60	68.1	1930	23.2	19.1	.0099
2	1	7.50-16D	6N	Firestone	VAWYCMM309	40	51.7	1930	27.5	22.6	.0117
3	1	7.50-16D	6N	Firestone	VAWYCMM309	50	58.9	1460	18.6	15.3	.0105
4	1	7.50-16D	6N	Firestone	VAWYCMM309	60	75.5	2440	28.8	23.7	.0097
5	11	9.50R16.5D	1s+4s	Michelin	ZUE869191	65	71.9	2190	17.9	14.9	.0068
6	11	9.50R16.5D	1s+4s	Michelin	ZUE869191	45	52.7	2190	19.8	16.5	.0075
7	11	9.50R16.5D	1s+4s	Michelin	ZUE869191	55	63.1	1670	15.2	12.6	.0075
8	11	9.50R16.5D	1s+4s	Michelin	ZUE869191	65	76.1	2780	22.1	18.4	.0066
9	25	7.50-16D	-	Goodyear	MDWYCM0489	60	69.4	1930	21.8	17.9	.0093
10	25	7.50-16D	-	Goodyear	MDWYCM0489	40	50.9	1930	26.8	22.0	.0114
11	28	9.50R16.5D	2p+(2s+2N)	Dunlop	DAXL8A7158	65	75.2	2190	21.8	18.0	.0082
12	28	9.50R16.5D	2p+(2s+2N)	Dunlop	DAXL8A7158	45	55.9	2190	22.3	18.5	.0084
13	5	8.00-16.5D	6N	Firestone	VJXJDPM349	60	71.5	1610	17.7	14.8	.0092
14	5	8.00-16.5D	6N	Firestone	VJXJDPM349	40	52.2	1610	20.5	17.2	.0107
15	23	8.00-16.5D	4N+2N	Goodyear	MEXJDP0509	60	67.4	1610	17.3	14.5	.0090
16	23	8.00-16.5D	4N+2N	Goodyear	MEXJDP0509	40	50.2	1610	19.6	16.5	.0102
17	4	8.75-16.5E	6N	Firestone	VDXKDUN399	75	86.0	2240	23.0	19.2	.0086
18	4	8.75-16.5E	6N	Firestone	VDXKDUN399	55	72.2	2240	27.3	22.7	.0101
19	19	8.75-16.5E	4N+2N	Goodyear	MEXKDU1379	75	82.8	2240	21.4	17.9	.0080
20	19	8.75-16.5E	4N+2N	Goodyear	MEXKDU1379	55	66.2	2240	24.1	20.1	.0090
21	3	9.50-16.5D	6N	Firestone	VJXLDPM268	60	68.8	2190	22.9	18.9	.0086
22	3	9.50-16.5D	6N	Firestone	VJXLDPM268	40	52.4	2190	28.4	23.5	.0107
23	26	9.50-16.5D				60		2190			
24	26	9.50-16.5D				40		2190			
25	6	9.50-16.5E	6N	Firestone	VJXLDUM409	75	84.7	2650	28.2	23.4	.0088
26	6	9.50-16.5E	6N	Firestone	VJKXDUM409	55	72.1	2650	30.4	25.1	.0095
27	22	9.50-16.5E	4N+2N	Goodyear	MFXLDU1159	75	85.4	2650	25.4	21.0	.0079
28	22	9.50-16.5E	4N+2N	Goodyear	MFXLDU1159	55	69.0	2650	27.5	22.8	.0086
29	10	10-15B	4p	Dunlop	DAAN457398	30	36.1	1390	21.6	18.0	.0129

N = NYLON
P = POLYESTER
R = RADIAL
S = STEEL

TABLE 1. TIRE IDENTIFICATION AND TEST DATA LIGHT TRUCK TIRES (CONT.)

Test Number	Tire Number UMLT	Tire Description (All LT Tires)	Construction	Manufacturer	Serial Number	Cold Inflation Press. psi	Equil. Infla. Press. psi	Radial Load lb	Meas.[1] Equil. Rolling Resis. lb	Equivalent[2] Equil. Rolling Resistance on Highway lb	Coeff.[3] of Rolling Resist. lb/1000 lb.
30	10	10-15B	4p	Dunlop	DAAN457398	20	27.2	1390	24.8	20.6	.0148
31	20	10-15B	4p	Goodyear	MLANL9N348	30	34.7	1390	20.2	16.7	.0120
32	20	10-15B	4p	Goodyear	MLANL9N348	20	24.7	1390	25.0	20.7	.0148
33	7	8.75R16.5E	3p+2s	Firestone	VJXK8DC059	80	89.3	2240	21.6	18.0	.0080
34	7	8.75R16.5E	3p+2s	Firestone	VJXK8DC059	60	69.9	2240	22.9	19.0	.0085
35	27	8.75R16.5E				80	91.4	2240	22.7	18.9	.0084
36	27	8.75R16.5E				60	76.2	2240	24.3	20.2	.0090
37	21	8.00R16.5E	2p+2s	Goodyear	MMXJW30398	80	87.7	1945	18.0	15.0	.0077
38	21	8.00R16.5E	2p+2s	Goodyear	MMXJW30398	60	70.0	1945	19.5	16.3	.0084
39	29	8.00R16.5D	1s+4s	Michelin	XVI486191	65	71.9	1610	14.3	12.0	.0075
40	29	8.00R16.5D	1s+4s	Michelin	XVI486191	45	50.4	1610	15.4	12.9	.0080
41	2	7.50-16E	6N	Firestone	VAWYCPM159	75	85.8	2310	27.3	22.5	.0097
42	2	7.50-16E	6N	Firestone	VAWYCPM159	55	68.4	2310	29.3	24.3	.0105
43	24	7.50-16E	4N+2N	Goodyear	MDWYCP0439	75	89.3	2310	25.2	20.7	.0090
44	24	7.50-16E	4N+2N	Goodyear	MDWYCP0439	55	70.1	2310	29.1	23.9	.0103

p = Polyester

N = NYLON
P = POLYESTER
R = RADIAL
S = STEEL

[1] Measured on a 67.23" drum by torque cell method at 50 mph.

[2] Obtained by dividing the rolling resistance measured on the 67" drum by

$$(1+r/R)^{1/2}.$$

where r = tire radius, R = drum radius.

[3] Defined as flat surface rolling resistance divided by load carried.

passenger car tires, as a reasonable approximation. All measurements were made under fully equilibrated conditions at 50 mph surface speed.

The thrust of the present addendum is to obtain data on a variety of present-day light truck tires and to present this data in such a way that fuel economy studies may be carried out with realistic tire rolling resistance input information. Because of limited resources, it was decided to utilize the previous analytical framework represented by equation (1) in order to reduce the cost of the test program substantially. This was done in a two-part sequence, consisting of the following:

1) Two tires were tested at several combinations of load and pressure in order to validate the concept of equation (1), again using capped air tests for all test points. Two of the test points in each sequence were used to obtain c_p, the pressure coefficient. The predictions from equation (1) were compared with measured points.

2) The remaining tires of the test program were tested under a two-point test program designed to determine the pressure coefficient and to give baseline values so that equation (1) could be evaluated at a variety of other load and pressure conditions. This is even more necessary in light truck tires than passenger car tires, since light truck tires tend to be operated under a wider variety of load and pressure conditions than passenger car tires.

The test data are presented in two groups. In the first group, the data from the two test tires selected for multiple test point studies are given. These tires are described in Table 2.

The comparisons between measured and predicted rolling resistance are given in Table 3. These were made at combinations of load and pressure, different from those used to obtain the pressure coefficients in Table 2.

TABLE 2. TIRES SELECTED FOR MULTIPLE TEST POINT STUDIES

TEST TIRE	7.50-16LT	9.50R16.5LT
LOAD RANGE	D	D
MFGR	FIRESTONE	MICHELIN
S/N	VAWYCMM309	ZUE869191
BASE LINE CONDITIONS		
LOAD LBS	1930	2190
PRESSURE PSI	60	65
MEASURED F_{r_o} *	23.21	17.9
MEASURED c_p USING TWO TEST POINTS	0.370	0.239

TABLE 3. TIRE TEST COMPARISONS BETWEEN MEASURED AND PREDICTED ROLLING RESISTANCE

TEST TIRE	7.50-16LT LR D	FIRESTONE VAWYCMM309
LOAD	1460	2440
PRESSURE	50	60
PREDICTED F_r**(Eq. 1)	18.85	29.34
MEASURED F_r**	18.57	28.75
TEST TIRE	9.50R-16.5LT LR D	MICHELIN ZUE869191
LOAD	1670	2780
PRESSURE	55	65
PREDICTED F_r**(Eq. 1)	14.24	22.72
MEASURED F_r**	15.20	22.10

* Measured on 67-in. drum but reduced to flat surface by use of equation (2).

**Expressed as flat surface values by converting from 67-in. drum data using equation (2).

These test points are shown in Figures 1 and 2, along with the linear maps predicted by use of equation (1).

Tables 1 and 2 demonstrate good agreement of predictions using equation (1) with test data. Based on this, the remainder of the test program was carried out by measuring two rolling resistance values for each tire, both at a load of 80 percent of the maximum recommended Tire and Rim Association load, but at two different inflation pressures. From these measurements, the pressure coefficient c_p, used in equation (1), was found along with the baseline values of load, inflation pressure, and rolling resistance denoted respectively by F_{z_o}, p_o, and F_{r_o}, which are also used in equation (1).

Having these values available for each tire, equation (1) was used to prepare maps of tire rolling resistance as a function of various loads and reciprocal pressures. These are presented in Figures 3 through 19. In these figures the small circles represent the actual test data, reduced to flat road conditions by use of equation (2), while the lines represent predictions from equation (1).

Because of the general tendency of rolling resistance data to be linear with load and to be linear with the reciprocal of inflation pressure, those variables were chosen for plotting the data. The subsequent maps presented show the rolling resistance in terms of load and in terms of the reciprocal of inflation pressure, although both scales are given on the abscissa of inflation pressure. Because of the linear nature of the data, it now becomes quite easy to interpolate between load and pressure points.

It is not possible to find a simple means to compare the various tires tested since they are designed for different loads, different inflation pressures, and even different service. Nevertheless, one interesting generalization can be obtained by plotting the load carrying efficiency of the tire, defined at some baseline condition, against its inflation pressure. These variables are chosen because it is generally conceded that in the low to medium pressure range the tire rolling resistance decreases, so that load carrying efficiency should increase. The efficiency of load carrying is arbitrarily defined as

$$\left(\frac{F_z}{F_r}\right) = \text{Efficiency}$$

where the load F_z is that at which the rolling resistance F_r is measured. It was chosen to plot this against inflation pressure, but in order to retain the dimensionless character of the plot, the ratio of inflation pressure to atmospheric pressure is used. Data for the tires studied are given in this form in Figure 20.

Note that rearrangement of equation (1) results in a tire load carrying efficiency which varies with pressure according to the relationship

$$\text{Efficiency} = (\text{Efficiency})_{\substack{\text{BASE}\\ \text{LINE}}} \times \frac{\left(1+\frac{\Delta p}{p_o}\right)}{\left[1+(1-c_p)\frac{\Delta p}{p_o}\right]}$$

where Δp is the departure from p_o, i.e., $p = p_o + \Delta p$. This is a near-linear relationship for relatively modest values of $\Delta p/p_o$.

Figure 20 displays the rolling resistance data in such a way that two conclusions are available:

(1) For both bias and radial tires, there is a strong correlation between tire efficiency and inflation pressure.

(2) Not all tires fall in a narrow band. Some are markedly more efficient than others at the same pressure. This strongly implies that design influences can be substantial.

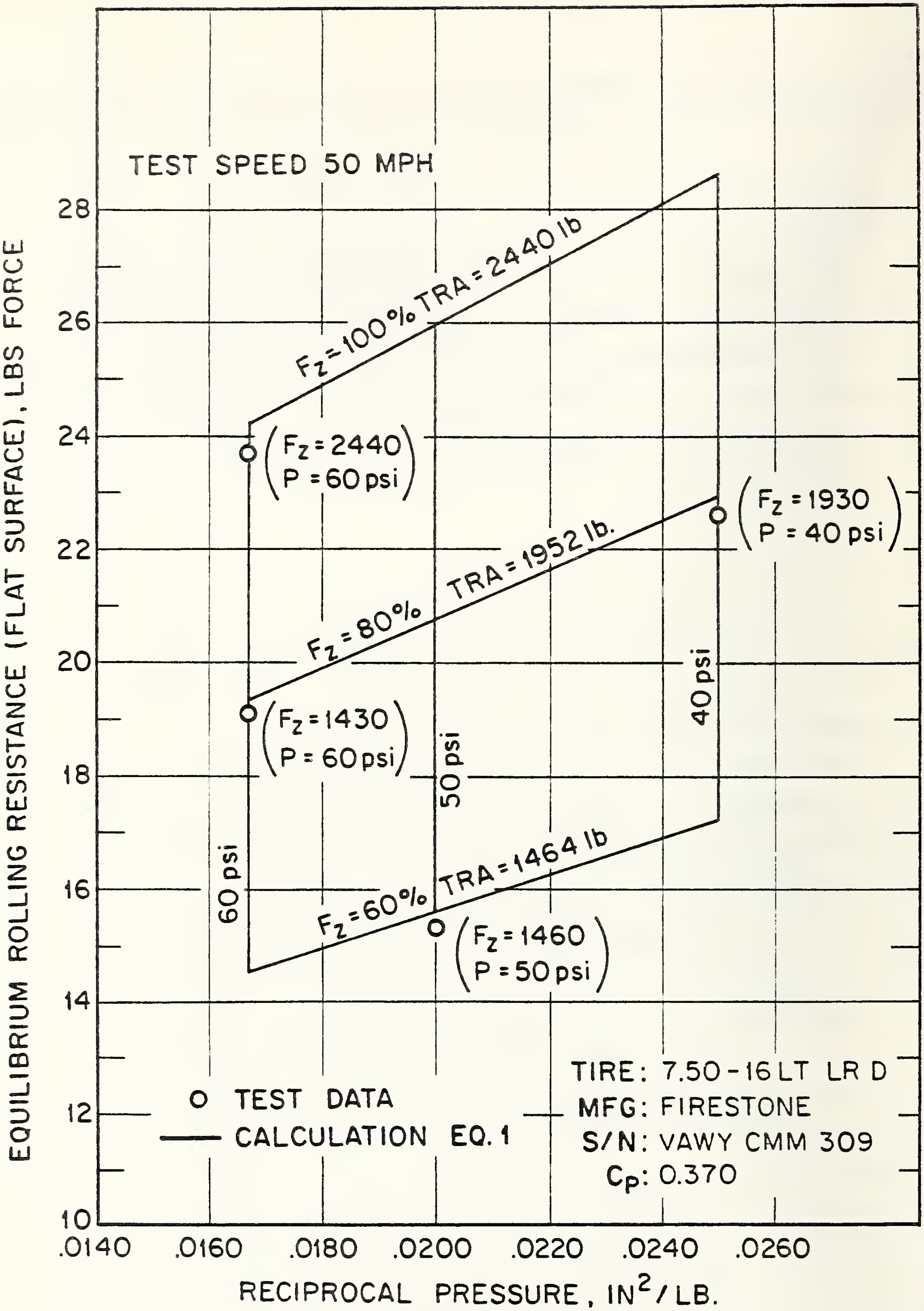

FIGURE 1. EQUILIBRIUM ROLLING RESISTANCE (FLAT SURFACE) VS. LOAD AND INFLATION PRESSURE: FIRESTONE 7.50-16LT LR D

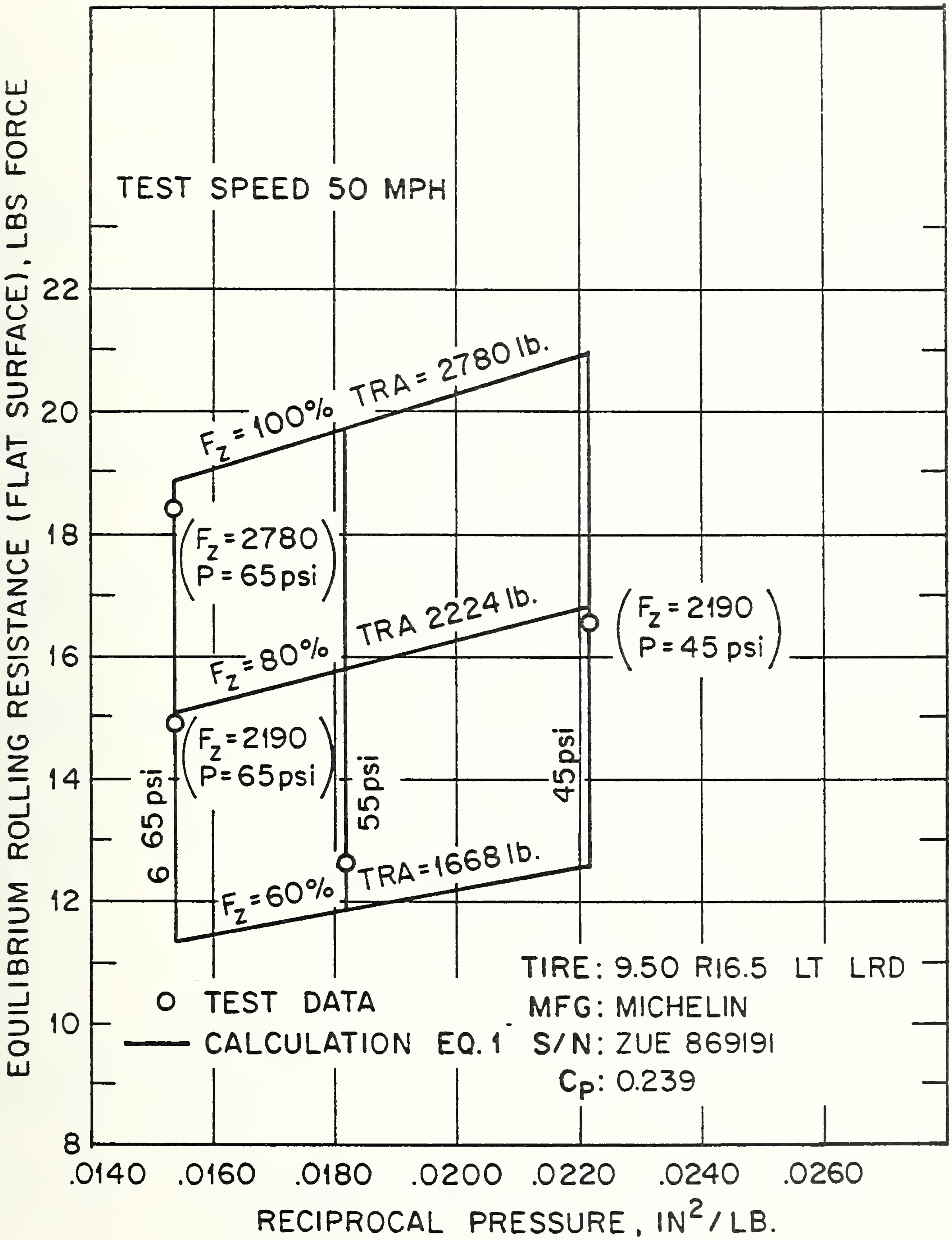

FIGURE 2. EQUILIBRIUM ROLLING RESISTANCE (FLAT SURFACE) VS. LOAD AND INFLATION PRESSURE: MICHELIN 9.50-R16.5 LT LR D

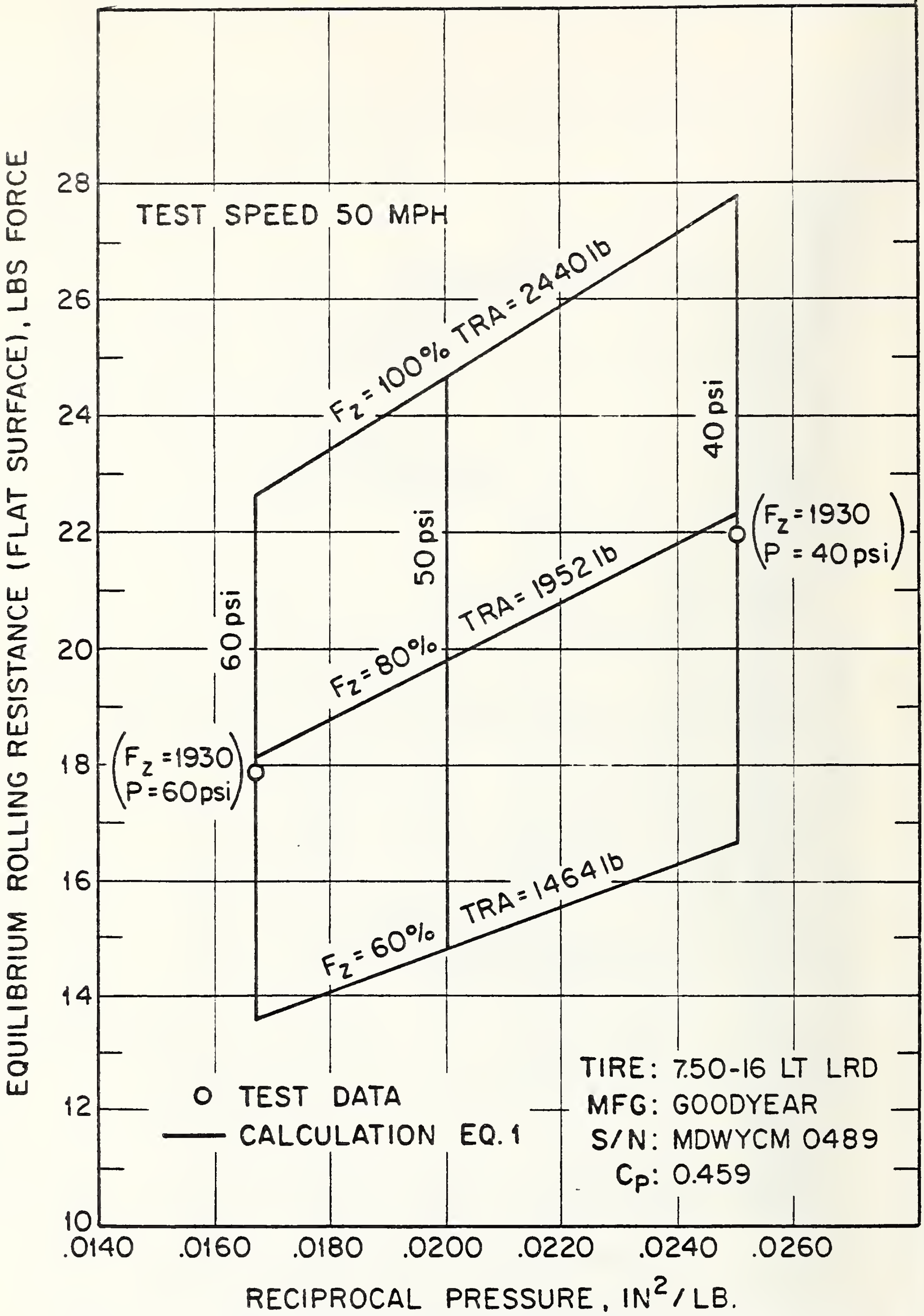

FIGURE 3. EQUILIBRIUM ROLLING RESISTANCE (FLAT SURFACE) VS. LOAD AND INFLATION PRESSURE: GOODYEAR 7.50-16 LT LR D

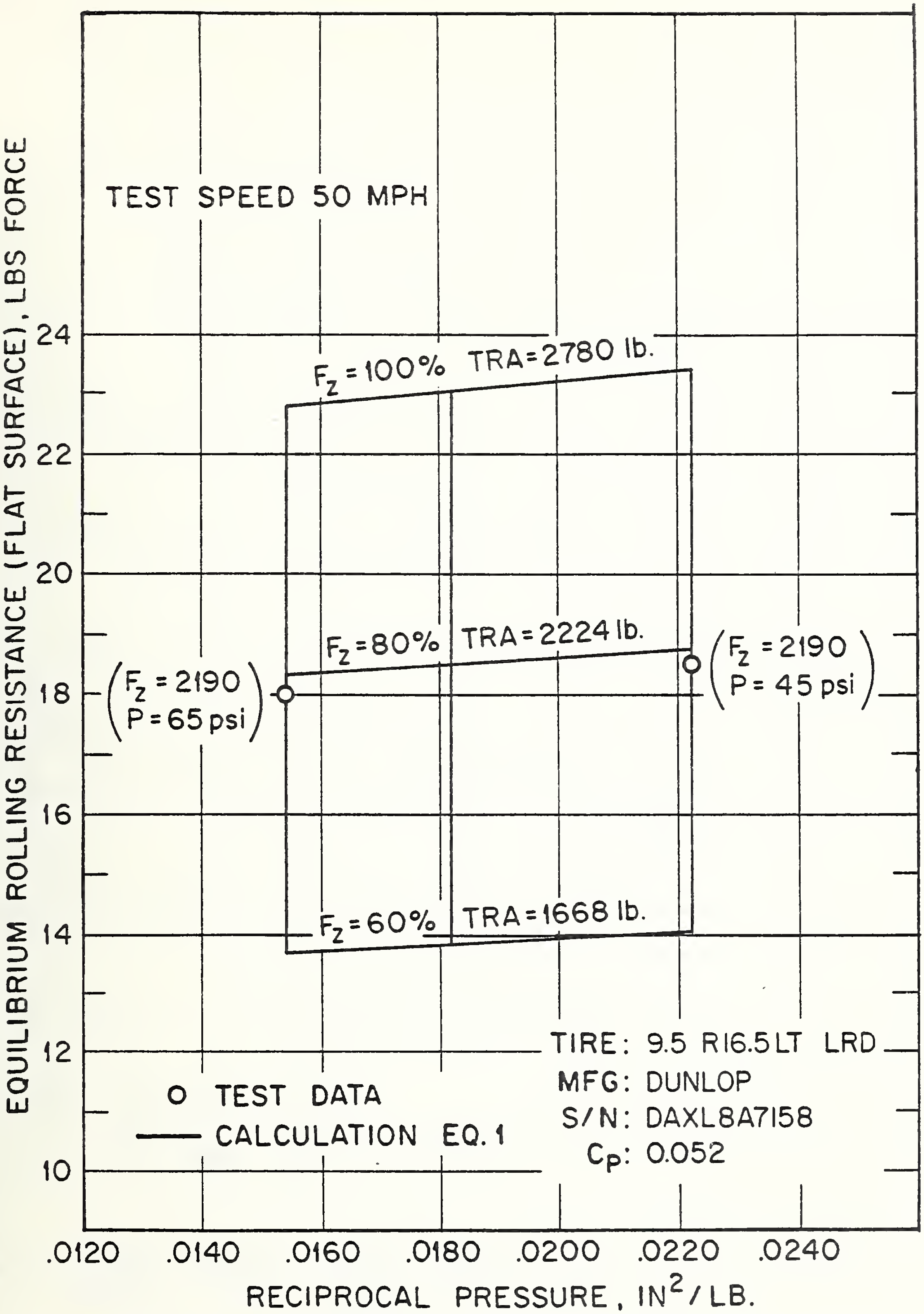

FIGURE 4. EQUILIBRIUM ROLLING RESISTANCE (FLAT SURFACE) VS. LOAD AND INFLATION PRESSURE: DUNLOP 9.50-R16.5LT LRD

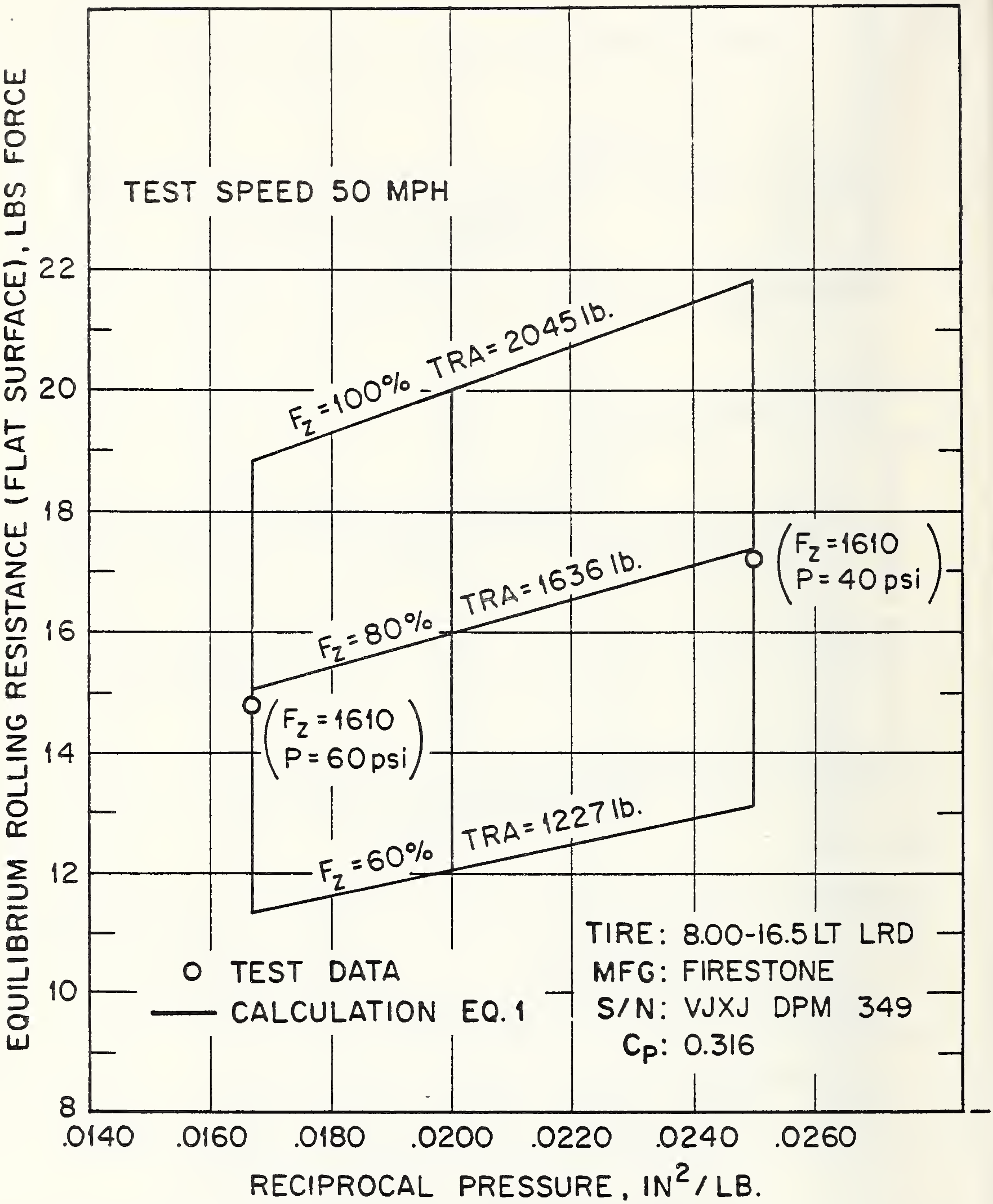

FIGURE 5. EQUILIBRIUM ROLLING RESISTANCE (FLAT SURFACE) VS. LOAD AND INFLATION PRESSURE: FIRESTONE 8.00-16.5LT LRD

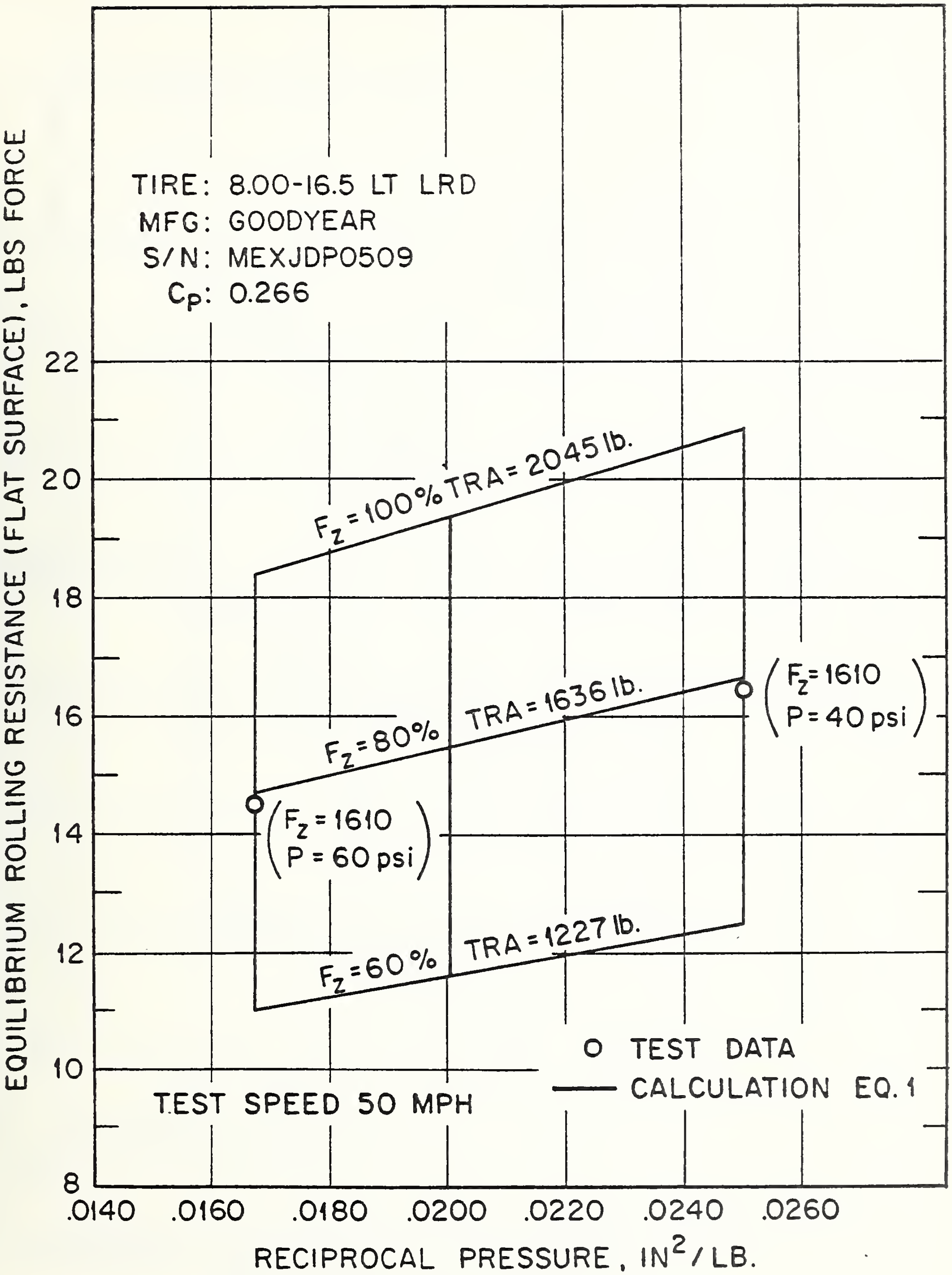

FIGURE 6. EQUILIBRIUM ROLLING RESISTANCE (FLAT SURFACE) VS. LOAD AND INFLATION PRESSURE: GOODYEAR 8.00-16.5 LT LRD

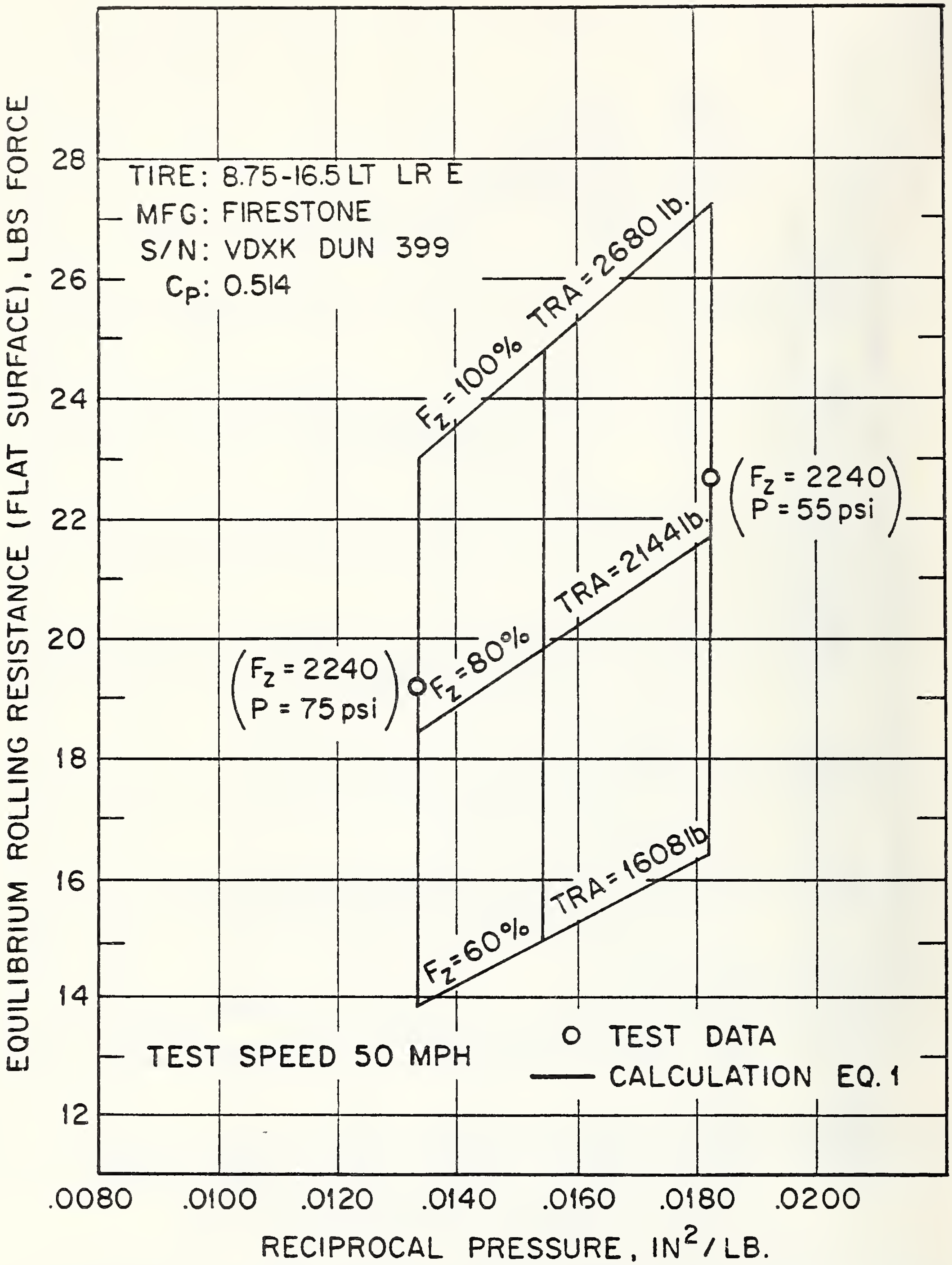

FIGURE 7. EQUILIBRIUM ROLLING RESISTANCE (FLAT SURFACE) VS. LOAD AND INFLATION PRESSURE: FIRESTONE 5.75-16.5 LT LR E

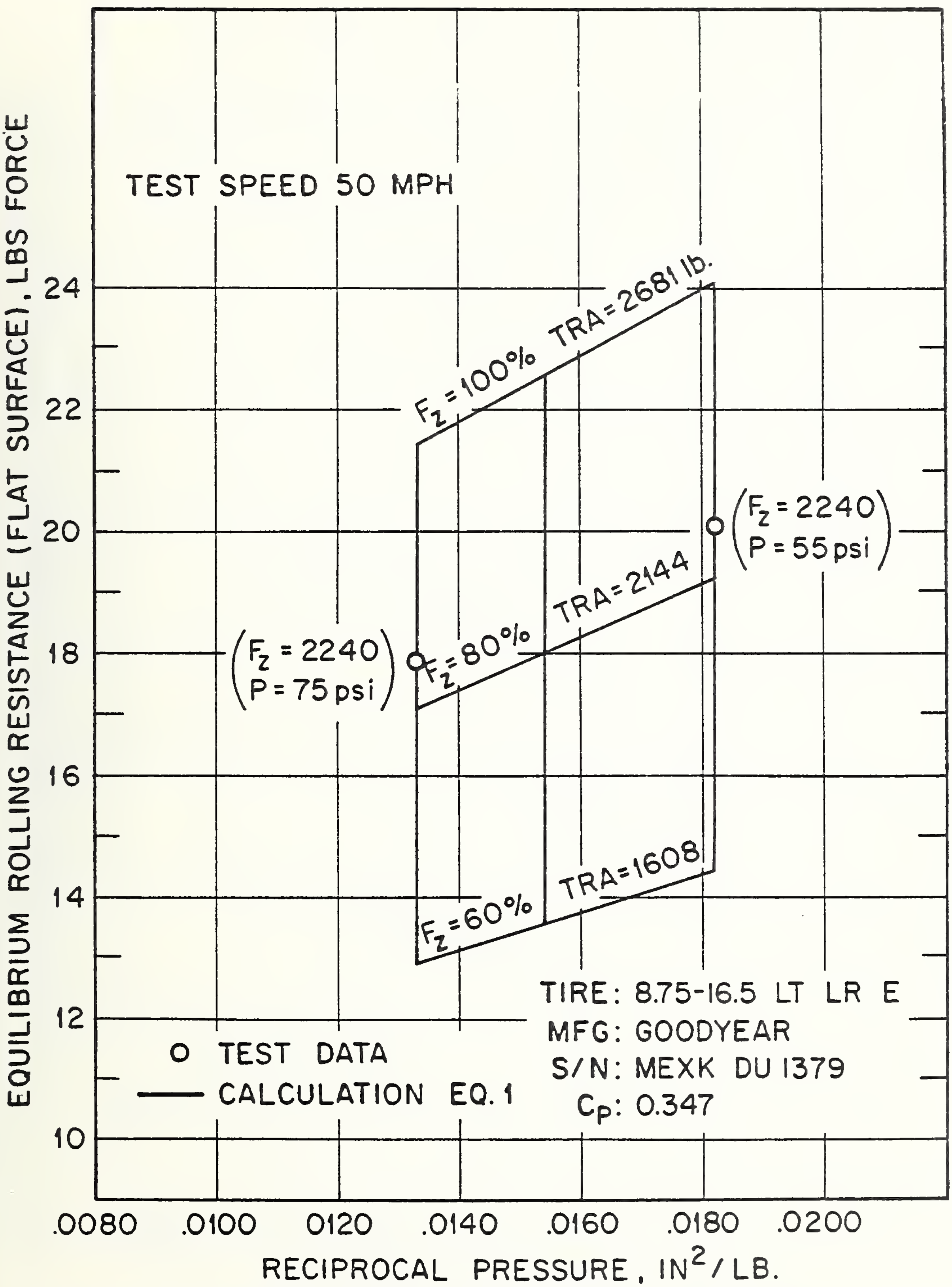

FIGURE 8. EQUILIBRIUM ROLLING RESISTANCE (FLAT SURFACE) VS. LOAD AND INFLATION PRESSURE: GOODYEAR 8.75-16.5 LT LR E

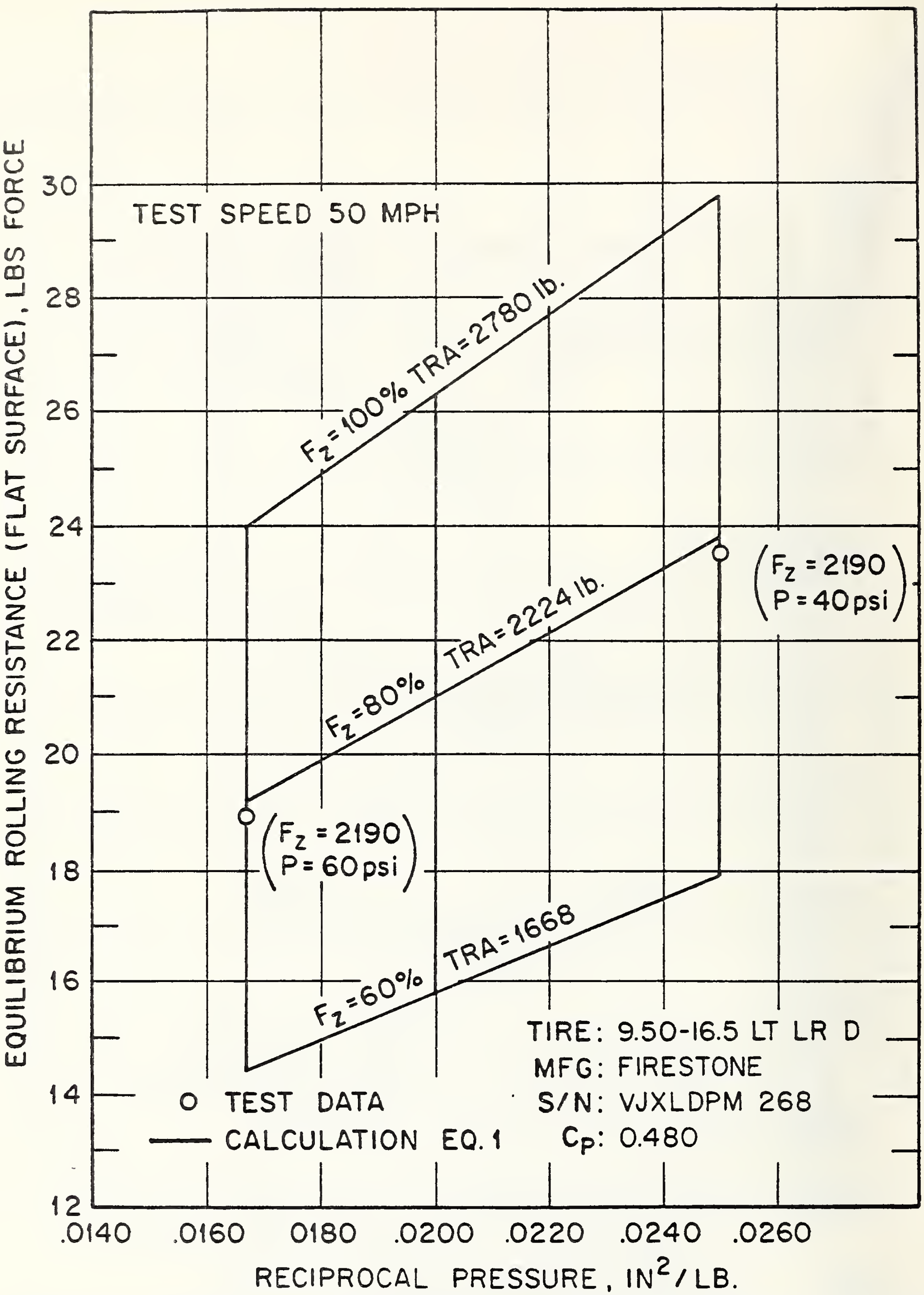

FIGURE 9. EQUILIBRIUM ROLLING RESISTANCE (FLAT SURFACE) VS. LOAD AND INFLATION PRESSURE: FIRESTONE 9.50-16.5 LT LR D

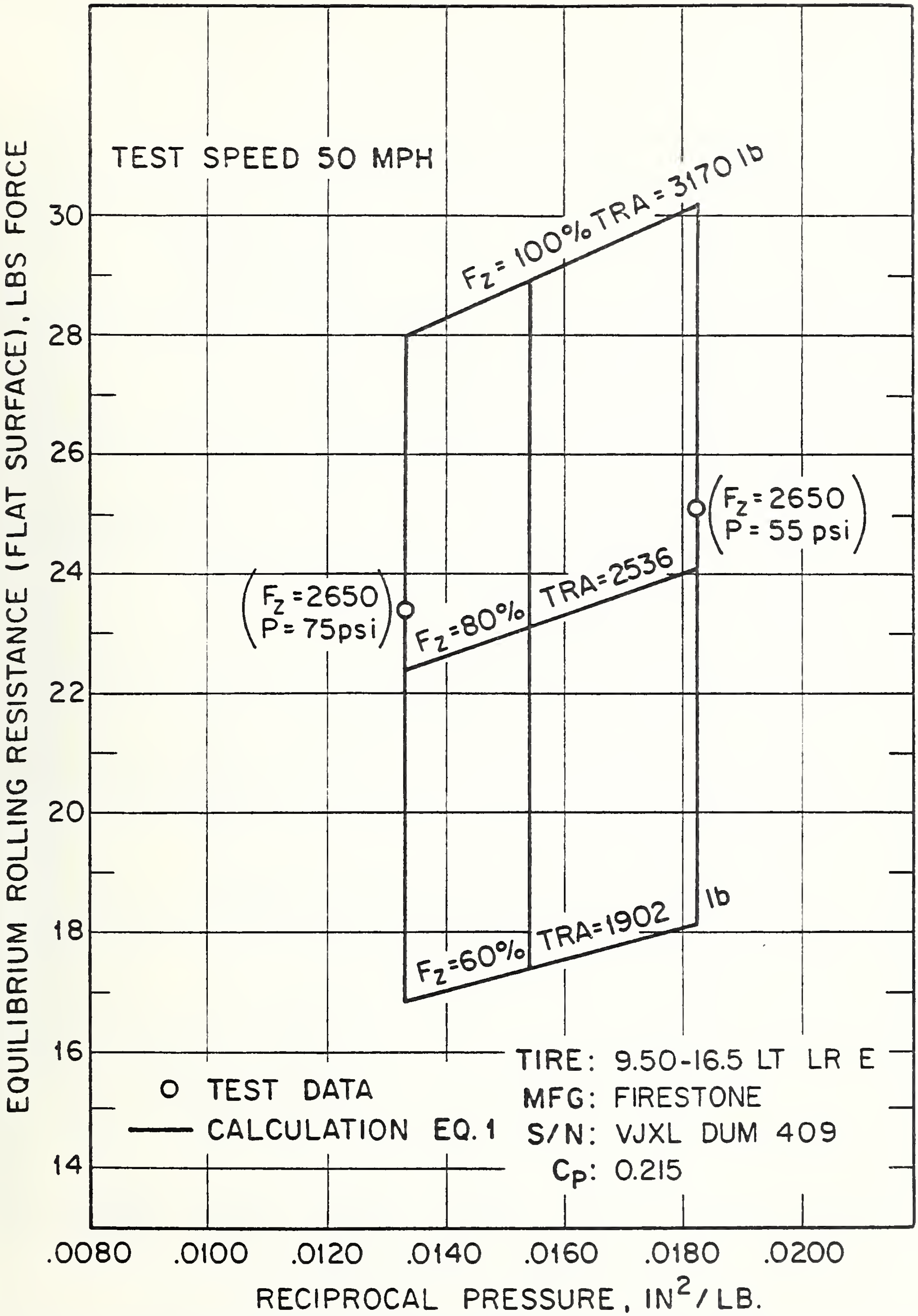

FIGURE 10. EQUILIBRIUM ROLLING RESISTANCE (FLAT SURFACE) VS. LOAD AND INFLATION PRESSURE: FIRESTONE 9.50-16.5 LT LR E

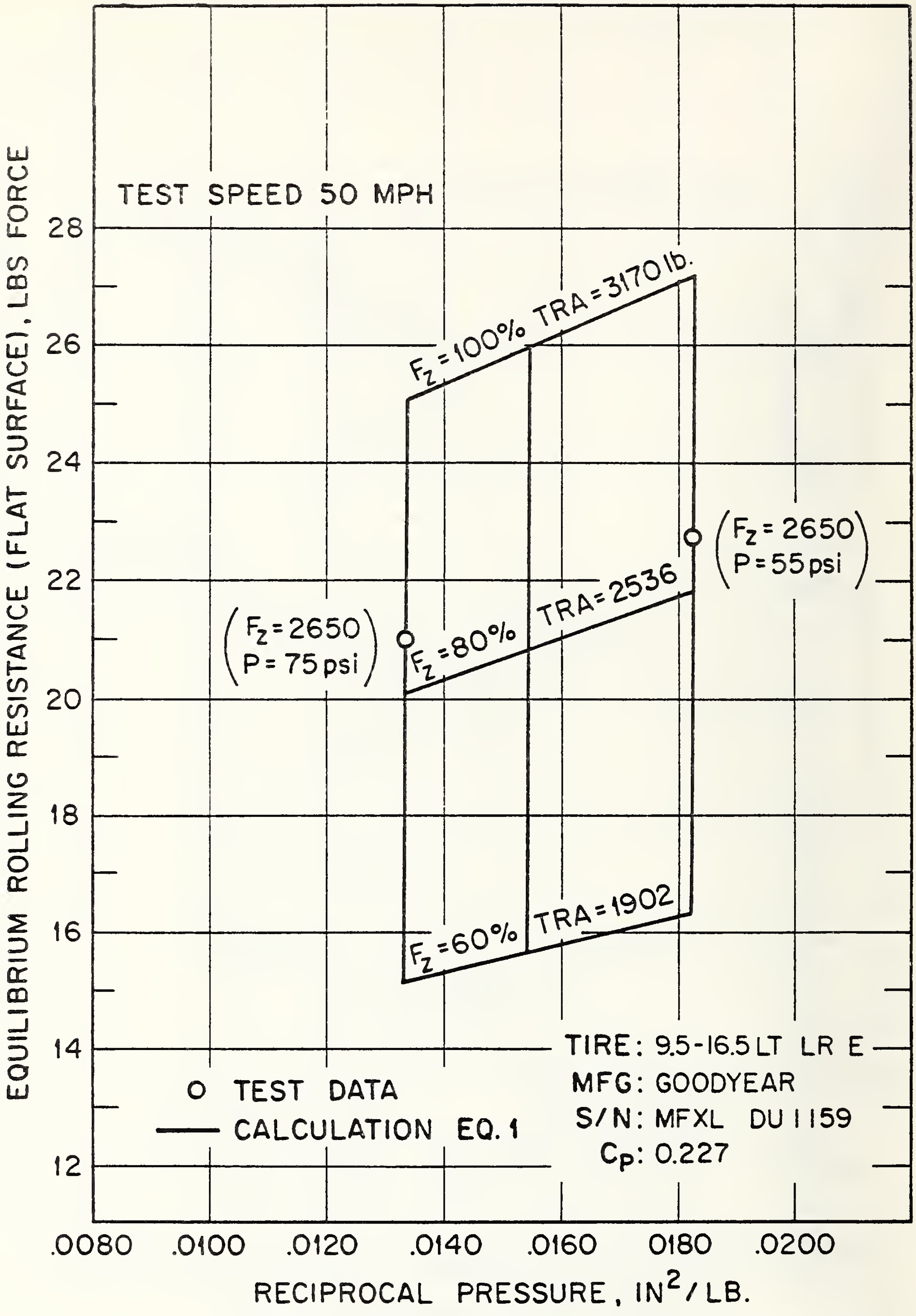

FIGURE 11. EQUILIBRIUM ROLLING RESISTANCE (FLAT SURFACE) VS. LOAD AND INFLATION PRESSURE: GOODYEAR 9.5-16.5LT LR E

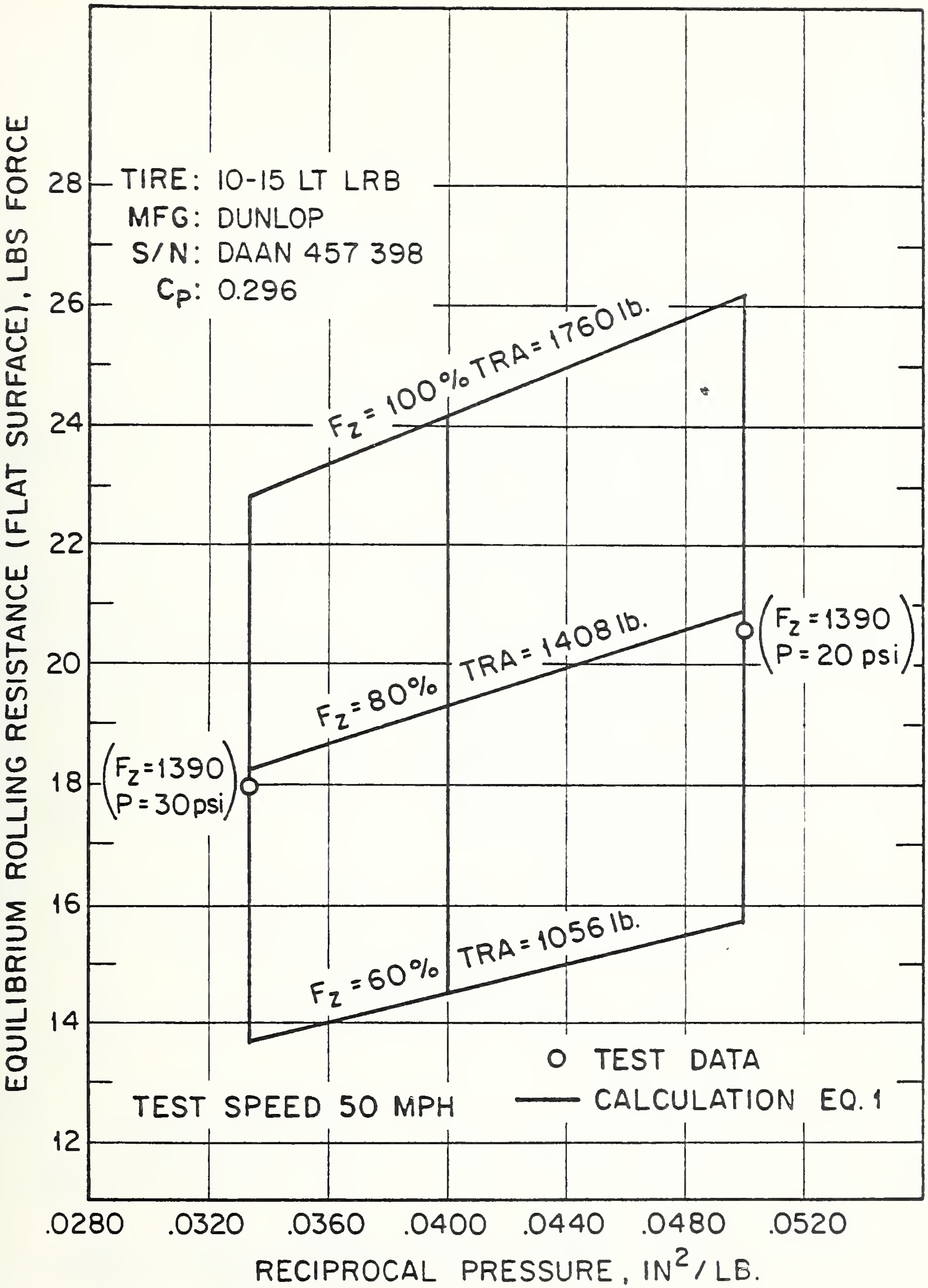

FIGURE 12. EQUILIBRIUM ROLLING RESISTANCE (FLAT SURFACE) VS. LOAD AND INFLATION PRESSURE: DUNLOP 10-15 LT LRB

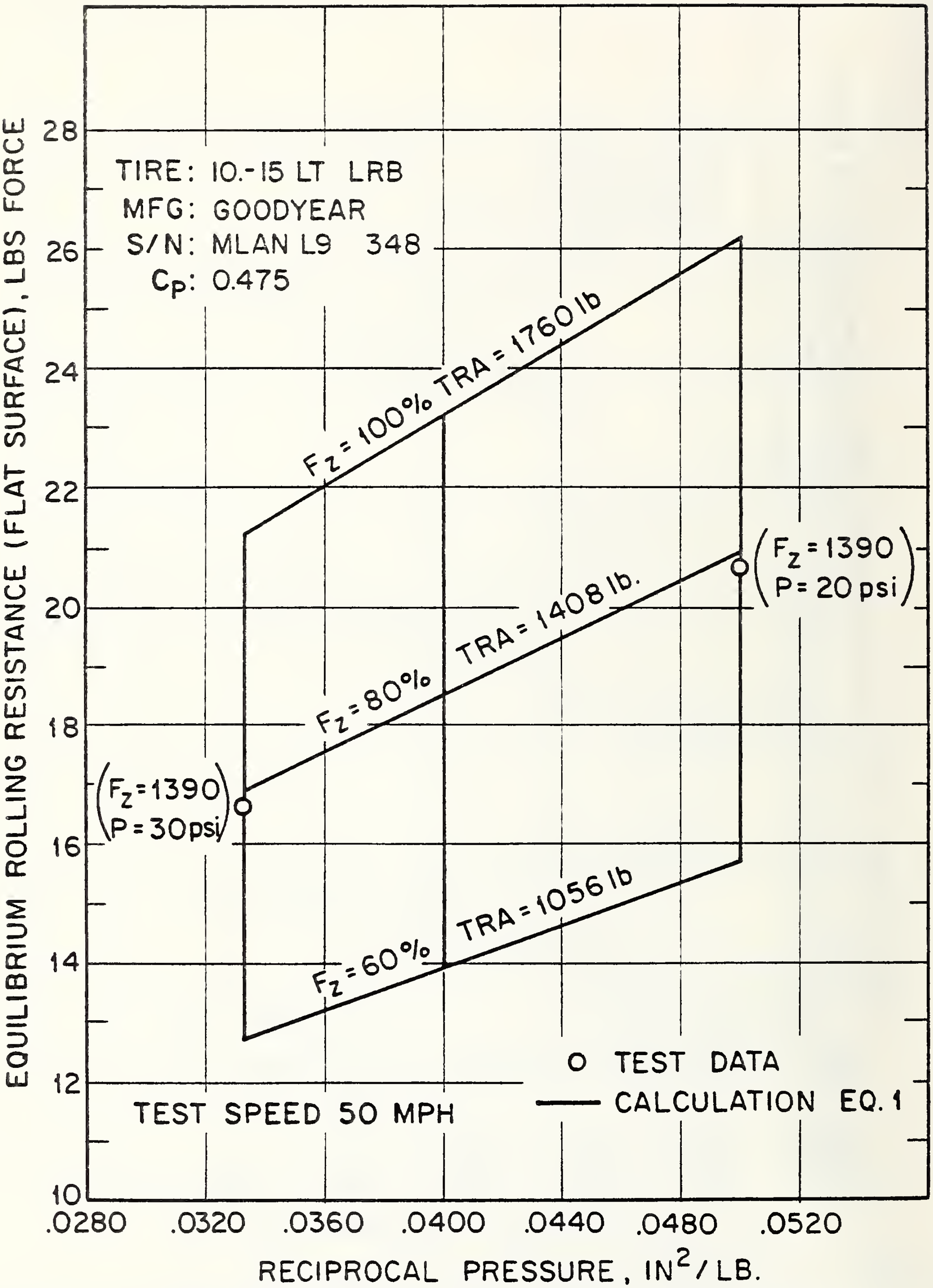

FIGURE 13. EQUILIBRIUM ROLLING RESISTANCE (FLAT SURFACE) VS. LOAD AND INFLATION PRESSURE: GOODYEAR 10-15 LT LRB

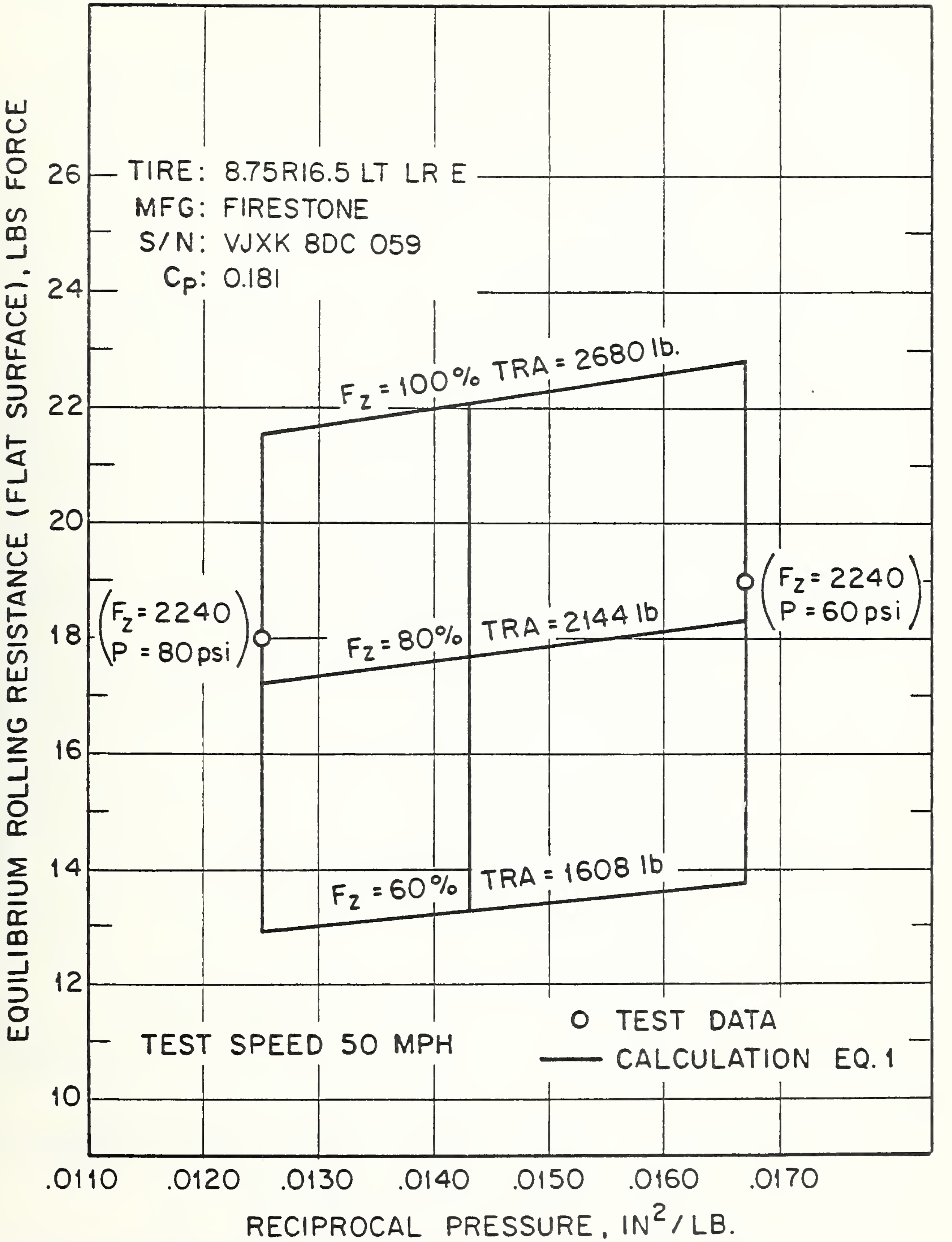

FIGURE 14. EQUILIBRIUM ROLLING RESISTANCE (FLAT SURFACE) VS. LOAD AND INFLATION PRESSURE: FIRESTONE 8.75R16.5 LT LR E

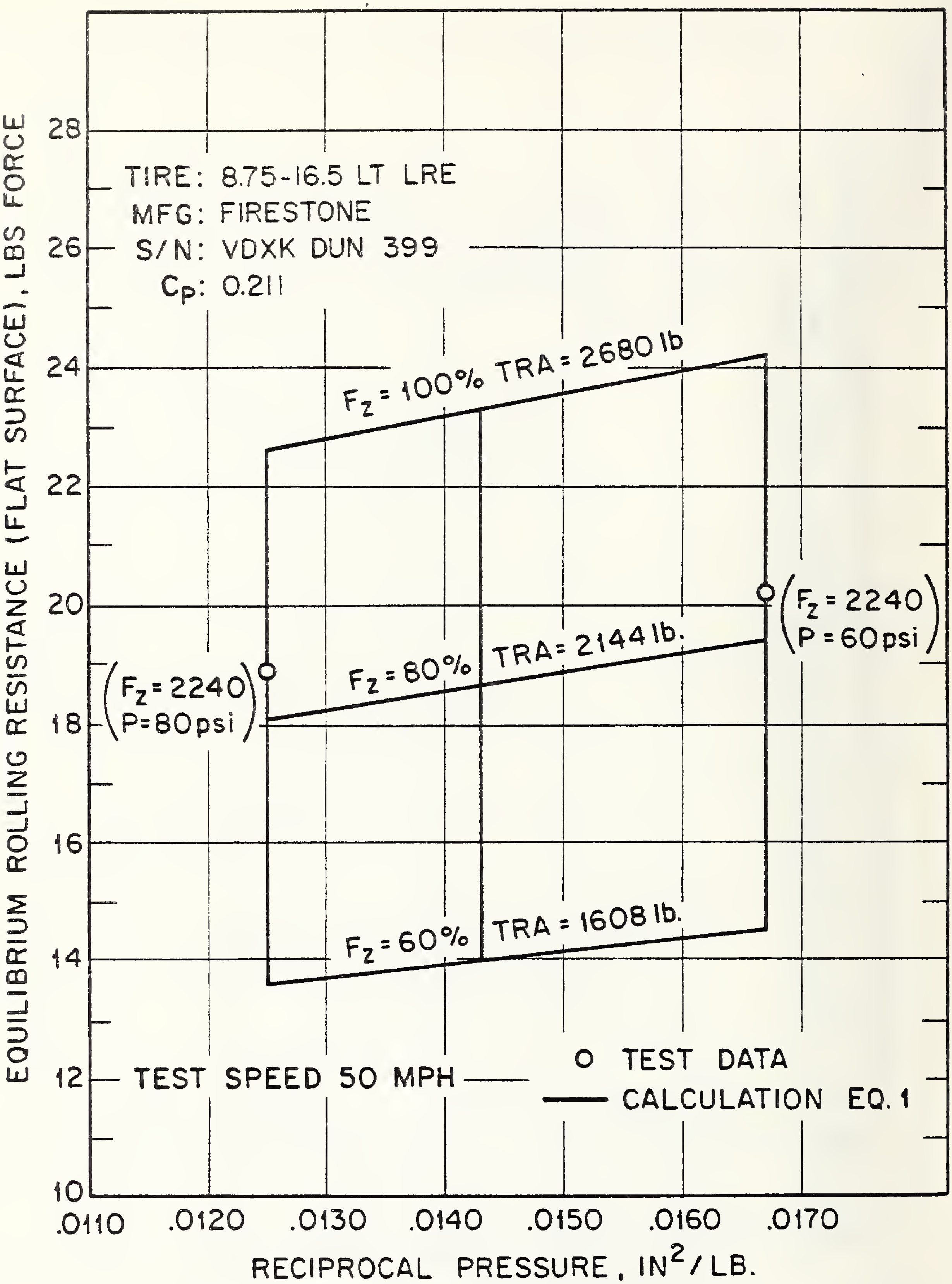

FIGURE 15. EQUILIBRIUM ROLLING RESISTANCE (FLAT SURFACE) VS. LOAD AND INFLATION PRESSURE: FIRESTONE 8.75-16.5 LT LRE

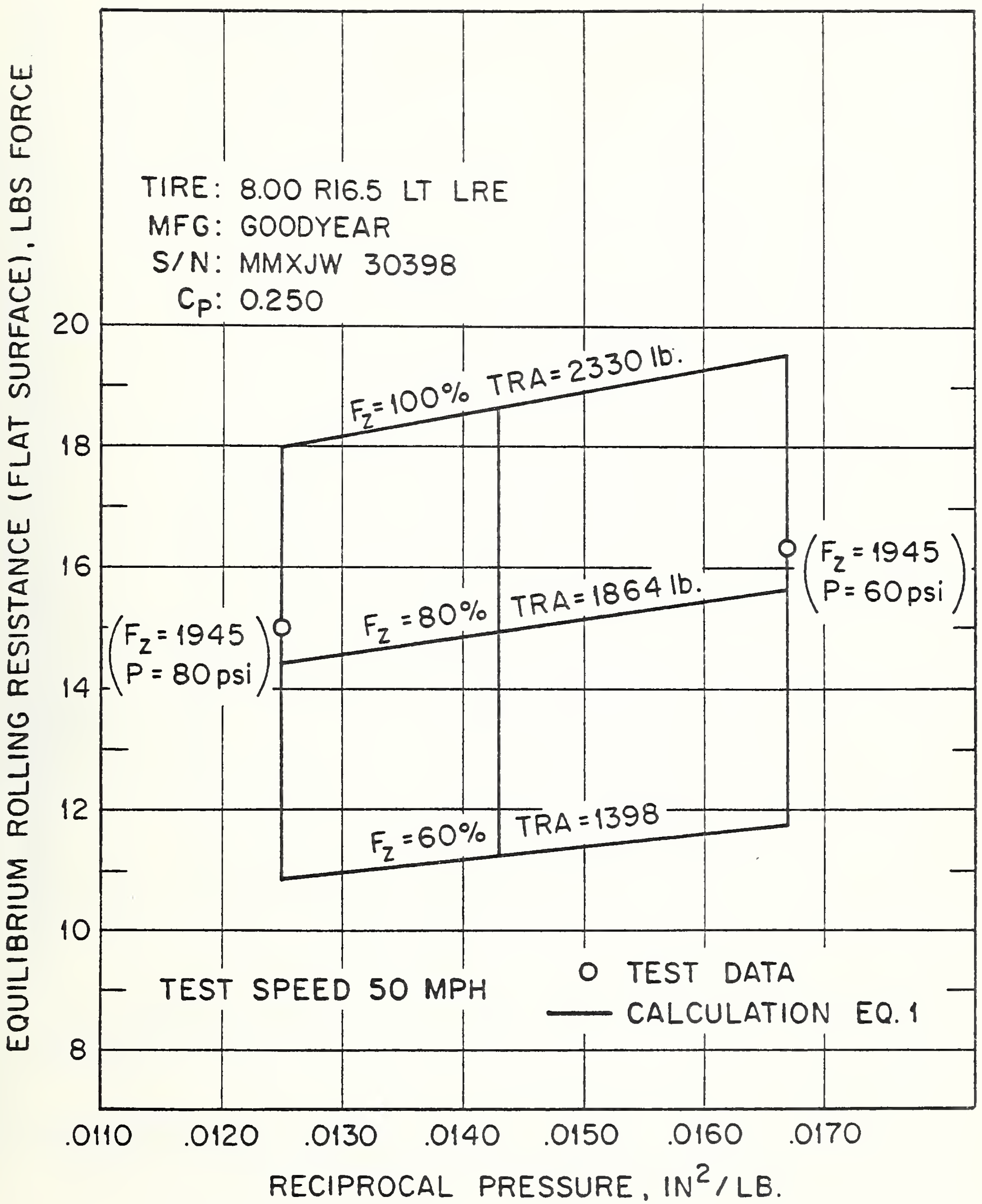

FIGURE 16. EQUILIBRIUM ROLLING RESISTANCE (FLAT SURFACE) VS. LOAD AND INFLATION PRESSURE: GOODYEAR 8.00 R16.5 LT LRE

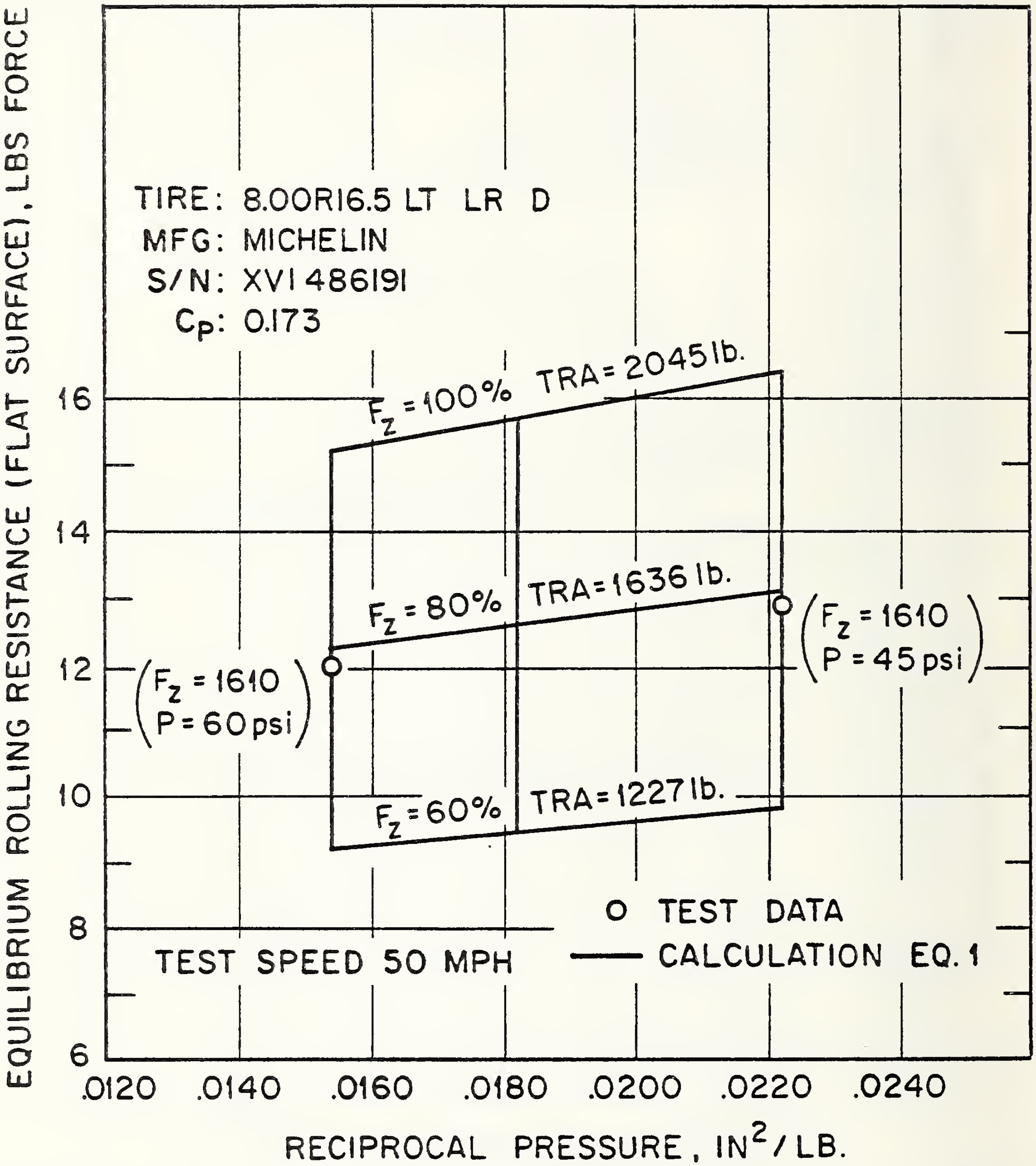

FIGURE 17. EQUILIBRIUM ROLLING RESISTANCE (FLAT SURFACE VS. LOAD AND INFLATION PRESSURE: MICHELIN 8.00 R16.5 LT LR D

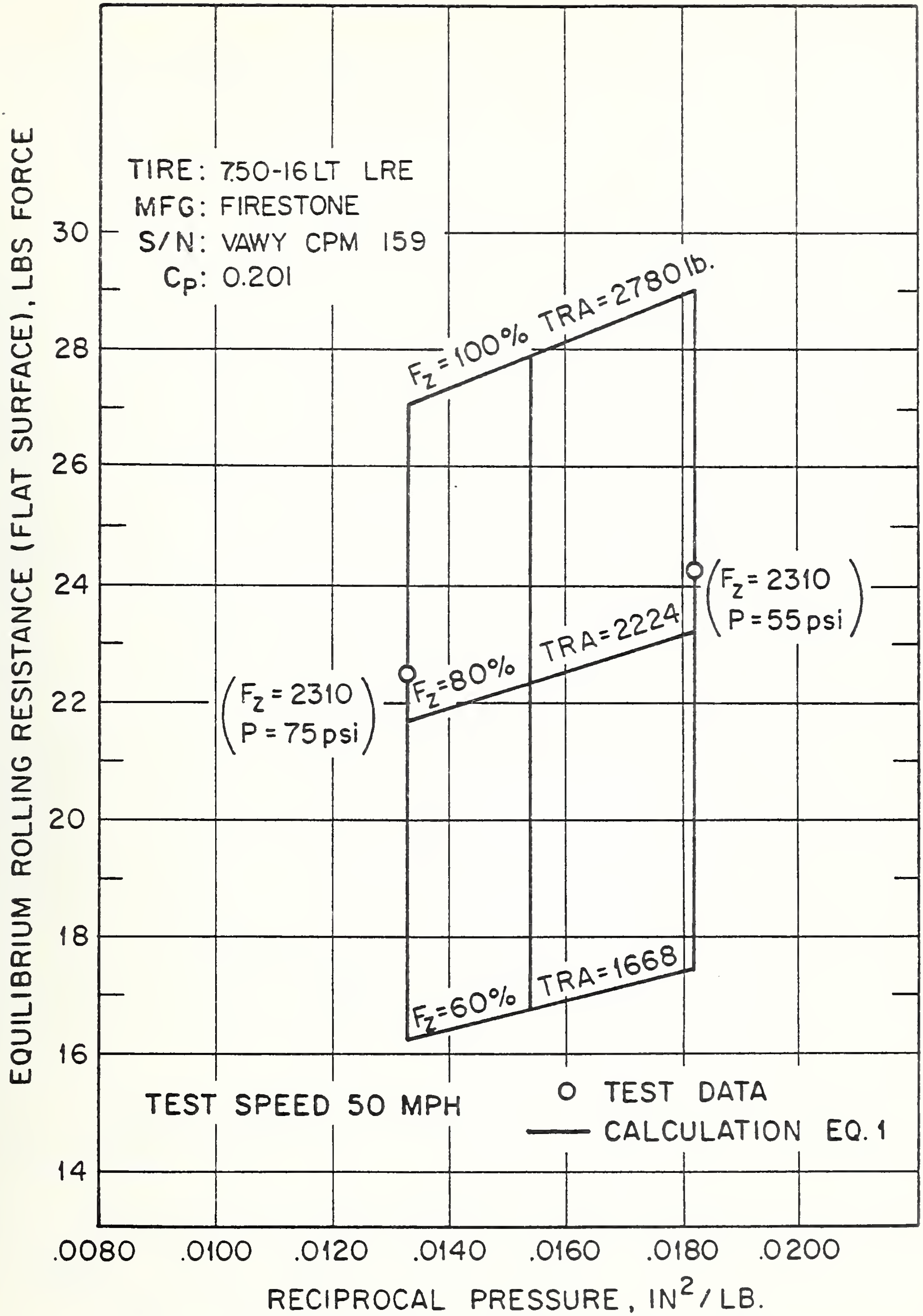

FIGURE 18. EQUILIBRIUM ROLLING RESISTANCE (FLAT SURFACE) VS. LOAD AND INFLATION PRESSURE: FIRESTONE 7.50-16LT LR E

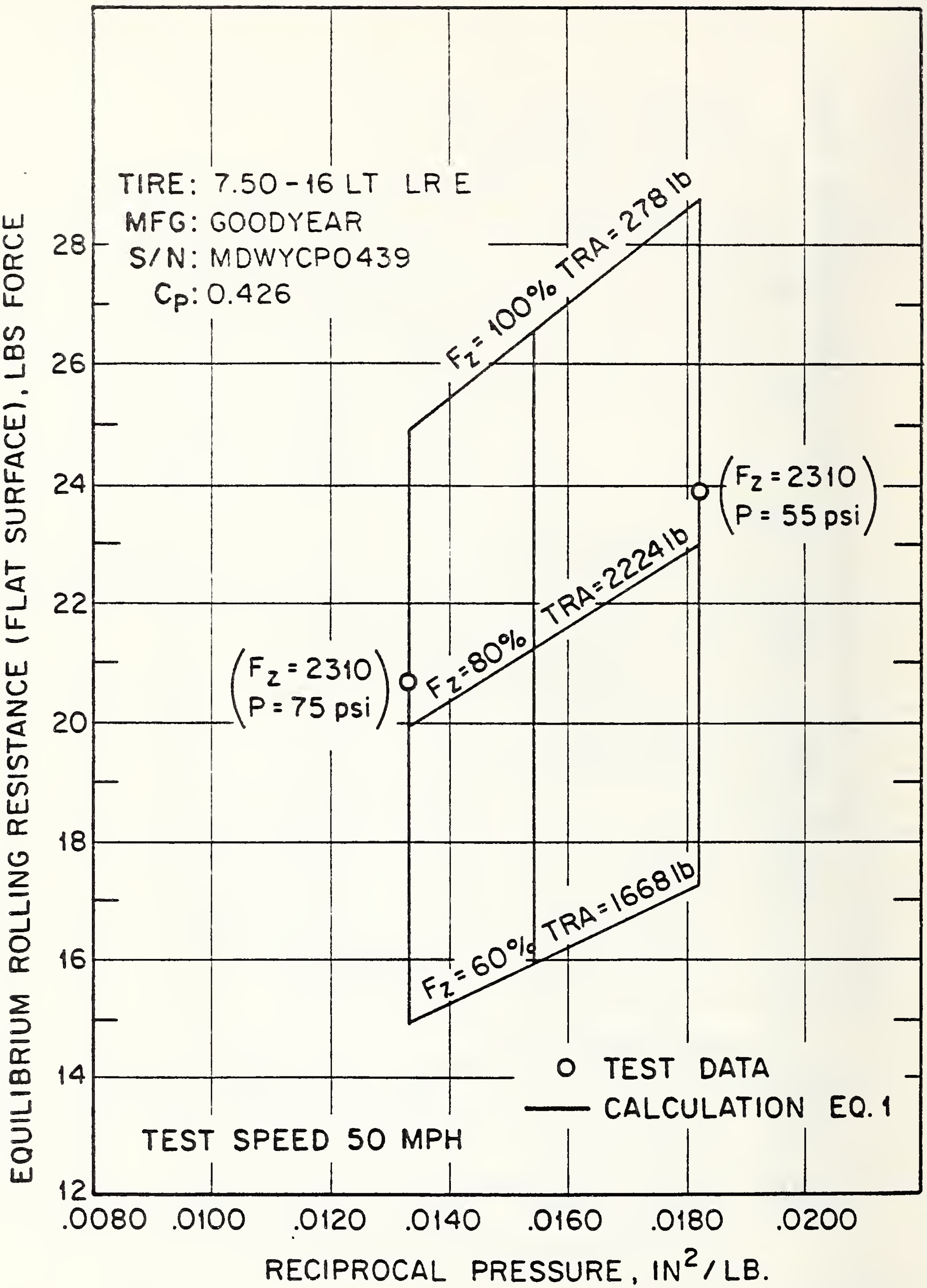

FIGURE 19. EQUILIBRIUM ROLLING RESISTANCE (FLAT SURFACE) VS. LOAD AND INFLATION PRESSURE: GOODYEAR 7.50-16 LT LR E

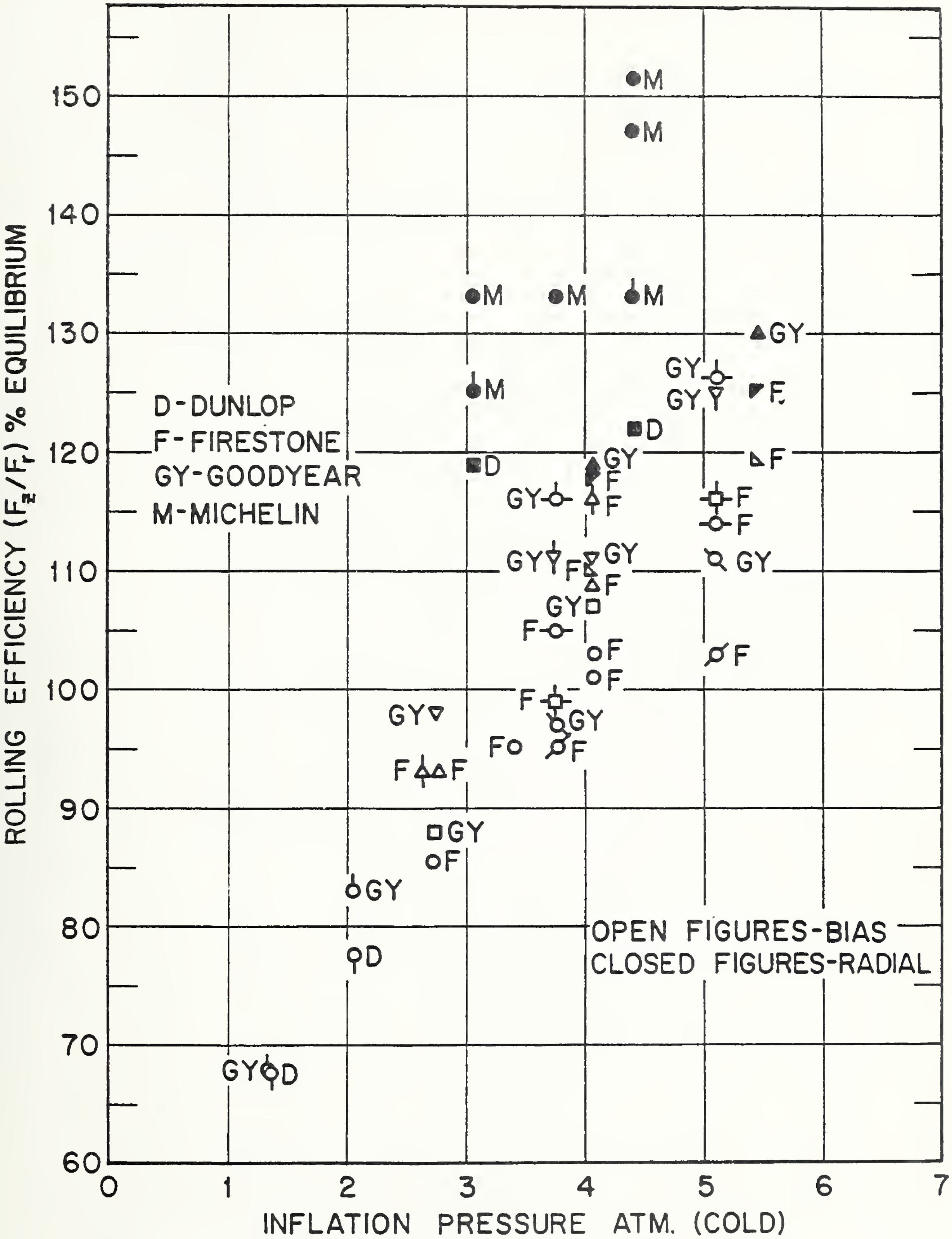

FIGURE 20. ROLLING RESISTANCE EFFICIENCY VS. INFLATION PRESSURE

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