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Technical Report

Tire-Dynamometer Roll Effects

by

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Notice

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Standards Development and Support Branch
Emission Control Technology Division
Office of Mobile Source Air Pollution Control
Office of Air and Waste Management
U. S. Environmental Protection Agency

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I. Introduction

Currently, the Federal Government determines light-duty vehicle fuel economy and emissions on the twin small-roll dynamometer. The vehicle is driven according to a specific speed-time cycle while its emissions are monitored and then its fuel consumption derived. It has been speculated that a vehicle being driven on a dynamometer may not be representatively tested. The geometry of the dynamometer-vehicle system is one which cannot be duplicated under actual driving conditions because only the vehicle rear tires are placed on the dynamometer and the surface upon which they are placed is curved. In the case of the twin small-roll dynamometer, the tires are placed between two cylinders approximately 17" apart. Due to this configuration, the tire deforms in two areas, one area at each cylinder-tire contact point, instead of only one area as on the road. The abnormal deformation on the dynamometer tends to require the tire to absorb a greater portion of the power transmitted to it than would the same tire on a flat road surface. It is generally assumed that the power absorbed by the tire (at 45 psi) on the dynamometer is twice that of the tire (at 26 psi) on the road. If such an assumption is true, the use of the twin small-roll dynamometer for emissions and fuel economy testing is technically justified if all tires behave in the same manner and in-use tire pressures remain at 26 psi. The increase in tire power absorption by a factor of two on the dynamometer accounts for the front two tires on the road.

Recently, questions have been raised as to the validity of the assumption that two tires on the dynamometer equals four tires on the road with regard to all tire construction types (radial, bias belted, and bias ply). Technical literature dealing with tire rolling forces on a flat surface, reports that, in general, radial tires exhibit lower rolling resistance (it takes less force to start and perpetuate tire roll) than the other two tire construction types.[1] However, it has been suggested that when radial tires are operated on the twin small-roll dynamometer they exhibit higher rolling resistance than the other two construction types under the same conditions.

To resolve the above question, all available technical literature was reviewed. Unfortunately, information concerning tire rolling resistance on the twin small-roll dynamometer was scarce.[2,3] This lack of information prompted an in-house investigation into the effects of the twin small-roll dynamometer on tires.

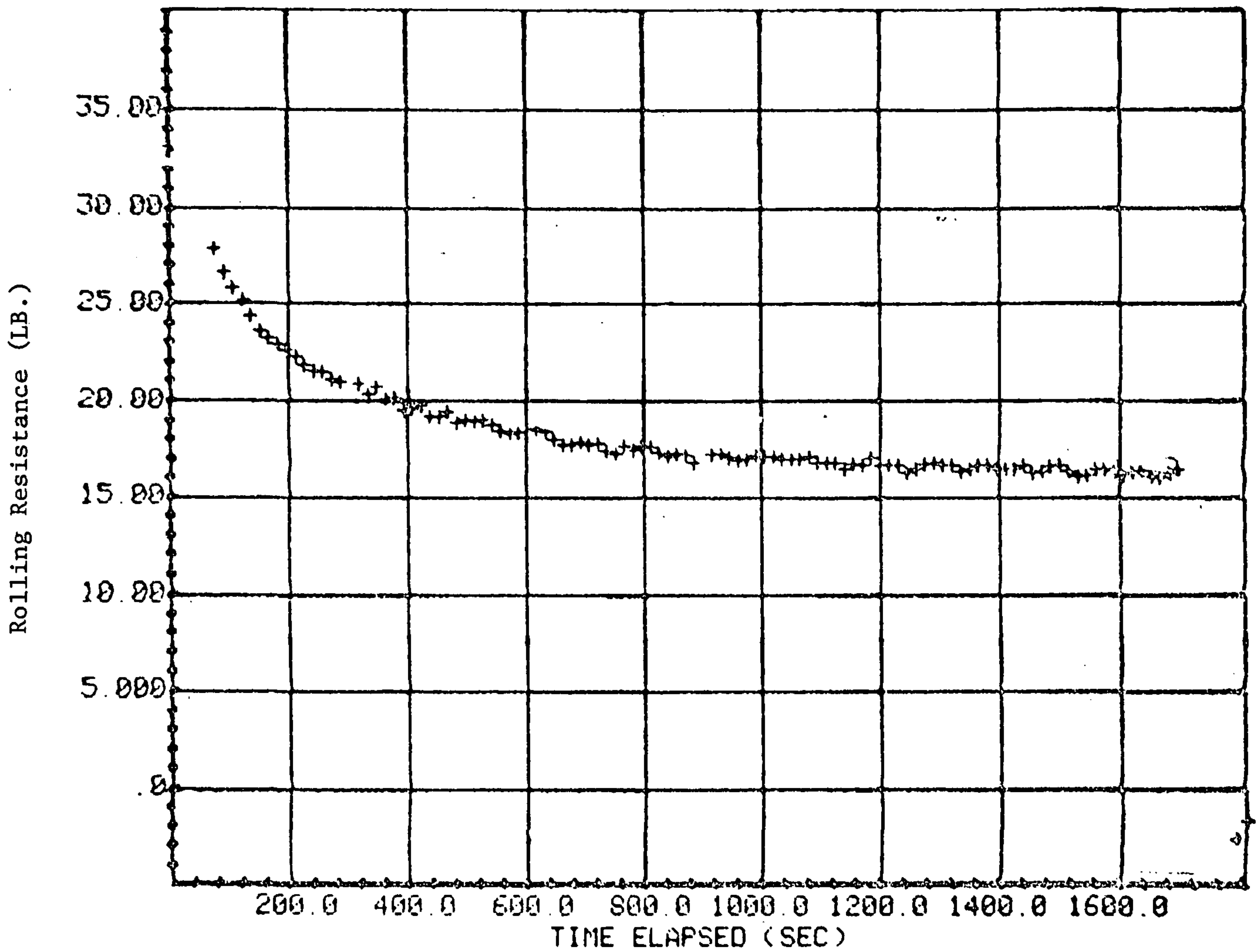
II. Summary and Conclusions

In order to resolve the question concerning the effects of the twin small-roll dynamometer on tire power absorption, 29 pairs of tires ranging in size from a BR78x13 to an LR78x15 and consisting of three common construction types (radial-belted, bias belted, and bias ply) were tested. The construction-type distribution of the sample consisted of 72% radial (belted), 14% bias belted and 14% bias ply tires. The method chosen to evaluate the effects on tire power absorption of the twin small-roll dynamometer was to monitor the power transmitted from a vehicle traveling at a velocity of 50 mph and the power received by the dynamometer. Any difference was considered to be the amount of power absorbed by the tire. The identical process was then repeated on a single large-roll (48" diameter) dynamometer. The single large-roll dynamometer test results were then corrected to a flat surface so that a comparison to the road could be accomplished. All the tires tested had an initial (cold) pressure of 45 PSIG which was unregulated during testing (capped air method). Each test period consisted of an acceleration, by the vehicle, to a velocity of 50 mph and this velocity sustained for a minimum period of 20 minutes. The initial 15 minutes of each test period were considered warm-up to insure tire, vehicle and dynamometer temperature stability throughout each test. Figure 1 depicts typical tire rolling resistance characteristics as a function of time at a velocity of 50 mph on a flat test surface.[1] Note that after approximately 900 seconds the tire rolling resistance is nearly constant, so that the assumption of stability was justified. At the end of the test period the vehicle was then decelerated to 0 mph and a different pair of tires installed. The vertical load on each test tire was held as constant as the vehicle rear suspension system would allow and was considered to be one-half the rear weight of the vehicle.

From the data collected, the effects of the twin small-roll dynamometer were quite evident. Initial data analysis indicated that at 45 PSIG, radial, bias belted and bias ply tires of the sample absorbed 2.65, 2.04 and 1.82 times, respectively, more power on the small twin-roll dynamometer than would the same tires at the same pressure (45 psi) on the road.

The increased power absorbed by the tire on the twin small-roll dynamometer is to take into account the front two tires of the vehicle which are not on the dynamometer, but would be operating on the road. This is the same as saying, "two tires on the small twin-roll dynamometer act like four tires on the road." However, if this explanation is accepted, then the power absorbed by the tire on the small twin-roll dynamometer should be twice that required by the road. As can be seen from the results above, this is not quite the case for all tire types at 45 psi inflation pressure. However a pressure of 45 PSIG is not a normal operating tire pressure on the road. Therefore, a correction factor to estimate the tire power absorption on the road at 26 PSIG, a reasonable operating tire pressure for the road, was applied and the analysis repeated. The results indicated that radial, bias belted and bias ply tires in this sample absorb 1.68, 1.30 and 1.15 times, respectively, more power on the small twin-roll dynamometer (with the standard test inflation pressure) than the same tires on the road with a tire inflation pressure of 26 PSIG. This implies that the tires are not totally accounted for by the interaction of the tires and the dynamometer rolls when a vehicle is tested for emissions and fuel economy.

According to the Federal Test Procedure the aerodynamic road load effects are estimated based on the test vehicle's aerodynamic characteristics. For radial tires, these procedures assume that the two tires on the twin small-roll dynamometer absorb the same power required by a vehicle on the road (i.e., two tires on the dynamometer equal four on



Tire Rolling Resistance Characteristics versus Time[5]

Figure 1

the road). However, this experiment suggests that two radial tires on the dynamometer are equivalent to approximately 3.4 tires on the road. Perhaps different dynamometer road load power absorber settings (e.g., correction factors) or lower tire pressures should be used for federal testing to account for differences among tire types. A different dynamometer which would better simulate the tire-road interaction may also be indicated.

In addition to the above results, an investigation into the effects of dynamometer horsepower setting, tire size, tire type and manufacturer was conducted. In general, this experiment could not detect a significant effect on tire rolling resistance due to dynamometer horsepower setting or tire size. However, it was found that when tire rolling resistance values were ranked by tire type in an increasing order, the rankings for each test dynamometer were different. The single large-roll dynamometer ranked the tire types as one would expect of the road; radials, bias belted, bias. The twin small-roll dynamometer ranked the same tires; bias belted, radials, bias. It was found that significant differences between tire types on the twin small-roll dynamometer could not be detected, whereas, on the single large-roll each tire type was significantly different from each of the other tire types. As for tire manufacturer, significant differences could be detected for radial and bias belted tires on the twin small-roll dynamometer, however, on the single large-roll, significant differences could only be detected for bias belted tires.

III. Technical Discussion

A. Program Objectives

The basic objectives of this test program were as follows:

1. To determine the relative power consumption rankings of bias, bias belted and radial ply tires on the twin small-roll (Clayton) and single large-roll (Electric) dynamometers,

2. If possible, determine the effects of dynamometer horsepower setting, tire size and tire manufacturer on tire power absorption for each of the dynamometers above, and

3. To possibly develop a correction factor which will allow a better simulation of tire power consumption on the road when a vehicle is tested on a Clayton dynamometer.

B. Program Design

Tire power absorption data were collected on both single large-roll and twin small-roll dynamometers. Twenty-nine pairs of tires were tested on each dynamometer at an average of two (2) dynamometer road load horsepower settings per pair of tires. The dynamometer horsepower settings were based on nominal tire size and normal vehicle weight. All the tires tested had an initial inflation pressure of 45 psig which was permitted to increase during testing (capped air method).

A mean tire power absorption was computed by tire type for each dynamometer and statistical tests for significant differences between dynamometers were then performed. The data generated were analyzed with respect to tire type, tire size, dynamometer horsepower setting and manufacturer.

C. Equipment

1. Test Vehicles

For the program, two vehicles were utilized, a 1971 Ford stationwagon and a 1972 Vega stationwagon. The 14 and 15 inch tires were tested on the Ford and the 13 inch tires were tested on the Vega. Each vehicle was equipped with an optical encoder from a "T" in the speedometer cable at the transmission to measure vehicle speed and a driveshaft torque sensor to measure the torque output of the engine-transmission. With those items, the power to the tire was monitored.

Although a driveshaft torque sensor measures the torque supplied by the engine-transmission, the actual torque at the tire is somewhat less due to rear axle and bearing losses. The torque supplied to the tire may be expressed by the following equation:

$$T_{tire} = T_{eng.} - T_{diff.} \quad (1)$$

where

$T_{eng.}$ = torque from the engine/transmission (measured by the driveshaft torque sensor)

$T_{diff.}$ = torque required to revolve the rear axle and associated bearings and gearing which make up the differential. Note: Brake drag was minimized by backing off the brake shoes and deactivating the self-adjusters.

In order to determine the torque due to the differential losses, $T_{diff.}$, the rear wheels of each vehicle were raised off the ground and the driveshaft torque at velocities from 10-60 mph was monitored. Vehicle velocity was increased and decreased in 10 mph increments. Thirty seconds of data were collected at each velocity. Prior to data collection, the differential underwent a 30 minute warm-up period to stablize the differential lubricant temperature and minimize any bearing losses. A linear regression analysis was then performed to obtain the torque $T_{diff.}$ as a function of driveshaft speed for both vehicles to be utilized during tire testing.

D. Dynamometers

Two dynamometers were utilized for the experiment, a standard twin small-roll Clayton and a single large-roll (48" diameter) LABECO. Each dynamometer roll was equipped with magnetic proximity detectors to record roll speed. In addition, each dynamometer load cell torque sensor signal was interfaced and recorded throughout the experiment. Although the dynamometer load cell torque is a good indication of the torque being transmitted by the tire, the sensor does not detect the torque the tire must apply to the roll in order to overcome the internal friction of the dynamometer. Therefore, to determine the torque at the roll surface, the torque due to bearing losses must be added to the load cell torque as indicated by equation 2:

$$T_R = T_{LC} + T_{BL} \qquad (2)$$

where

T_R = Torque at the tire/roll interface

T_{LC} = Total torque from the load cell

T_{BL} = Torque due to bearing and friction losses in the dynamometer.

To determine the torque due to bearing friction losses, the dynamometer was coasted down from 55 mph to 45 mph and the roll speed and T_{LC} monitored. T_R may be computed using the following equation:

$$T_R = I_D \propto$$

where

I_D = the inertia of the system

$\propto$ = angular acceleration of the roll

$\propto$ may be approximated by:

$$\propto \approx \frac{\Delta w}{\Delta t}$$

where

Δw = rate of change of the angular velocity

Δt = the time required to make the change in angular velocity

T_{LC} may be averaged over the time interval and then subtracted from T_R to obtain the torque due to the bearing and friction losses, T_{BL}.

$$T_{BL} = T_R - \overline{T}_{LC_{\Delta t}} \qquad (3)$$

A coastdown of the dynamometer was conducted at least once daily preceeded by a 30 minute warm-up.

The road load horsepower for each test on the twin small-roll dynamometer was set using the method described in the Federal Register. For each test on the single large-roll dynamometer, the torque at 50 mph observed on the twin small-roll dynamometer was duplicated. The equation used to obtain this specified torque is presented below:

$$T = \frac{550 \text{ x horsepower setting}}{W}$$

where

T = electric dyno torque at 50 mph

$$W = \text{the angular velocity} = \frac{\text{linear velocity}}{\text{radius of rotation (Clayton)}}$$

The computed torque was then "dialed in" while the test vehicle was operating at 50 mph. This was accomplished utilizing the "windage" potentiometer of the dynamometer controller. The "windage" electrical signal increases or decreases the absorption torque as a function of the velocity squared, as does the twin small-roll water brake power absorber, therefore, approximately duplicating the twin small-roll dynamometer horsepower curve.

E. Tires

A total of 29 pairs of tires were tested for their relative power absorption on two dynamometer types. Twenty-one of the 29 pairs of tires sampled were General Motors (GM) specification tires procured from GM. The balance were procured from local tire dealerships and were considered to be of original equipment manufacturer replacement quality. Of the tires tested, 72% were belted radials, 14% were bias belted, and 14% were bias ply tires. The range of sizes tested were from a B 78x13 to an LR 78x15. A complete list of the tires tested is contained in Appendix C.

Available literature indicates that all new tires undergo a period of cord settling and stretching once placed into service. Any measurements of tire power absorption during this period would be inaccurate and not considered typical. Therefore, a minimum of 300 miles were accumulated on each pair of tires. 250 miles of the 300 miles were accumulated on a large single-roll dynamometer by mounting the tires on a vehicle and then maintaining a velocity of 50 mph. The remaining 50 miles were accumulated on the road at varying speeds. The initial cold tire pressure during mileage accumulation was 26 PSIG and 28 PSIG for 13" and 14"-15" tires, respectively.

F. Data Collection

In order to collect as much data in as short a period of time as possible, all parameters were recorded at a second-by-second rate on magnetic tape. A 7-track Kennedy tape recorder was utilized to record vehicle and dynamometer-roll speeds, vehicle and dynamometer torques, real time, test identification code, tire manufacturer code, and tire size code. Data were collected for a minimum period of 20 minutes per dynamometer type and tire pair, in order to allow the tires to reach approximate temperature and pressure equilibrium. However, only data collected after the first 15 minutes were utilized.

G. Analysis

The power absorbed by the tire was computed each second for all data points after the first 900 seconds according to the following equations:

$$P_{AT} = P_{engine} - P_{abs.\ diff.} - P_{abs.\ dyno} - P_{bearing\ lossed\ dyno.} \quad (4)$$

$$= T_{eng} W_E - T_{diff} W_E - T_{LC} W_D - T_{BL} W_D$$

$$= (T_{eng} - T_{diff}) W_E - (T_{LC} + T_{BL}) W_D \quad (5)$$

where

P_{AT} is the power absorbed by the tire,
$T_{eng.}$ and $T_{diff.}$ are as defined in (1),
T_{LC} and T_{BL} are as defined in (2),
W_E and W_D are the angular velocities of the vehicle drive-shaft and dynamometer roll, respectively.

From each P_{AT} the rolling force was then derived as follows:

$$P_{AT} = T_T W_T \quad (6)$$

where T_T is the torque at the tire/roll interface and W_T is the angular velocity of the tire. However, T_T can be defined as the product of a force and a lever arm as follows:

$$T_T = F_R \times r \quad (7)$$

where F_R is the rolling force of the tire and r is the tire radius. Substituting equation (7) into (6) yields:

$$P_{AT} = (F_R \times r)\ W_T \quad (8)$$

Since the angular velocity W_T can be represented as a ratio of the linear velocity, V_T, and the radius of the tire, r, a substitution for W_T in equation (8) produces:

$$P_{AT} = \frac{(F_R \times r) V_T}{r} = F_R V_T \quad (9)$$

the linear velocity V_t is in actuality the ground or test surface velocity. However, with all vehicle tests on dynamometers, a certain amount of tire slip occurs. For this reason, the vehicle linear velocity, the one parameter common to both dynamometers, rather than the dynamometer-roll linear velocity was utilized for this analysis. Therefore, F_R can be expressed as,

$$F_R = \frac{P_{AT}}{V_T} \quad \text{where } V_T \text{ is the vehicle speed.} \quad (10)$$

Mean values for the vehicle speed, V_T, power absorbed P_{AT}, and the rolling force F_R, were then computed for each test and considered a data point for that particular set of tires. Due to technician error and accelerator-control drift, it was found that the mean vehicle speeds varied from test to test by a maximum of 5 mph. These speed variations make any direct data comparisons difficult. In order to resolve this problem and enable valid statistical comparisons to be made, a specific velocity of 50 mph was chosen and a new P_{AT} computed. This was accomplished by first determining F_R from equation 10 utilizing the test P_{AT} and the test velocity. This value of F_R and the chosen V_T were then substituted into equation 9 and the new value for P_{AT} computed. It should be noted from equation 10 that F_R is far less sensitive to speed variations than is P_{AT}. Indications from the technical literature are that an approximate error of only 0.3% per mph is introduced by such an estimate.[1,4,5]

Of all the parameters affecting tire power absorption, the vertical load on the tire has yet to be discussed. In general, tire power absorption is directly proportional to the load upon it.[1] As the vertical load increases, the tire power absorption also increases. Therefore, all the above computations are a function of the vertical load under which a particular set of tires was tested. The vertical load used for this experiment was arrived at by weighing the rear portion of each test vehicle with a full tank of fuel and a driver. Fuel was added to each test vehicle at the completion of every second test in order to maintain as constant a vertical load as possible. However, the vertical load of the two test vehicles differed, therefore, making direct tire rolling force, F_R, data comparisons difficult. By calculating the ratio of F_R to the test vertical load, F_{ZT}, all tire test results could then be directly compared. This is expressed in the equation below:

$$F_{RR} = \frac{F_R}{F_{ZT}} \qquad (11)$$

However, statements concerning the power absorbed at 50 mph, P_{AT}, for all the data still could not be made. Since the tire rolling force, F_R, is nearly linear with vertical load,[1,6,7] estimates of the power absorbed at 50 mph can be obtained using a form of equation 11. Using the rolling resistance values, F_{RR}, previously obtained, a standard vertical load was chosen and the power absorbed at 50 mph was predicted. The equations presented below outline this process:

$$F_{RN} = F_{RR} \times F_{ZN} \qquad (12)$$

$$P_{ATN} = F_{RN} \times 50 \text{ mph} \qquad (13)$$

where F_{RR} is as defined in equation 11 and

F_{RN} = normalized F_R

$F_{ZN} = 2.985 \times 10^3$ lbs.

P_{ATN} = normalized P_{AT}

The standard vertical load was chosen to be the rear weight of the Ford stationwagon used to test 14" and 15" tires. This selection was based on the number of tests conducted at that vertical load, so that only those data generated for 13" tires required normalization. Data from all the tires tested were then grouped by test dynamometer (Clayton, Electric) and statistical tests for significant differences between mean test results were then performed. In addition, analyses of variance were conducted to determine the effects of tire size, dynamometer horsepower setting and tire manufacturer on P_{ATN} for each test dynamometer.

H. Test Procedure

Prior to the commencement of testing on a given day, the test dynamometer and vehicle were warmed-up for 30 minutes at a steady state velocity of 50 mph. Upon completion of this warm-up period, the dynamometer road load horsepower was set, if required. The warm-up tires were then removed from the vehicle and a pair of test tires were installed. An initial cold tire pressure of 45 PSIG was set upon installation of the test tires. The test vehicle was then accelerated to 50 mph and this velocity sustained for a minimum of 20 minutes. Data collection began upon vehicle acceleration. Upon completion of the test period, the vehicle was decelerated to 0 mph and a new pair of test tires installed. The time to change tires averages approximately 5 minutes. The above process was repeated for each pair of test tires for approximately 4 different road load horsepower settings per test dynamometer.

The purpose of the rapid tire changing was to minimize dynamometer and vehicle lubricant cooling which would increase the bearing and frictional losses. Once tested, a given pair of tires were not retested unless a minimum of 4 hours had elapsed. This allowed the tires to return to ambient temperature and reduced tire damage from excessive heat. Fuel was added to the vehicle after every second test to minimize tire verticle load fluctuations. Each set of tires was tested at an average of two (2) dynamometer horsepower settings. A total of 120 tests (61 Electric and 59 Clayton) were conducted.

IV. Results

The following analyses for the effects of dynamometer horsepower setting, tire size, tire manufacturer and tire type on tire power absorption were conducted on the data for tires inflated to 45 psig on each dynamometer.

A. Effects of Dynamometer Horsepower Setting

In order to isolate the effects of dynamometer horsepower setting, the sample was separated by nominal tire size and tire type for each dynamometer. A correlation analysis was performed on the test data. The results of this analysis indicate that, in general, no significant effects on P_{ATN} could be discerned due to dynamometer horsepower setting on either dynamometer. There were, however, two cases (one on each dynamometer) where a significant correlation resulted. These cases were for 14" radial tires on the twin small-roll dynamometer and 13" radial tires on the single large-roll dynamometer. In both cases the power absorbed at 50 mph, P_{ATN}, decreased with increasing dynamometer horsepower setting. These results are consistent with those reported in the literature[1] on a flat test surface within the range of forces applied in this experiment. Plots of P_{ATN}, the power absorbed at 50 mph, as a function of dynamometer horsepower setting by tire size and type are presented in Appendix F for both dynamometers. The fact that, in general, no effect could be discerned could be due to tire slip on the rolls and test variability. By defining tire slip for the small twin-roll dynamometer as the difference between rear roll speed and front roll speed and plotting tire slip as a function of dynamometer horsepower setting, it can be seen that tire slip increases with increasing horsepower setting. Figure 2 depicts these variables for 13" radial tires. The effect of horsepower setting may be masked by this loss of tractive effort in combination with test variability. It is assumed that tire slip occurs on the road, but to what extent is not yet known.

Since the effects identified as significant were small (1 case in 6) it was deemed that the overall conclusions would not be affected. The data were therefore combined for further analysis.

B. Effects of Tire Size

The sample was segregated into three groups based on nominal tire size (13", 14", and 15") to determine the effects on P_{ATN} and F_{RR}. It was found that on either dynamometer, 13" tires were significantly different from 14" and 15" tires. These initial findings could have been caused by the interaction effect of tire type (i.e., 13" tires exhibited lower rolling resistance because there were more radial 13" tires than radial 14" and 15" tires). Therefore, to isolate this interactive effect, the ANOVA was repeated, however, this time controlling for tire type. The results of the second ANOVA indicated that an effect on P_{ATN} could not be detected on either dynamometer. This does not mean to say that tire size has no effect on rolling resistance, but that this experiment could not detect any. To resolve any effects due to tire size, variables such as manufacturer and tire type would have to be controlled when performing the ANOVA. Unfortunately, attempts to do so created holes in the analysis matrix which made any results questionable.

C. Effects of Tire Type

Since significant effects on P_{ATN} and F_{RR} due to dynamometer horsepower setting and tire size could not be detected, the combined data were segregated by tire type. An analysis of variance was then performed on these data for each test dynamometer. The results indicated that for the case of the twin small-roll dynamometer, differences between tire types could not be discerned. For the single large-roll dynamometer, each tire type was significantly different from the other tire types. A summary of the statistical comparisons are presented in Tables 1 and 2 by dynamometer. These results would indicate that the geometry of the twin small-roll dynamometer forces the tires to absorb a similar amount of power regardless of construction type.

Figures 3 and 4 are plots of the normalized power absorbed at 50 MPH, P_{ATN}, as a function of tire type for the twin small-roll and single large-roll dynamometers, respectively. The overall shift of the

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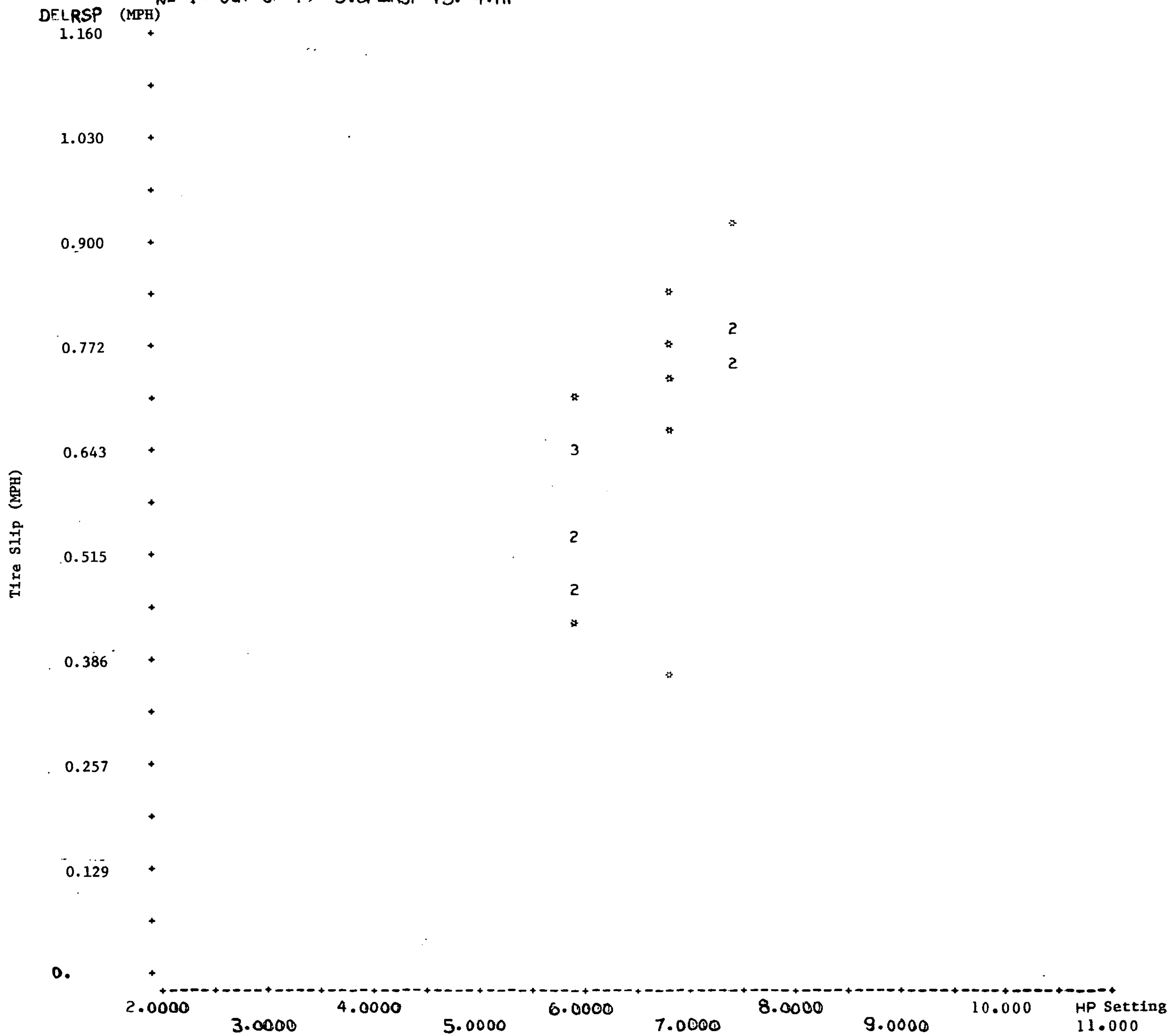

Figure 2
Tire Slip as a Function of Dynamometer Horsepower Setting for 13" Radial Tires

Table 1

Mean Level Comparisons Between Tire Construction Types On The Twin Small-Roll (Clayton) Dynamometer

	Mean Power Absorbed at 50 mph, P_{ATN} (watts)	Mean Rolling Resistance F_{RR} (lb/k-lb)	F-Stat	Degrees of Freedom	Significance at 95% Confidence
Radial/ Bias Belted	5721.961/5212.867	19.282/17.567	2.515	39,10	No
Radial/ Bias	5721.961/5829.297	19.282/19.644	0.086	7,39	No
Bias Belted/ Bias	5212.867/5829.297	17.567/19.644	1.979	7,10	No

Table 2

Mean Level Comparisons Between Tire Construction Types On The Single Large-Roll (Electric) Dynamometer

	Mean Power Absorbed at 50 mph, P_{ATN} (watts)	Mean Rolling Resistance F_{RR} (lb/k-lb)	F-Stat	Degrees of Freedom	Significance at 95% Confidence
Radial/ Bias Belted	2689.754/3150.111	9.064/10.615	4.078	41,10	Yes
Radial/ Bias	2689.754/3994.747	9.064/13.462	25.262	7,41	Yes
Bias Belted/ Bias	3150.111/3994.747	10.615/13.462	7.294	7,10	Yes

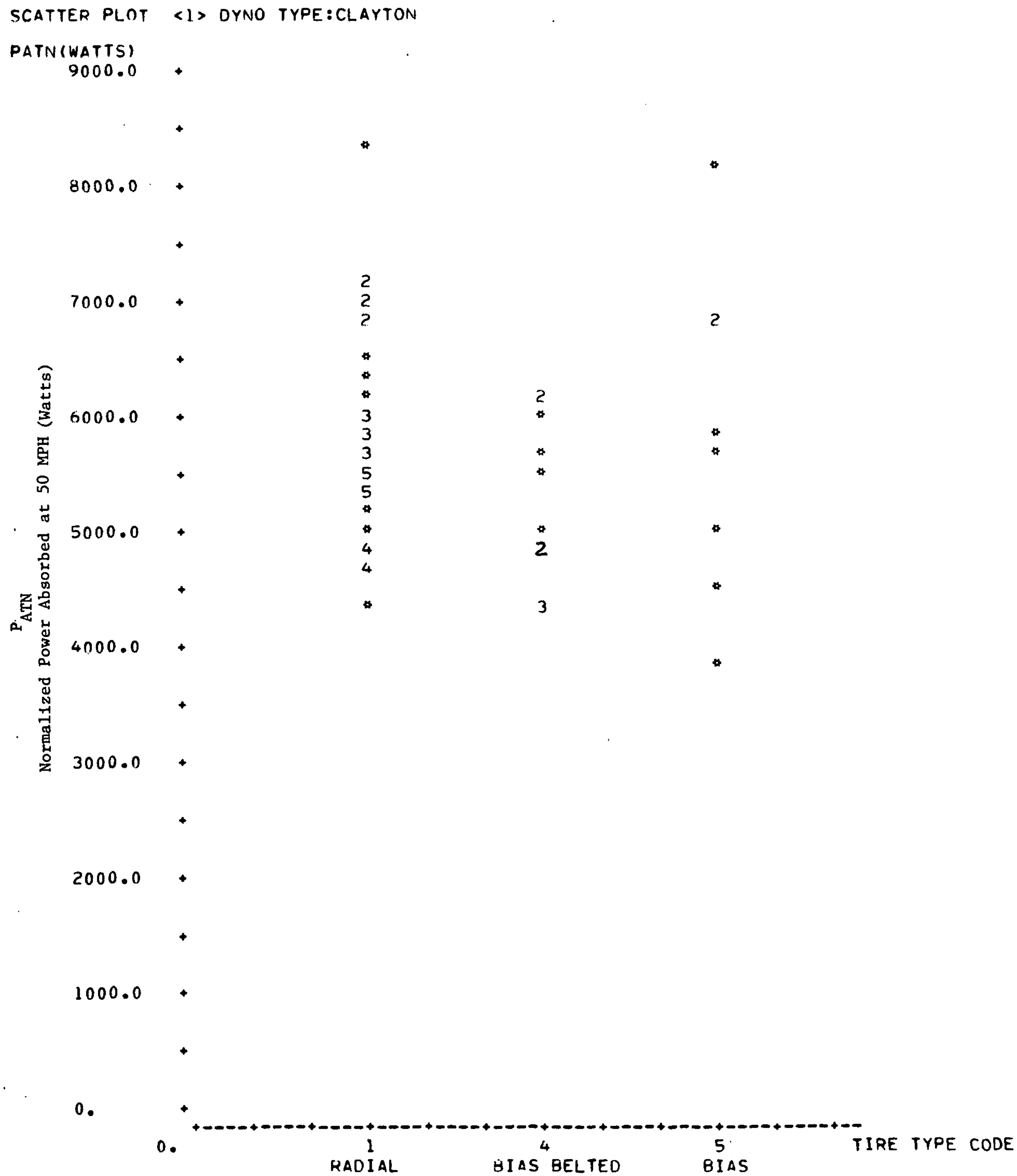

FIGURE 3

NORMALIZED POWER ABSORBED AT 50 MPH AS A FUNCTION OF TIRE TYPE
FOR THE TWIN SMALL-ROLL DYNAMOMETER

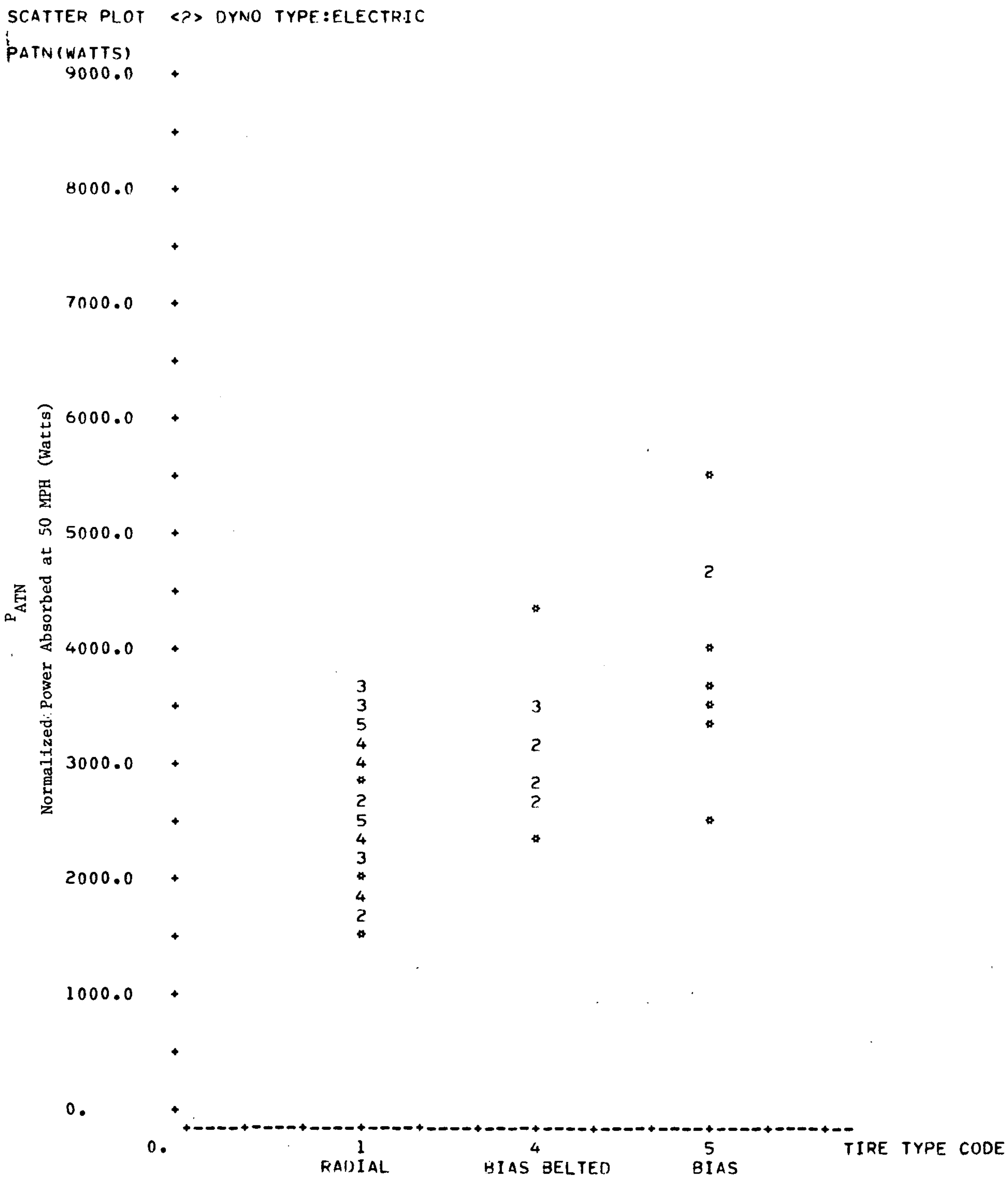

FIGURE 4
NORMALIZED POWER ABSORBED AT 50MPH AS A FUNCTION OF TIRE TYPE
FOR THE SINGLE LARGE-ROLL (ELECTRIC) DYNAMOMETER

data, in Figure 4, to lower power absorption is due to the more natural footprint of the tire on the single large-roll dynamometer. The large amounts of overlap in P_{ATN} of the different tire types may be due to the differences in load carrying capacity (F, G, H, etc.) within each tire manufacturer and between each manufacturer. The corresponding plots to Figures 3 and 4 for F_{RR} are presented in Appendix A. In addition, scatter plots of P_{ATN} and F_{RR} as a function of dynamometer type for each tire type are also presented in Appendix A.

The large scatter of the data for the bias and radial ply tires on the twin small-roll dynamometer lead to an investigation of the maximum and minimum P_{ATN} values. The tires with maximum and minimum P_{ATN} values in these categories were identified for each dynamometer. It was found, in the bias ply category, that the tire with the maximum P_{ATN} value on the twin small-roll dynamometer also had the maximum value on the single large-roll dynamometer. The same was indicated for the minimum values. In the radial ply category, the tire with the minimum P_{ATN} value on the twin small-roll dynamometer also had the minimum value on the single large-roll dynamometer. However, the tire with the maximum P_{ATN} value on the twin small-roll dynamometer in this category did not have the maximum value on the single large-roll, but its value was above average. Conversely, the tire with the maximum P_{ATN} value on the single large-roll dynamometer attained an above average value of P_{ATN} on the twin small-roll dynamometer.

A comparison of the replicate tests conducted on the tires in question indicates that these tires displayed a large test-test variability. This variability may be due to a change in some parameter or parameters, such as vehicle speed or vertical load, which went unnoticed and unrecorded. Since rejection of these data points affects the mean values only slightly and does not affect the overall results obtained above, these data points were not removed.

The increasing variability from radial to bias belted and from bias belted to bias ply tires could be the presence (or lack of) a belt beneath the tread. The material and design of the belt may also have an effect on P_{ATN}. Test to test variability could also be another explanation. Figure 5 depicts P_{ATN} as a function of manufacturer for 15" radial tires tested on the small twin-roll dynamometer. Beside each data point, the corresponding tire identification number appears. As can be seen, in most cases the test to test repeatability for a given manufacturer's tire is fairly good (approximately 8%). However, some tires are more repeatable than others.

Upon completion of the data analysis as described above, rankings of the three tire types for each dynamometer were completed. Tables 3 and 4 present the rankings of the computed mean values for the power absorbed at 50 mph, P_{ATN}, and the tire rolling resistance, F_{RR}. The tire type with the lowest power absorption was ranked "1" and that with the highest ranked "3". As can bee seen from the Tables, the rankings of the respective tire types differ from test dynamometer to test dynamometer. Although the single large-roll dynamometer is not the road, the rankings for the respective tire types are in agreement with previously published data on a flat test surface.[1]

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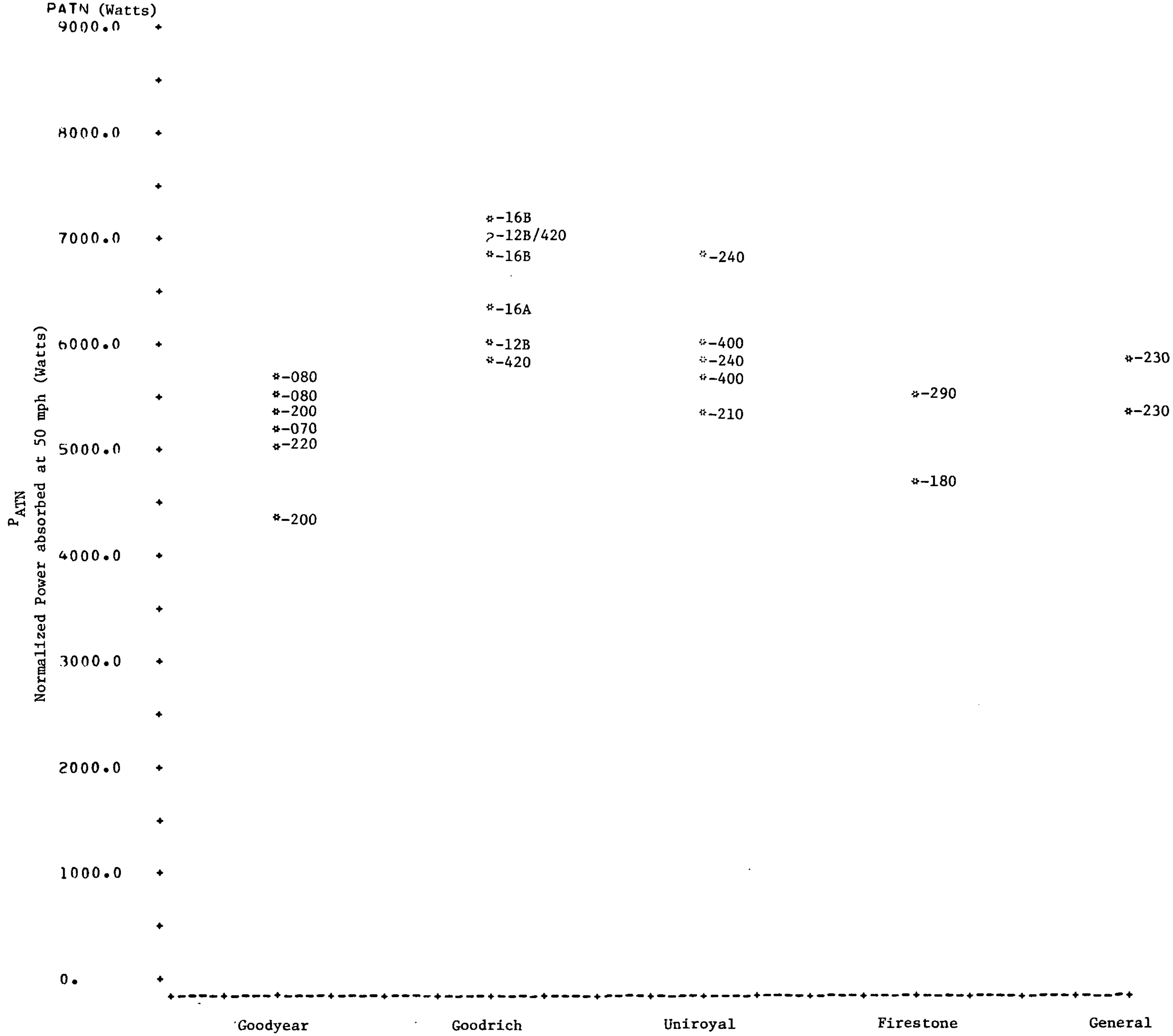

Figure 5
Normalized Power Absorbed at 50 mph as a Function of Tire Manufacturer, for 15" Radial Ply Tires on the Small Twin-Roll Dynamometer

Table 3

Relative Ranking On Tire Construction Types
On The Twin Small-Roll Dynamometer

Tire Type	Ranking	Mean Power Absorbed at 50 mph (Watts) (P_{ATN})	Mean Rolling Resistance (lb/k-lb load) (F_{RR})
Radial	2	5721.961	19.282
Bias Belted	1	5212.867	17.567
Bias	3	5829.297	19.644

Ranking Scheme
1 = lowest power absorption at 50 mph.
3 = highest power absorption at 50 mph.

Table 4

Relative Ranking Of Tire Construction
Types On the Single Large-Roll Dynamometer

Tire Type	Ranking	Mean Power Absorbed at 50 mph (Watts) (P_{ATN})	Mean Rolling Resistance (lb/k-lb load) (F_{RR})
Radial	1	2689.754	9.064
Bias Belted	2	3150.111	10.615
Bias	3	3994.747	13.462

D. Effects of Tire Manufacturer

The tires for this test program were made by five popular American Manufacturers; Good year, B.F. Goodrich, Uniroyal, Firestone, and General. By analyzing the test data with respect to tire type and manufacturer it is possible to determine the relative rankings of the manufacturers' products based on the power absorbed at 50 mph, P_{ATN}, mean values for each tire type. Tables 5 and 6 show these results as the percent deviation from the mean P_{ATN} for the twin small-roll dynamometer and the large single-roll dynamometer respectively. As an example, note that for radial tires on the single large-roll dynamometer (Table 5), Goodyear is 10.61% below the mean P_{ATN} (indicated by the "minus" sign) and B.F. Goodrich is 9.76% above. This same type of ranking is also displayed on the twin small-roll dynamometer. Scatter plots of P_{ATN} versus manufacturer for each dynamometer tire type are presented in Appendix B.

By performing an analysis of variance (ANOVA) on the power absorbed at 50 mph, P_{ATN}, the tire rolling resistance, and F_{RR}, the effect due to tire manufacturer with respect to tire type was determined. The results of the ANOVA are summarized below:

Large Single-Roll Dynamometer	Significant Difference due to Manufacturer
Radials	NO
Bias Belted	YES
Bias	NO

Small Twin-Roll Dynamometer	Significant Difference due to Manufacturer
Radials	YES
Bias Belted	YES
Bias	NO

A more detailed ANOVA was then conducted to determine which manufacturers were causing the effect. For radial tires on the small twin-roll dynamometer it was found that Goodyear, Uniroyal and Firestone displayed significantly less rolling resistance (and absorbed power) than B.F. Goodrich. No conclusions were drawn concerning General tires due to insufficient data. For bias belted tires, Goodyear was signficantly different from Uniroyal and Firestone on either dynamometer and in the case of the twin small-roll, Uniroyal and Firestone tires were significantly different from each other (B.F. Goodrich and General bias belted tires were not tested).

The relative insensitivity of the large single-roll dynamometer is most likely due to the abnormal tire pressure (45 PSIG) at which the tires were tested. If a reasonable tire pressure of 26 PSI were utilized, more normal cord and sidewall flexing would take place so that the method of manufacture would become more critical in regard to the tires ability to transmit power. Attempts to further segregate the sample by controlling the analysis by manufacturer as well as tire size and construction type, left holes in the analysis matrix rendering any results questionable.

Table 5

Percent From The Power Absorbed at 50 MPH, P_{ATN}, Grand Mean by Manufacturer and Tire Type (Single Large-Roll Dynamometer - Uncorrected to Road or Increase Tire Pressure).

Tire Type	Grand Mean	Percent Deviation from Grand Mean				
		Goodyear	Goodrich	Uniroyal	Firestone	General
Radial	2689.754	-10.61	9.76	1.64	6.25	-8.77
Bias Belted	3150.111	-14.48	NONE	15.69	8.45	NONE
Bias	3994.747	NONE	-0.38	1.15	NONE	NONE

NONE = None tested.

Table 6

Percent From The Power Absorbed at 50 MPH, P_{ATN}, Grand Mean by Manufacturer and Tire Type (Twin Small-Roll Dynamometer)

Tire Type	Grand Mean	Percent Deviation from Grand Mean				
		Goodyear	Goodrich	Uniroyal	Firestone	General
Radial	5721.961	-8.10	15.38	0.02	-0.74	-2.00
Bias Belted	5212.867	-12.98	NONE	3.49	18.14	NONE
Bias	5829.297	NONE	1.64	-2.74	NONE	NONE

NONE = None tested.

$$\text{Percent from } P_{ATN} \text{ Grand Mean} = \frac{\text{Manufacturer } P_{ATN} \text{ Mean} - P_{ATN} \text{ Grand Mean}}{P_{ATN} \text{ Grand Mean}}$$

E. Twin Small-Roll Dynamometer Road Correction Factor Development

One of the objectives of this experiment is to develop a twin small-roll dynamometer to road correction factor. It should be noted that the accuracy of any relationship developed is questionable due to the data scatter. The following computations attempt to take into account this variability.

The basic relationship between the test dynamometers can be obtained by comparing the mean value for the power absorbed at 50 mph, P_{ATN}, for each tire type across the two test dynamometers. From Figures 3 and 4 it can be seen that an obvious difference between the test dynamometers exists. In order to determine if this difference is significant, an analysis of variance was perfromed on P_{ATN} by tire type. It was found that for each tire type the difference between test dynamometers is significant. The magnitude of this difference was then determined by computing the ratio of mean P_{ATN} values on the twin small-roll dynamometer to the mean P_{ATN} values on the single large-roll dynamometer by tire type. The equation below summarizes the computation performed for each tire type. Table 7 presents the ratios obtained and their significance.

$$R_{CE} = \frac{\text{mean } P_{ATN} \text{ on twin small-roll}}{\text{mean } P_{ATN} \text{ on single large-roll}} \qquad (14)$$

Table 7

Ratio of Mean Levels and Relative Significance

	Mean Level Ratio R_{CE}*	Significance at 95% Confidence	Student's T Statistic	Degrees of Freedom
Radials	2.13	Yes	17.636	73.6
Bias Belted	1.65	Yes	7.42	20
Bias	1.46	Yes	3.014	14

* These results are for tires inflated to 45 PSIG on both dynamometers.

It should be noted that a correction factor is required when comparing force or power measurements obtained on the single large-roll dynamometer to that of the road. This is due to higher rolling losses produced by the roll curvature. The curved surface causes greater maximum deflection of the tire than would have occurred on the road with the same vertical load. The required correction factor is a function of the loaded tire radius and the roll radius.[1,6] Equation 15 shows this relationship:

$$C_{DR} = \left(1 + \frac{r}{R}\right)^{-1/2} \qquad (15)$$

where

C_{DR} = correction factor from dynamometer roll to the road

r = loaded tire radius

R = roll radius

Force or power measurements taken on the dynamometer would be multiplied by equation 15, therefore decreasing those values of F_{RR} and P_{ATN} obtained on the single large-roll dynamometer.

The loaded tire radii utilized for this correction were obtained by measuring each tire from the ground to the top surface while mounted on the appropriate test vehicle and dividing this measurement by 2. A complete listing of the tire loaded and unloaded radii by tire identification number is contained in Appendix E.

By substituting the appropriate values into Equation 14, a correction factor for each tire tested was generated. The mean correction factor for each tire size is present below.

Nominal Tire Size	C_{DR}
13 inch	.819
14 inch	.811
15 inch	.799

Using the correction factors computed for each tire, the single large-roll dynamometer power absorption and rolling resistance, F_{RR}, data were corrected to a flat surface and new mean power absorption values were calculated for each tire type. The corrected mean P_{ATN} F_{RR} values for each tire type are shown in Table 8.

Table 8

Curvature Corrected Single Large-Roll Dynamometer Power and Force Measurements To The Road At An Inflation Pressure Of 45 PSIG

Tire Type	Ranking	Mean Power Absorbed at 50 mph (Watts) (P_{ATN})	Mean Rolling Resistance (lb/k-lb load) (F_{RR})	Curvature Corrected R_{CE}
Radials	1	2165.252	7.297	2.65
Bias Belted	2	2548.489	8.588	2.04
Bias	3	3207.782	10.810	1.82

Although the single large-roll dynamometer results have been corrected to a flat road-type surface, another correction must be made to these data in order to compare the twin small-roll dynamometer data to the road. In actual operation, tires are not traditionally inflated to 45 PSIG. From tire testing at Calspan's Tire Research Laboratory,[1] it has been estimated that equilibrium tire rolling resistance is decreased by 3% per 1 PSI increased in inflation pressure. Therefore to estimate actual road tire power absorption and rolling resistance at 26 PSI, a 19 PSI reduction, the mean values of P_{ATN} and F_{RR} in Table 8 would have to be increased by approximately 57%. This correction was performed on the data contained in Table 8 and the ratio, R_{CE}, of mean values was recomputed to obtain a relationship between the twin small-roll dynamometer and the road at 26 psi. These results, in addition to the uncorrected data and the twin small-roll dynamometer data, are presented in Table 9 as a summary of the total correction process and a comparison to the twin small-roll dynamometer results.

Table 9

Comparison Of Twin Small-Roll Dynamometer Results With Corrected Single Large-Roll Dynamometer Results At 26 PSI

Tire Type	Twin Small-Roll		Large Roll Corrected To Road At 45 PSI		Large Roll Corrected To Road At 26 PSI		Curvature and Inflation Pressure Corrected
	P_{ATN} (watts)	F_{RR} (lb/k-lb)	P_{ATN} (watts)	F_{RR} (lb/k-lb)	P_{ATN} (watts)	F_{RR} (lb/k-lb)	R_{CE}
Radial	5721.96	19.282	2168.211	7.306	3404.091	11.470	1.68
Bias Belted	5212.867	17.567	2545.932	8.579	3997.113	13.469	1.30
Bias	5829.297	19.644	3239.604	10.916	5086.178	17.138	1.15

It can be seen from the R_{CE} values presented in Table 9 that the basic assumption of "two on the twin small-roll (at 45 psi) is equal to four on the road (at 26 psi)" may not be correct. In order for this assumption to be valid, R_{CE} in Table 9 would have to have a value of two for all tire types. Since this is not the case, one is lead to believe that the tires are not completely accounted for on the twin small-roll dynamometer.

In order to completely account for the tires on the twin small-roll dynamometer, the amount of power absorbed at 50 mph by the tire must be increased. The amount of increase can be determined from the values of R_{CE}. By doubling the value of R_{CE} in Table 9, the equivalent number of tires on the road at 26 PSI represented by the power absorbed by the tire on the twin small-roll dynamometer at 45 PSI may be obtained. By dividing this quantity into 4, the desired number of tires on the road, the amount of power absorption increase is obtained. Table 10 presents the correction factors obtained from the above computations for each tire type.

Table 10

Twin Small-Roll Dynamometer Correction Factors

Tire Type	Correction Factor
Radial	1.190
Bias Belted	1.534
Bias	1.745

By increasing the amount of power absorbed by the tire on the twin small-roll dynamometer by the appropriate tire type correction factor, the basic assumption should be realized. Two possible methods of increasing P_{ATN} on the twin small-roll dynamometer are; 1) reduce the test tire pressure or 2) increase the vertical loading on the tire. The former suggestion may prove to be hazardous, since tire life may be drastically reduced when operating at other than 45 PSI inflation pressures. A partial solution may be to increase the dynamometer power absorber setting to increase vehicle engine loading, however increased tire slip may result.

V. Conclusions

The results of this experiment make three things evident:

1) The ranking of radial, bias belted and bias ply tires based on tire rolling resistance is not the same on the small twin-roll dynamometer as it is on the road.

2) The power absorbed by the tire at 50 mph when operated on the small twin-roll dynamometer at 45 PSIG is not twice that of the same tire at 26 PSIG operated on the road, as was generally thought to be true.

3) The rolling resistance of one manufacturer's tires can be statistically distinguished from another's.

The data presented in this report also indicate several notable items:

Item 1: Federal emissions and fuel economy testing is conducted on the small twin-roll dynamometer. This experiment indicates that based on rolling resistance, the relative rankings of tires with respect to construction type on the small twin-roll dynamometer may not be the same as the road (i.e., the relationship between radial and bias belted tires at 50 mph is, on the average, reversed on the small twin-roll dynamometer). This would imply that a vehicle tested on the dynamometer may not receive any benefits (or penalties) based on the type of tires on that vehicle.

Item 2: Since only the two driving tires are operated on the dynamometer, twice the road power should be absorbed to account for the two non-driving tires not on the dynamometer. The data presented indicates that this is not occuring. This implies that an adjustment (increase) to the amount of power absorbed by the tires should be made when testing a vehicle on the twin small-roll dynamometer.

Item 3: When a vehicle is certified for production by the EPA, the manufacturer of the tires supplied on the test vehicle is not specified. As can be seen from the analysis above, the tire manufacturer has an effect on the tire rolling resistance and therefore the vehicle's emissions and fuel economy. It is common practice for a vehicle manufacturer to have several manufacturers for the same tire. This fact leads to the conclusion that a vehicle manufacturer could take advantage of the federal tests by supplying a vehicle with tires of the lowest rolling resistance available, certify and not bother equipping the production vehicles with the same tires (same size, but not the same manufacturer).

VI. Recommendations

It is obvious from the data presented that tires on the Clayton dynamometer do not exhibit the same power absorption characteristics as on the road. Assuming the approximations in Table 9 are reasonably accurate, it would appear that the Clayton dynamometer does a fair job of duplicating the road for the case of radial tires. However, for bias belted and bias ply tires, the Clayton does not do as well. Further tire testing at an initial cold pressure of 26 PSI is currently underway to verify the results of Table 9. For if true, the result of this report indicate that either a correction factor should be added to the Federal Test Procedure to account for tire differences or that the Clayton dynamometer should be replaced or altered. The idea of a correction factor is obviously the more cost effective. One suggestion to this end, is to decrease the test tire pressure by an appropriate percentage based on tire type to force the basic assumption for the tires provided as standard equipment on that vehicle at the recommended tire pressure. This type of correction assumes that the difference in power absorbed at 50 mph displayed in this experiment is constant throughout the Clayton power absorption curve and that the tires are in a state of equilibrium. It is recommeded that tire power absorption characteristics be investigated at other discrete speed intervals in order to make this determination.

The fact that the tire manufacturer had an effect on the power absorbed by the tire at 50 mph would tend to indicate that EPA should specify the tire to be installed on each vehicle from among those tires to be installed in production.

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APPENDIX A

PLOTS OF P_{ATN} AND F_{RR} VERSUS DYNAMOMETER TYPE AND F_{RR} VERSUS TIRE TYPE FOR EACH DYNAMOMETER TYPE

<SCATTER BYSTRATA VAR=4:2 CASES=ALL STRAT=V1 INTERVAL=(1000,9000);(0,3)>

SCATTER PLOT <1> TIRE TYPE:RADIAL

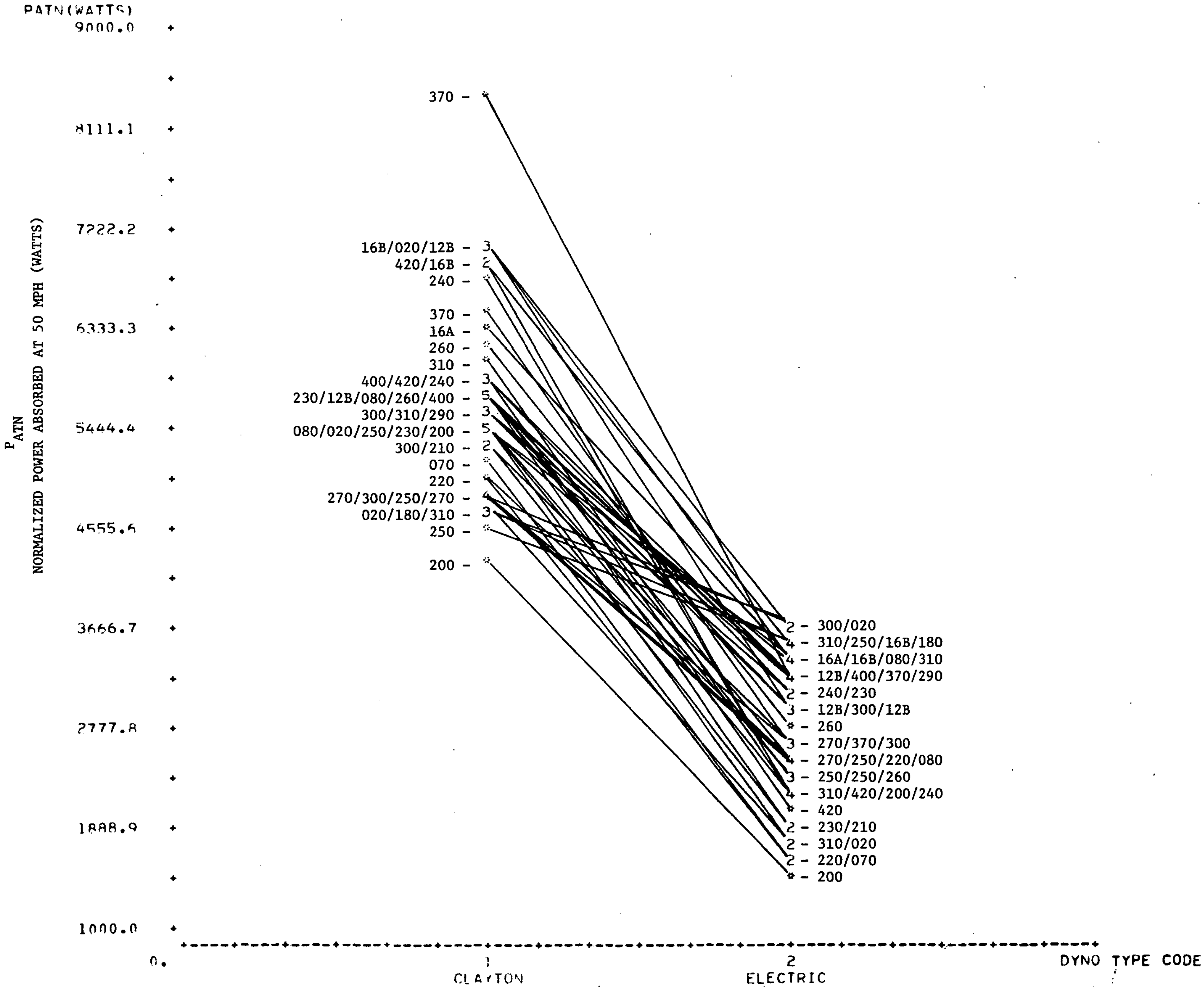

FIGURE A-1

P_{ATN} Versus Dynamometer Type for Radial (Belted) Tires

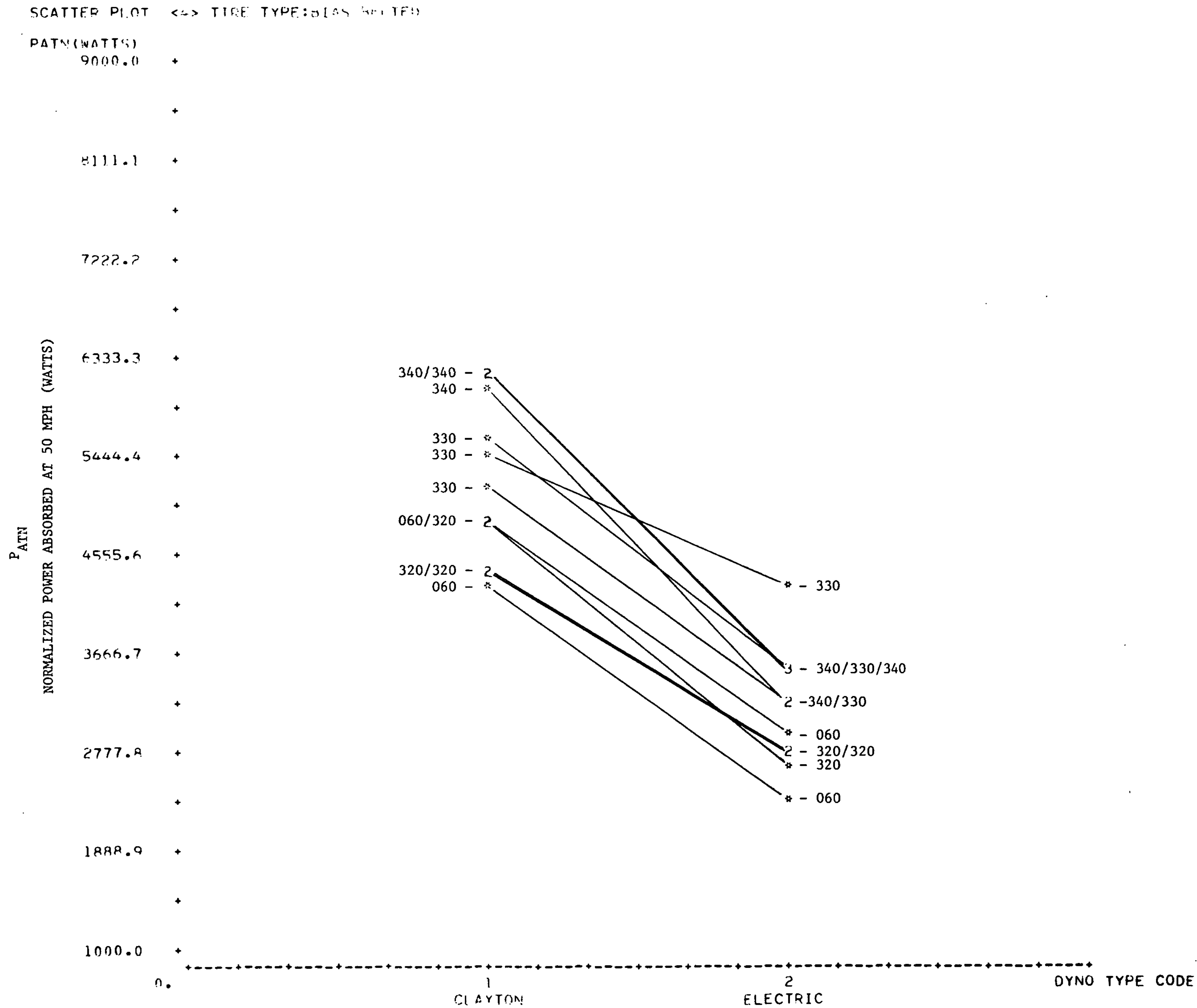

FIGURE A-2
P_{ATN} Versus Dynamometer Type for Bias Belted Tires

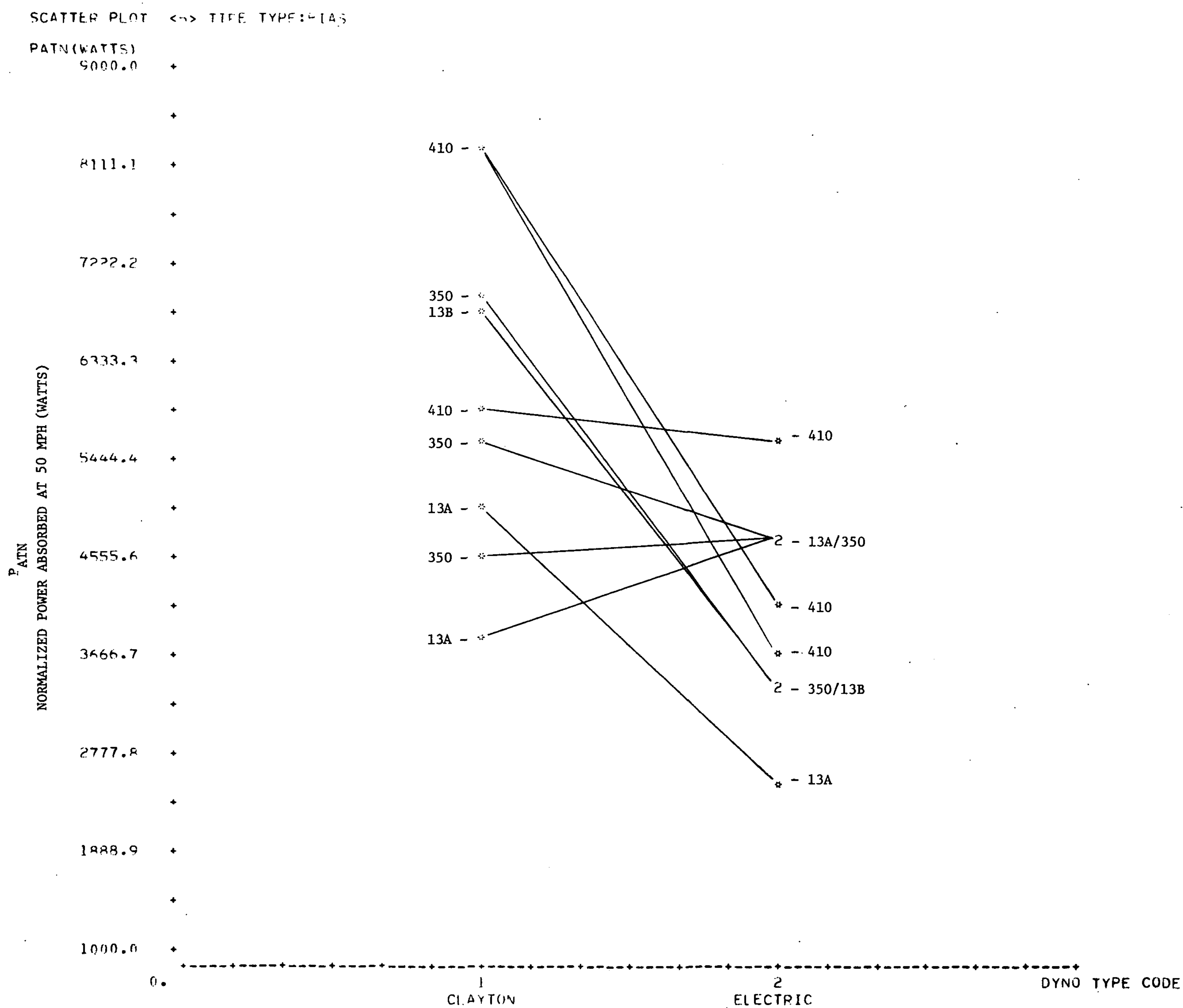

FIGURE A-3

P_{ATN} Versus Dynamometer Type for Bias Ply Tires

<SCATTER BYSTRATA VAR=3:2 CASES=ALL STRAT=V1 INTERVAL=(0,30):(0,3)>

SCATTER PLOT <1> TIRE TYPE:RADIAL

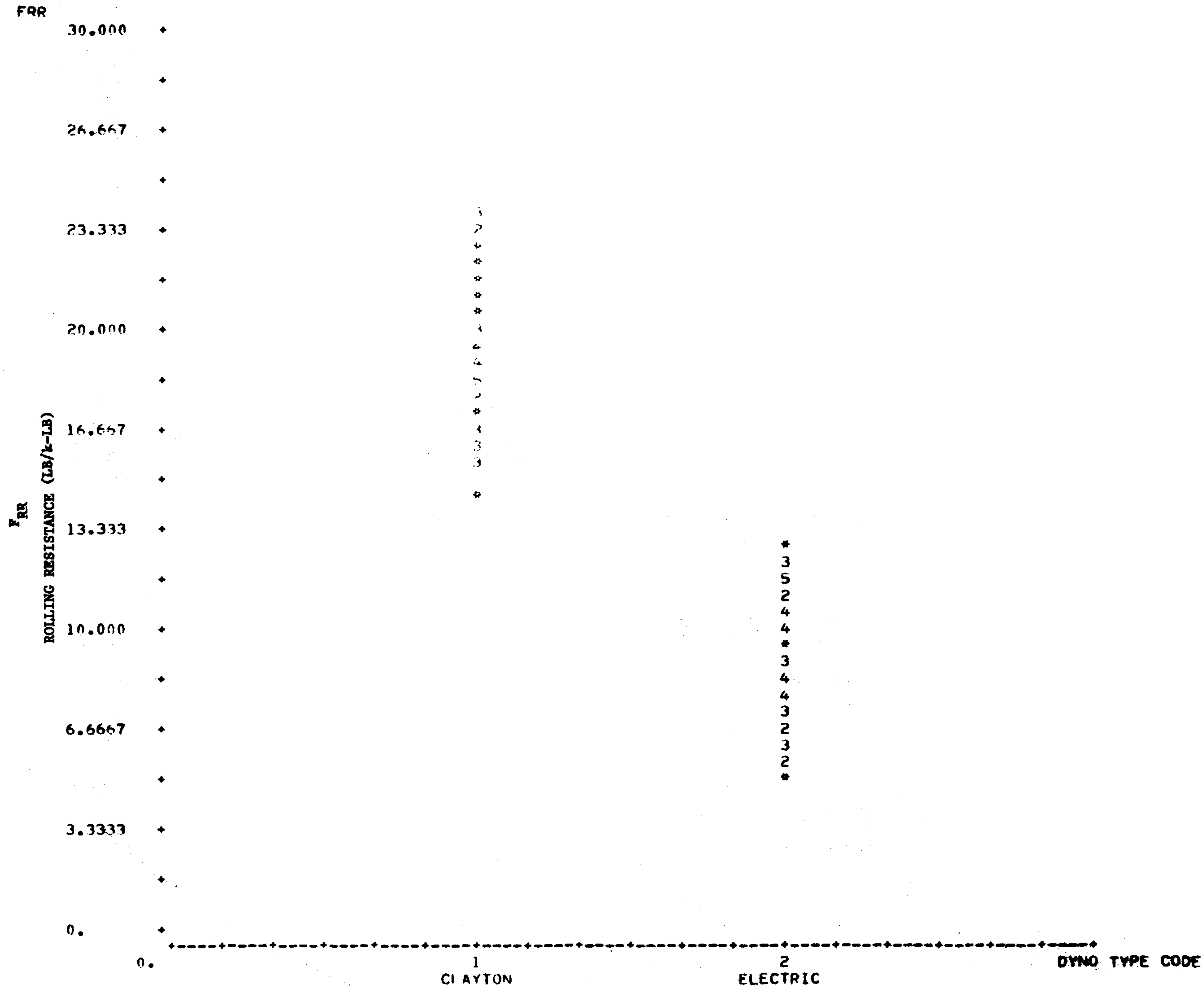

FIGURE A-4

F_{RR} Versus Dynamometer Type for Radial (Belted) Tires

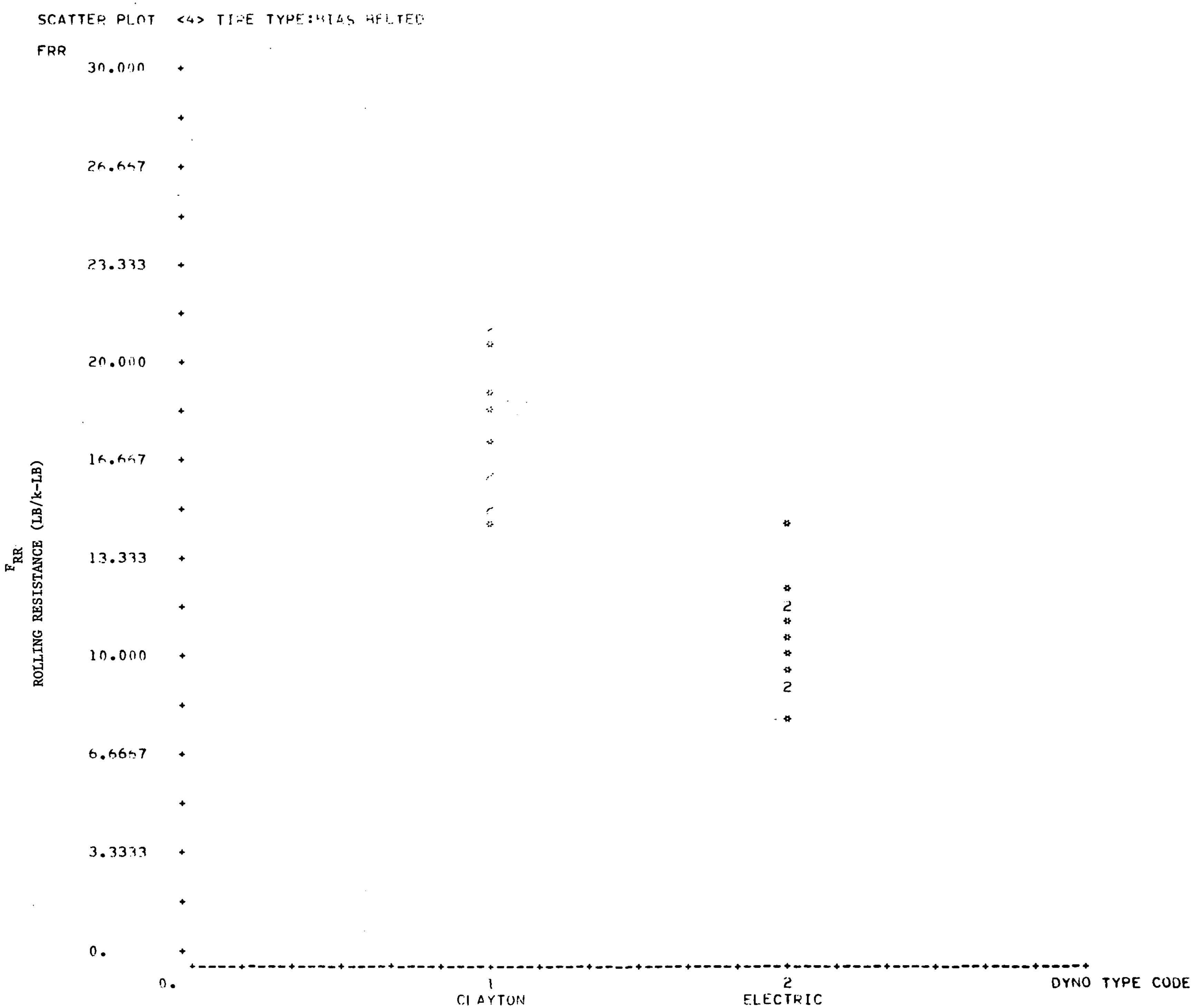

FIGURE A-5

F_{RR} Versus Dynamometer Type for Bias Belted Tires

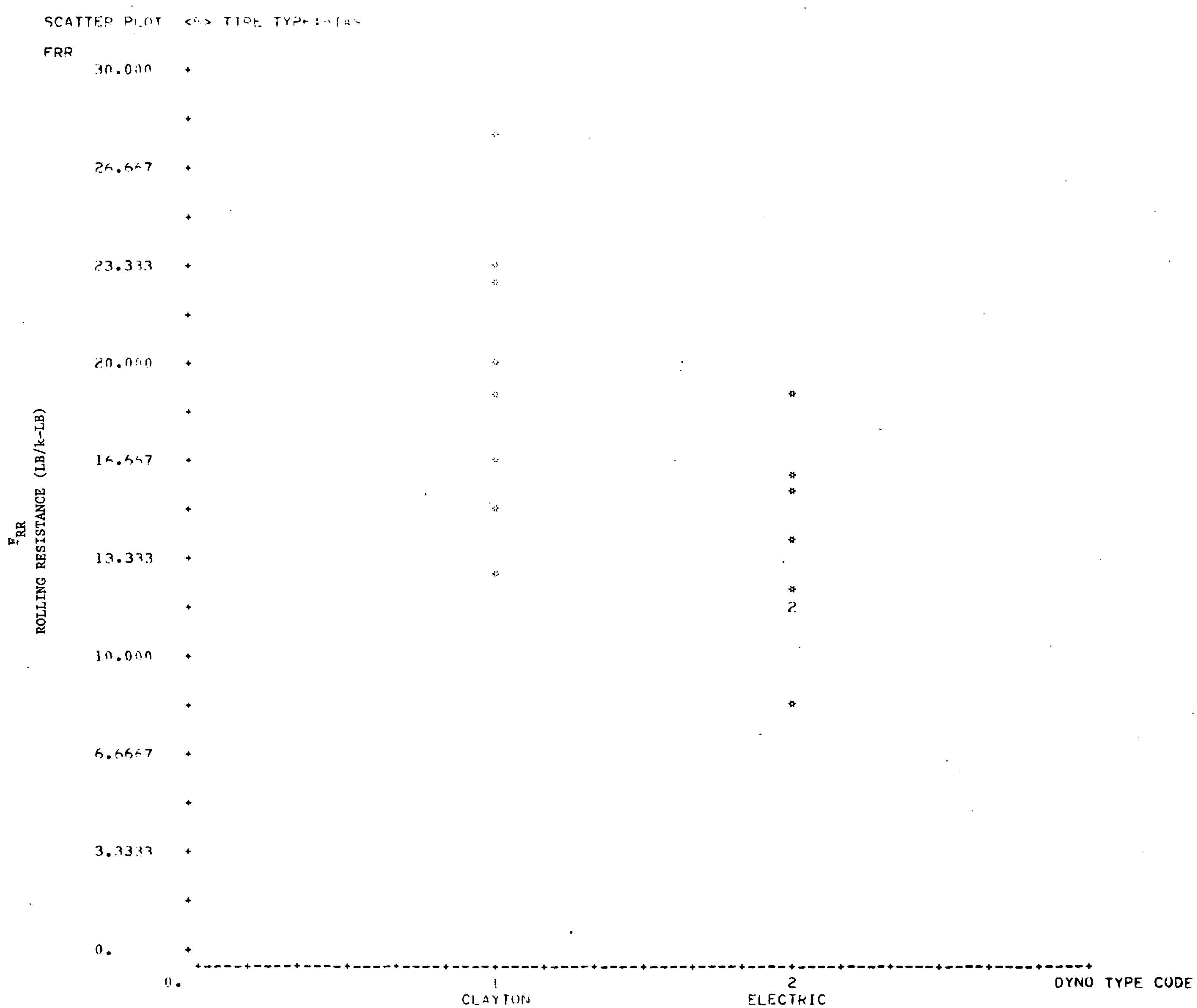

FIGURE A-6

F_{RR} Versus Dynamometer Type for Bias Ply Tires

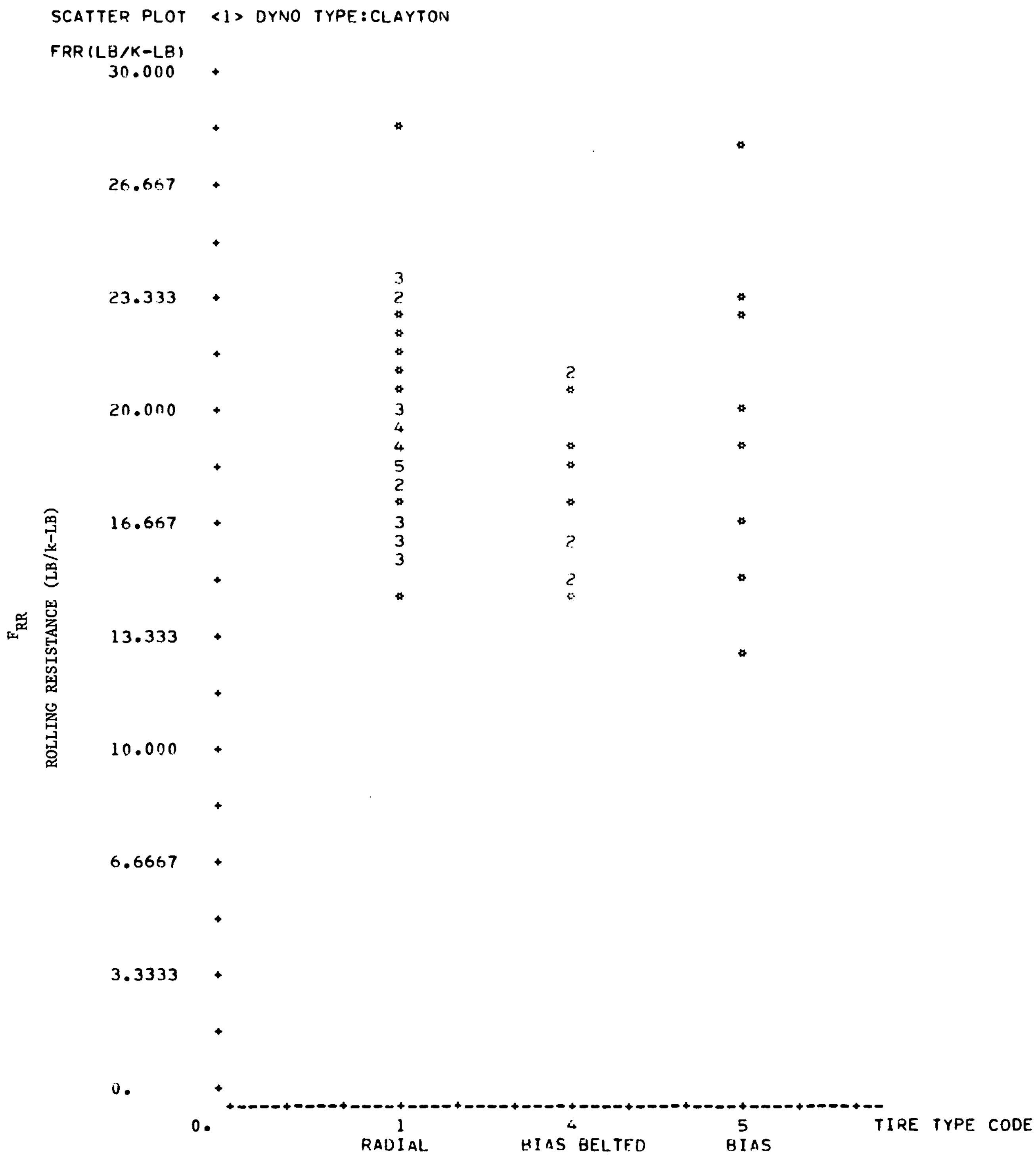

FIGURE A-7

Tire Rolling Resistance as a Function of Tire Type for the Clayton Dynamometer

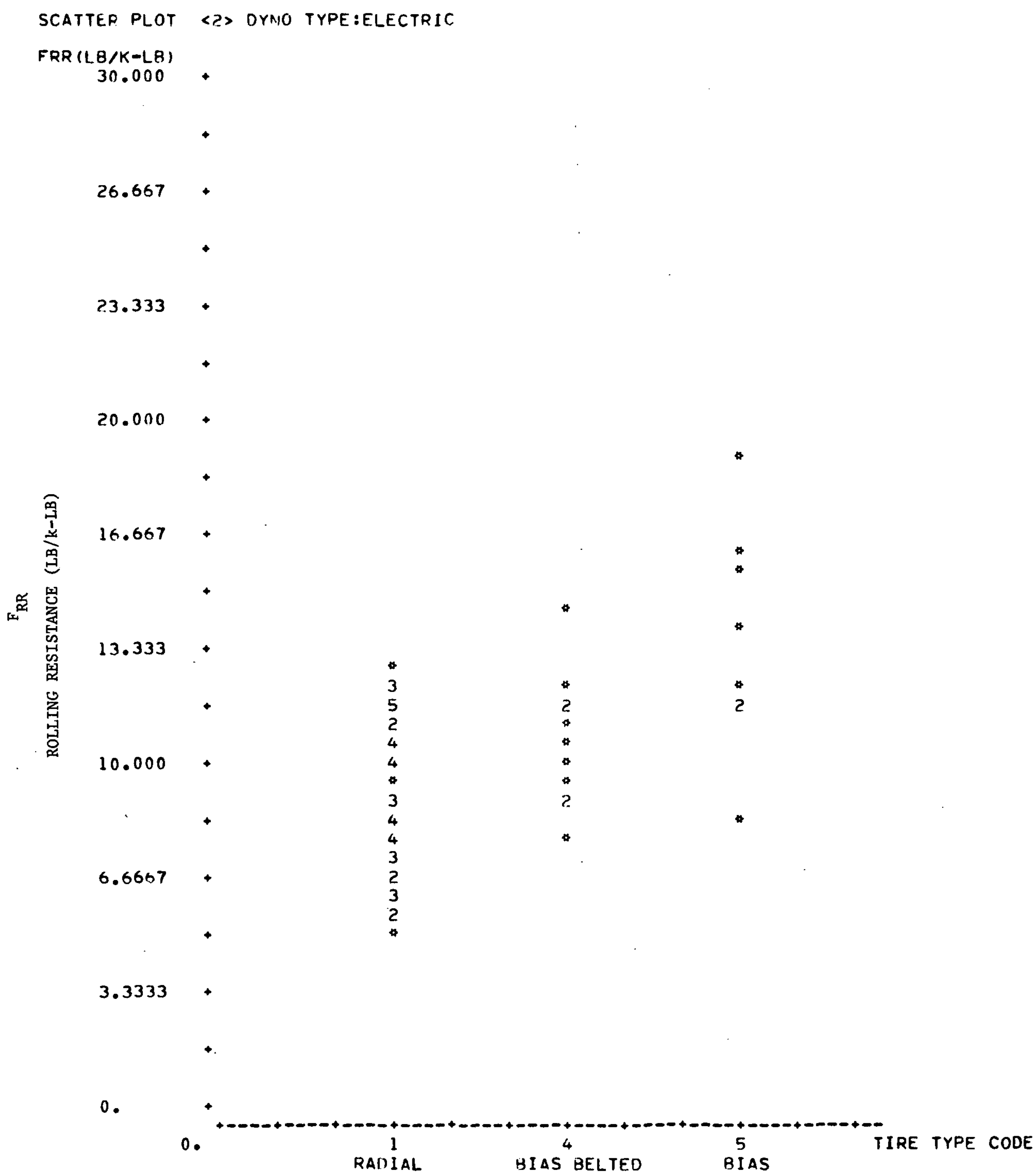

FIGURE A-8

Tire Rolling Resistance as a Function of Tire Type for the Single Large-Roll (Electric) Dynamometer

APPENDIX B

PLOTS OF P_{ATN} VERSUS MANUFACTURER FOR EACH DYNAMOMETER BY TIRE TYPE

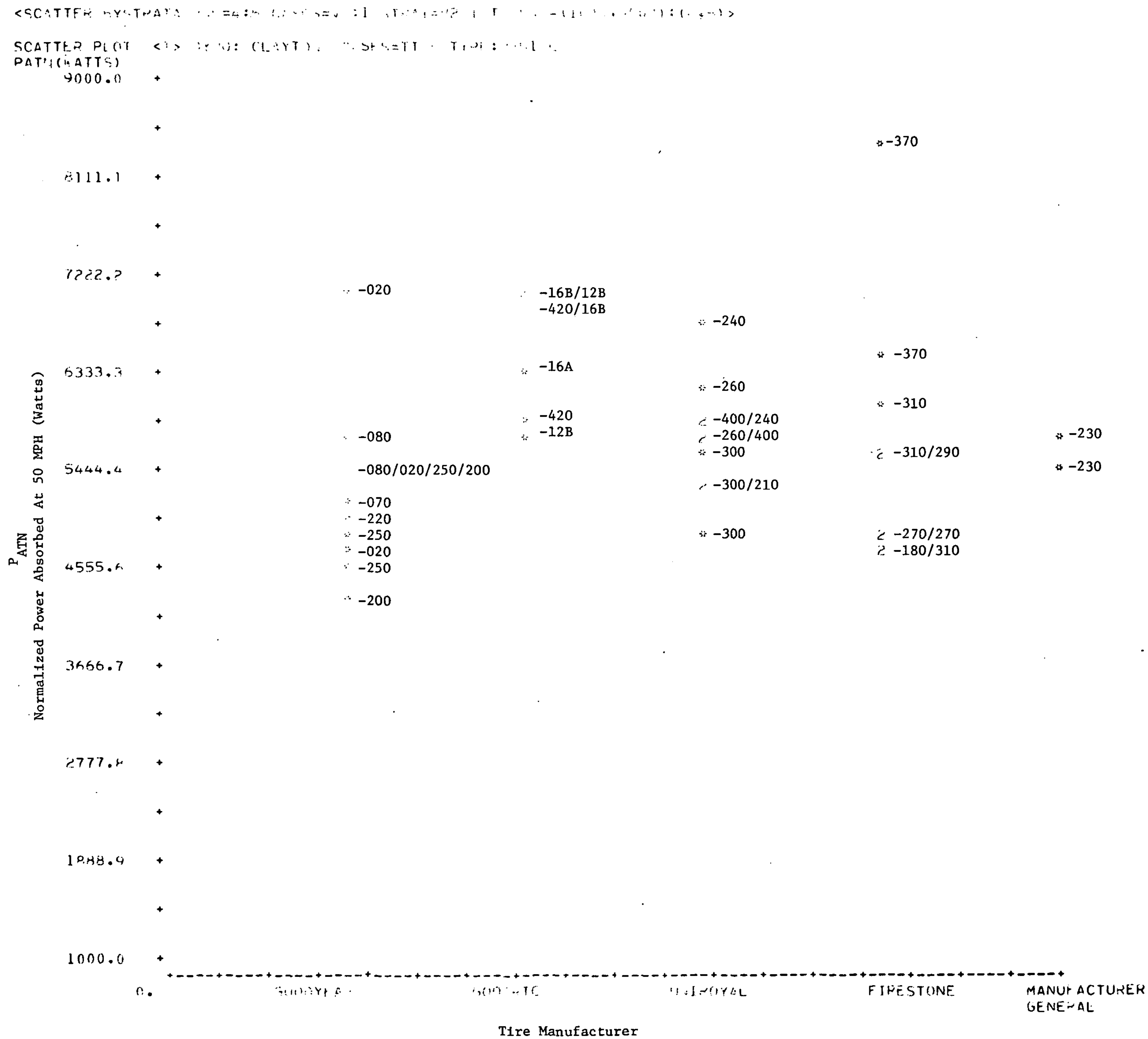

Figure B-1

Normalized Power Absorbed At 50 MPH As A Function Of Tire Manufacturer For Radial Tires On The Twin Small-Roll Dynamometer

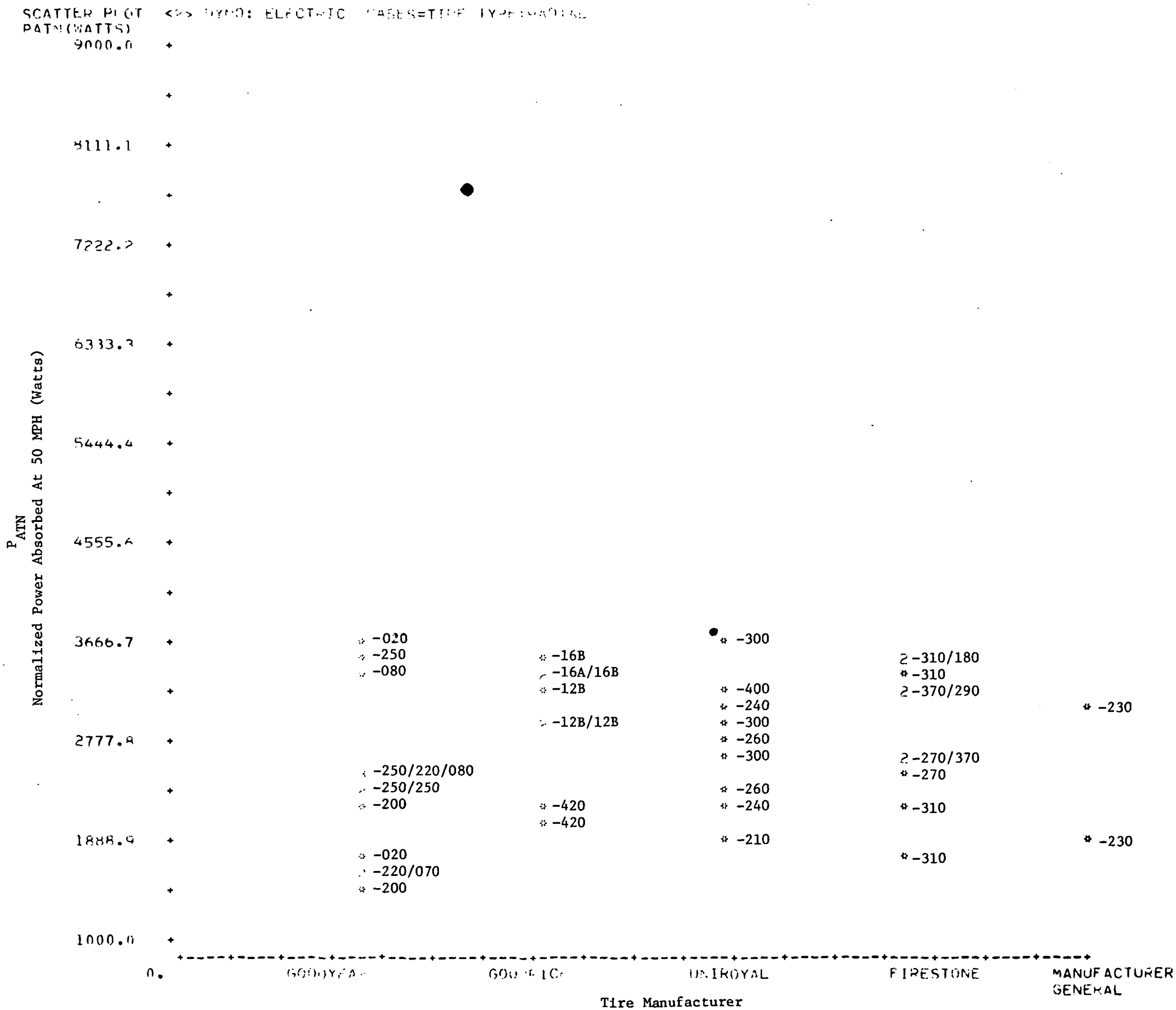

Figure B-2
Normalized Power Absorbed At 50 MPH As A Function Of Tire Manufacturer For Radial Tires On The Single Large-Roll Dynamometer

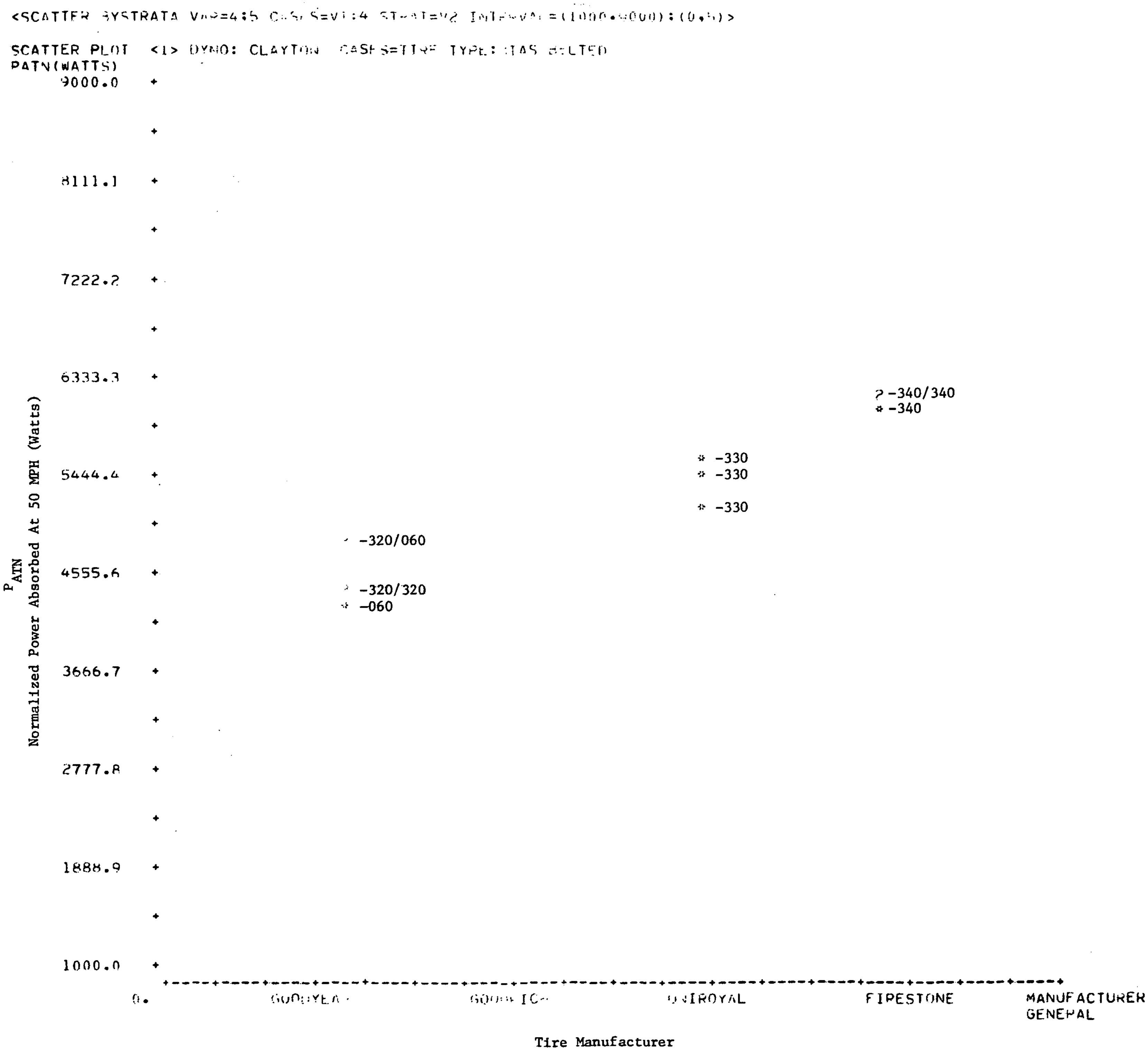

Figure B-3
Normalized Power Absorbed At 50 MPH As A Function Of Tire Manufacturer For Bias Belted Tires On The Twin Small-Roll Dynamometer

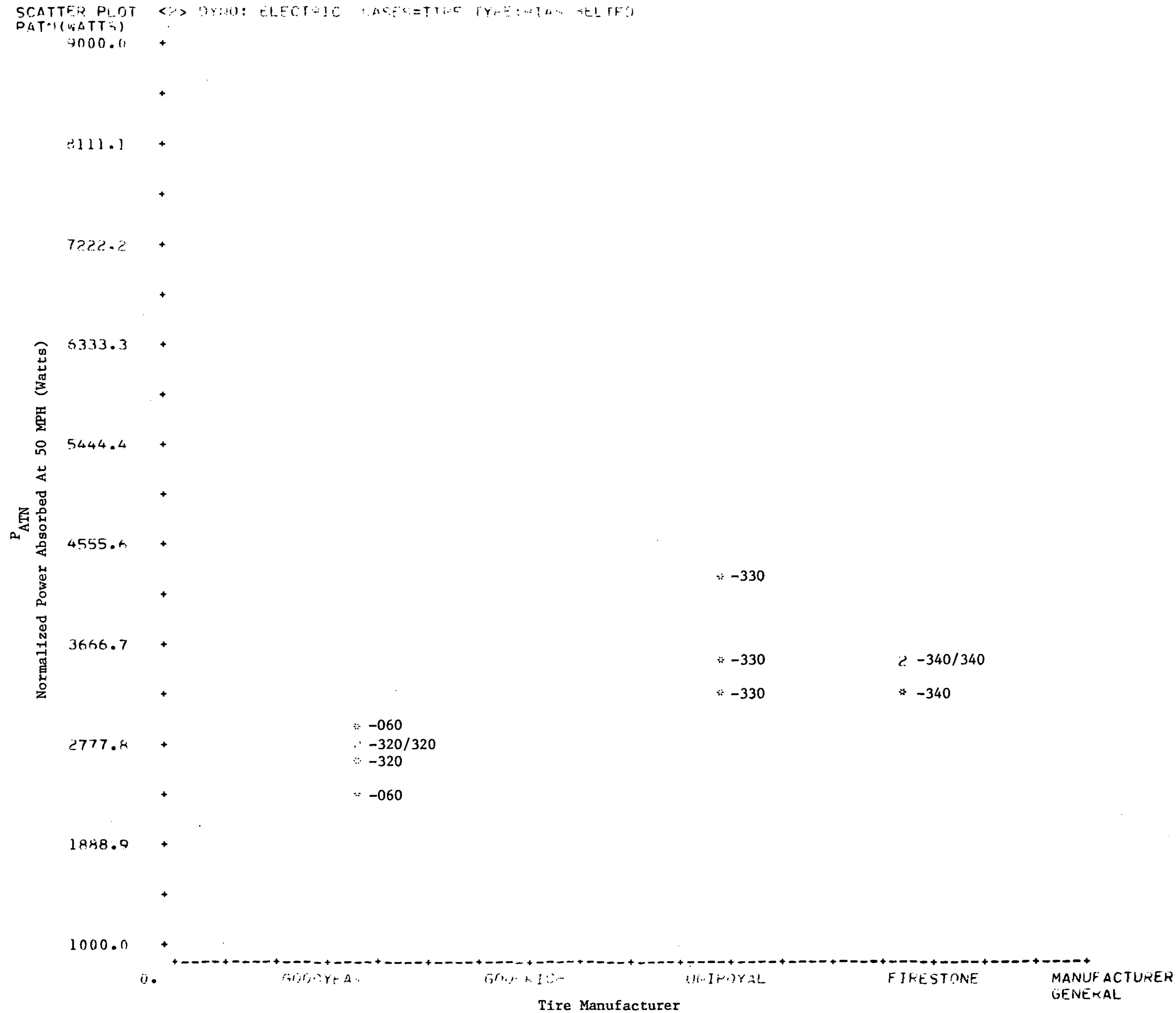

Figure B-4

Normalized Power Absorbed At 50 MPH As A Function Of Tire Manufacturer For Bias Belted Tires On The Single Large-Roll Dynamometer

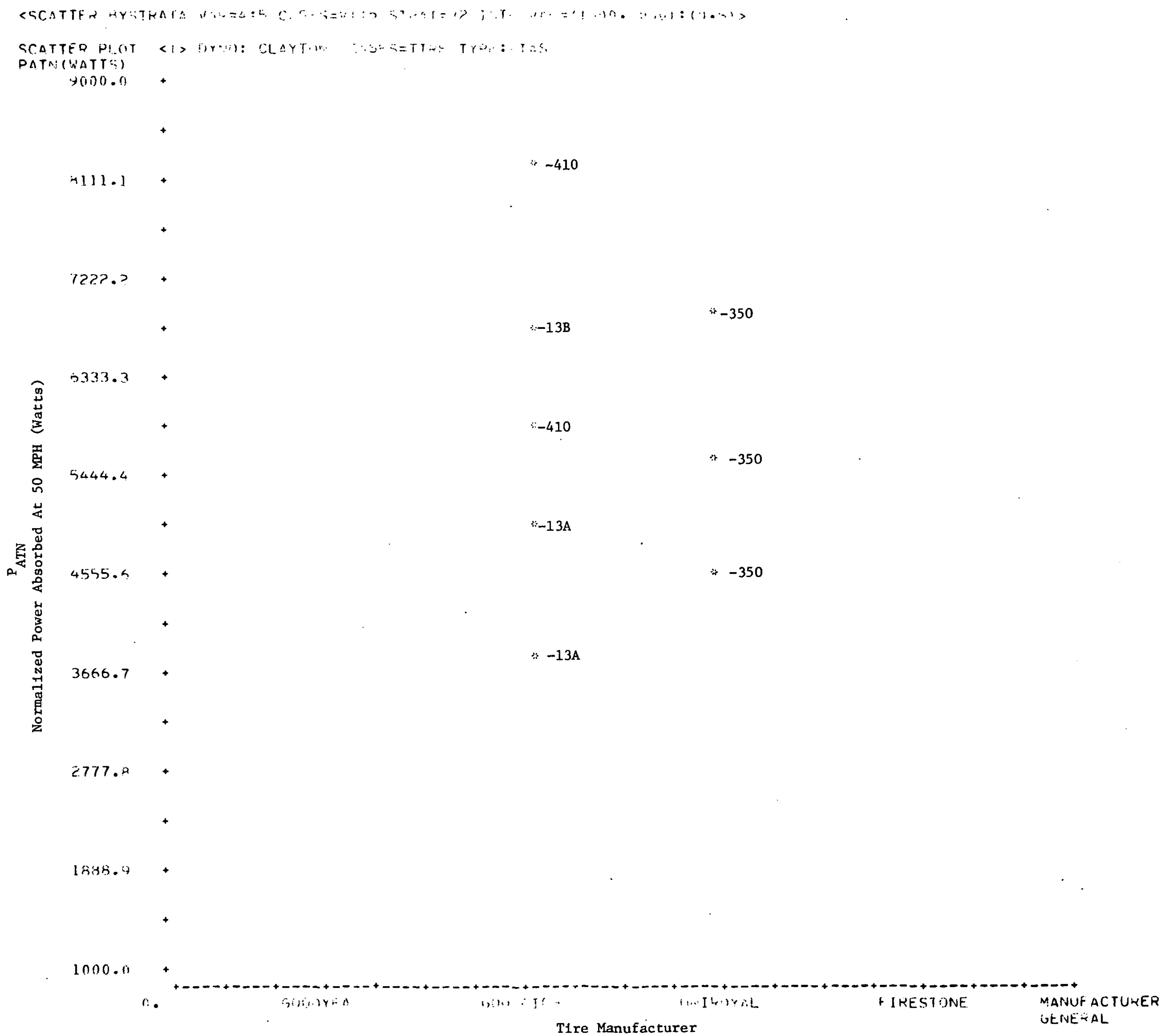

Figure B-5

Normalized Power Absorbed At 50 MPH As A Function Of Tire Manufacturer For Bias Ply Tires On The Twin Small-Roll Dynamometer

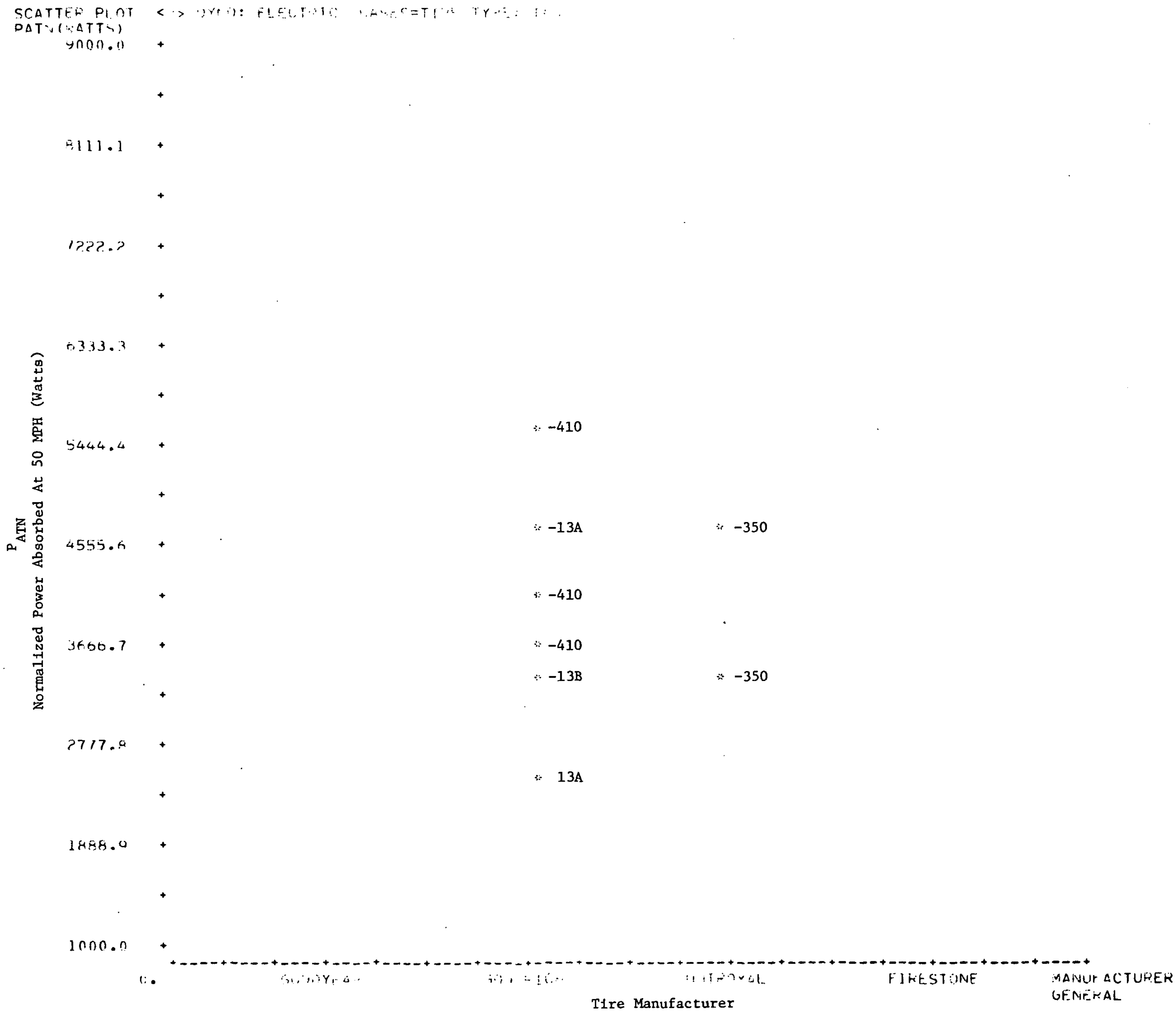

Figure B-6

Normalized Power Absorbed At 50 MPH As A Function Of Tire Manufacturer For Bias Ply Tires On The Single Large-Roll Dynamometer

APPENDIX C

DESCRIPTION OF TEST TIRES BY IDENTIFICATION NUMBER

Tire Description

ID Number	Manufacturer	Size	Model
020	Goodyear	BR 78x13	Polyglass Radial
060	Goodyear	H 78x15	Custom Power Cushion Polyglass
070	Goodyear	HR 78x15	Polyglass Radial
080	Goodyear	HR 70x15	Polyglass Radial WT
12B	B.F. Goodrich	HR 78x15	Steel Radial Silvertown
13A	B.F. Goodrich	H 78x15	Custom Long Miler
13B	B.F. Goodrich	H 78x15	Custom Long Miler
16A	B.F. Goodrich	HR 70x15	Silvertown Lifesaver XL-100
16B	B.F. Goodrich	HR 70x15	Silvertown Lifesaver XL-100
180	Firestone	GR 78x15	Steel Belted Radial
200	Goodyear	HR 78x15	Steel Belted Radial Custom Tread
210	Uniroyal	GR 78x15	Steel Belted Radial PR6
220	Goodyear	GR 78x15	Steel Belted Radial Custom Tread
230	General	GR 78x15	Dual Steel II Radial
240	Uniroyal	LR 78x15	Steel Belted Radial PR6
250	Goodyear	ER 78x14	Steel Belted Radial Custom Tread
260	Uniroyal	FR 78x14	Steel Belted Radial
270	Firestone	FR 78x14	Steel Belted Radial
290	Firestone	HR 78x15	Steel Belted Radial
300	Uniroyal	ER 78x14	Steel Belted Radial
310	Firestone	ER 78x14	Steel Belted Radial
320	Goodyear	E 78x14	Custom Power Belted Cushioned Polyglass
330	Uniroyal	E 78x14	Fastrak Belted
340	Firestone	E 78x14	Sup-R-belted Deluxe Champion
350	Uniroyal	B 78x13	Fastrak Belted
370	Firestone	BR 78x13	Steel Belted Radial
400	Uniroyal	HR 78x15	Steel Belted Radial
410	B.F. Goodrich	B 78x13	Silvertown Bias
420	B.F. Goodrich	GR 78x15	Lifesaver 78 Steel Belted Radial

APPENDIX D

NORMALIZED TEST RESULTS AT 50 MPH BY TIRE IDENTIFICATION NUMBER

TABLE D-1

NORMALIZED TEST RESULTS BY TIRE IDENTIFICATION NUMBER

TIRE ID	TEST DYNO	DYNO HP SET	MFR. CODE	ROLLING FORCE (NT)	ROLLING RESISTANCE (LB/K-LB)	POWER ABSORBED AT 50 MPH (WATTS)
270	1	5.9	4	214.263	16.138	4788.777
020	1	5.9	1	318.867	24.016	7126.680
260	1	5.9	3	277.830	20.925	6209.500
250	1	5.9	1	242.089	18.233	5410.688
020	1	5.9	1	211.985	15.996	4746.770
310	1	5.9	4	271.225	20.428	6061.879
300	1	5.9	3	248.923	18.748	5563.430
020	1	6.8	1	243.519	18.341	5442.641
370	1	6.8	4	292.339	22.018	6533.781
370	1	7.4	4	375.867	28.309	8400.617
310	1	7.4	4	247.823	18.665	5538.844
300	1	7.4	3	236.793	17.834	5292.324
260	1	7.4	3	254.925	19.200	5697.574
250	1	7.4	1	214.421	16.149	4792.309
168	1	8.4	2	306.953	23.119	6860.398
220	1	8.4	1	222.740	16.776	4978.238
420	1	8.4	2	266.534	20.074	5957.035
16A	1	8.4	2	286.363	21.568	6400.215
230	1	8.4	5	259.831	19.570	5807.223
080	1	8.4	1	244.348	18.403	5461.180
210	1	8.4	3	236.157	17.787	5278.109
180	1	8.4	4	209.757	15.798	4688.070
290	1	8.4	4	247.647	18.652	5534.910
128	1	8.4	2	316.487	23.837	7073.484
400	1	8.4	3	266.574	20.077	5957.930
400	1	8.4	3	253.768	19.113	5671.715
200	1	8.4	1	193.477	14.572	4324.211
070	1	8.4	1	228.500	17.210	5106.977
250	1	8.4	1	206.359	15.542	4612.125
240	1	8.4	3	305.471	23.007	6827.277
300	1	8.4	3	217.997	16.419	4872.234
310	1	8.4	4	209.629	15.789	4685.207
270	1	8.4	4	218.589	16.463	4885.465
240	1	10.5	3	262.152	19.744	5859.098
168	1	10.5	2	319.058	24.030	7130.945
128	1	10.5	2	259.784	19.566	5806.172
200	1	10.5	1	241.231	18.169	5391.512
230	1	10.5	5	241.985	18.225	5408.363
420	1	10.5	2	312.521	23.538	6984.844
080	1	10.5	1	255.517	19.245	5710.805
300	2	5.9	3	130.734	9.846	2921.905
020	2	5.9	1	161.452	12.160	3608.446
270	2	5.9	4	114.163	8.598	2551.543
310	2	5.9	4	100.672	7.582	2250.019
250	2	5.9	1	104.248	7.852	2329.943
260	2	5.9	3	123.708	9.317	2764.874
370	2	6.8	4	118.062	8.892	2638.676
020	2	6.8	1	79.770	6.008	1782.857

TABLE D-1 cont.

TIRE ID	TEST DYNO	HP SET	MFR CODE	ROLLING FORCE (NT)	ROLLING RESISTANCE (LB/K-LB)	POWER ABSORBED AT 50 MPH (WATTS)
260	2	7.4	3	102.725	7.737	2295.904
370	2	7.4	4	141.815	10.681	3169.557
250	2	7.4	1	110.563	8.327	2471.083
310	2	7.4	4	147.946	11.143	3306.593
300	2	7.4	3	115.121	8.671	2572.954
250	2	7.4	1	106.932	8.054	2389.930
300	2	8.4	3	167.087	12.584	3734.394
16B	2	8.4	2	157.663	11.875	3523.768
200	2	8.4	1	65.146	4.907	1456.013
210	2	8.4	3	84.118	6.335	1880.037
230	2	8.4	5	85.028	6.404	1900.376
080	2	8.4	1	151.477	11.409	3385.511
250	2	8.4	1	159.039	11.978	3554.522
220	2	8.4	1	109.334	8.235	2443.615
240	2	8.4	3	94.924	7.149	2121.551
400	2	8.4	3	143.499	10.808	3207.203
310	2	8.4	4	160.403	12.081	3585.007
310	2	8.4	4	80.645	6.074	1802.416
220	2	8.4	1	74.114	5.582	1656.448
16A	2	8.4	2	152.359	11.475	3405.224
12B	2	8.4	2	131.699	9.919	2943.473
290	2	8.4	4	141.404	10.650	3160.379
180	2	8.4	4	154.385	11.628	3450.505
070	2	8.4	1	71.770	5.405	1604.059
420	2	8.4	2	88.346	6.654	1974.533
080	2	10.5	1	108.150	8.145	2417.152
200	2	10.5	1	96.650	7.279	2160.127
16B	2	10.5	2	151.719	11.427	3390.920
12B	2	10.5	2	130.598	9.836	2918.865
12B	2	10.5	2	146.005	10.997	3263.212
420	2	10.5	2	98.388	7.410	2198.972
240	2	10.5	3	138.981	10.468	3106.225
230	2	10.5	5	134.572	10.136	3007.684
270	2	8.4	4	119.187	8.977	2663.830
340	1	5.9	4	278.243	20.956	6218.730
330	1	5.9	3	250.348	18.855	5595.277
320	1	5.9	1	216.169	16.281	4831.379
320	1	7.4	1	195.912	14.755	4378.633
340	1	7.4	4	271.722	20.465	6072.988
330	1	7.4	3	227.369	17.125	5081.695
320	1	8.4	1	196.342	14.788	4388.242
060	1	8.4	1	215.197	16.208	4809.652
340	1	8.4	4	276.695	20.840	6184.133
330	1	8.4	3	246.406	18.558	5507.176
060	1	10.5	1	191.215	14.402	4273.656
320	2	5.9	1	120.146	9.049	2685.263
330	2	5.9	3	155.767	11.732	3481.392
340	2	5.9	4	154.410	11.630	3451.063

TABLE D-1 cont.

TIRE ID	TEST DYNO	DYNO HP SET	MFR CODE	ROLLING FORCE (NT)	ROLLING RESISTANCE (LB/K-LB)	ABSORBED AT 50 MPH (WATTS)
340	2	7.4	4	144.461	10.880	3228.703
320	2	7.4	1	121.398	9.143	2713.245
330	2	7.4	3	141.334	10.645	3158.815
330	2	8.4	3	192.077	14.467	4292.922
340	2	8.4	4	159.679	12.026	3568.826
060	2	8.4	1	129.896	9.783	2903.176
320	2	8.4	1	125.506	9.453	2805.059
060	2	10.5	1	105.717	7.962	2362.775
410	1	5.9	2	263.859	19.873	5897.258
350	1	5.9	3	202.452	15.248	4524.801
350	1	5.9	3	251.830	18.967	5628.402
410	1	7.4	2	366.373	27.594	8188.441
13A	1	8.4	2	223.471	16.831	4994.578
13B	1	8.4	2	303.906	22.889	6792.301
13A	1	10.5	2	167.927	12.648	3753.168
350	1	7.4	3	306.732	23.102	6855.453
350	2	5.9	3	208.586	15.710	4661.898
410	2	5.9	2	247.276	18.624	5526.621
410	2	7.4	2	181.753	13.689	4062.173
350	2	7.4	3	153.007	11.524	3419.715
410	2	7.4	2	164.479	12.388	3676.104
13A	2	8.4	2	110.581	8.329	2471.485
13B	2	8.4	2	152.202	11.463	3401.715
13A	2	10.5	2	212.003	15.967	4738.266

Test Dyno Code

1 = Clayton
2 = Electric

Manufacturer's Code (MFR)

1 = Goodyear
2 = B. F. Goodrich
3 = Uniroyal
4 = Firestone
5 = General

APPENDIX E

UNLOAD AND LOAD TIRE RADII BY TIRE IDENTIFICATION NUMBER

Tire ID Number	Tire Size	Radius at 45 PSIG (Meters) Unloaded	Loaded
020	BR78 x 13	.305	.298
060	H 78 x 15	.362	.349
070	HR78 x 15	.355	.344
080	HR70 x 15	.361	.348
12B	HR78 x 15	.354	.343
13A	H 78 x 15	.367	.351
13B	H 78 x 15	.365	.355
16A	HR70 x 15	.375	.361
16B	HR70 x 15	.373	.364
180	GR78 x 15	.346	.333
200	HR78 x 15	.354	.341
210	GR78 x 15	.345	.334
220	GR78 x 15	.349	.334
230	GR78 x 15	.348	.336
240	LR78 x 15	.365	.353
250	ER78 x 14	.326	.311
260	FR78 x 14	.333	.318
270	FR78 x 14	.329	.318
290	HR78 x 15	.354	.341
300	ER78 x 14	.328	.315
310	ER78 x 14	.325	.312
320	E 78 x 14	.334	.319
330	E 78 x 14	.331	.318
340	E 78 x 14	.333	.321
350	B 78 x 13	.310	.302
370	BR78 x 13	.301	.295
400	HR78 x 15	.355	.344
410	B 78 x 13	.304	.300
420	GR78 x 15	.349	.337

APPENDIX F

PLOTS OF P_{ATN} VERSUS DYNAMOMETER HORSEPOWER SETTING

BY TIRE SIZE AND TYPE FOR EACH DYNAMOMETER

<SCATTER BYSTRATA VAR=6:4 CASES=V3:1 STRAT=V2:1*V7:1 INTERVAL=(0,8500):(4,11)>

SCATTER PLOT <1> TTYPE:RADIAL*TSIZE:13" CASES=DYNO:CLAYTO
N= 5 OUT OF 5 6.PATN VS. 4.HP

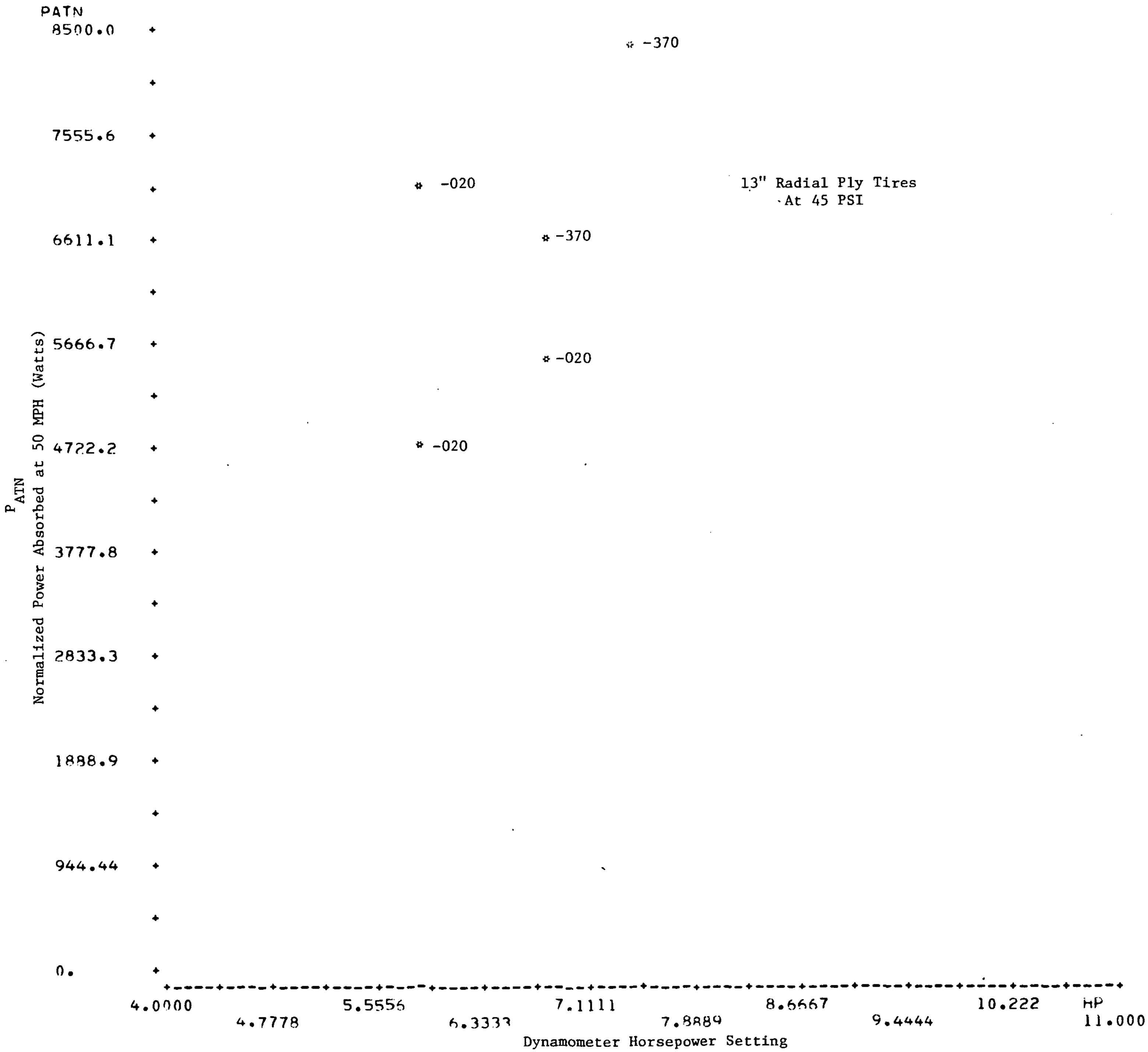

Figure F-1

Power Absorbed At 50 MPH As A Function Of Dynamometer Horsepower Setting For 13" Radial Ply Tires On The Twin Small-Roll Dynamometer

<SCATTER BYSTRATA VAR=6:4 CASES=V3:2 STRAT=V2:1*V7:1 INTERVAL=(0,8500);(4,11)>

SCATTER PLOT <1> TTYPE:RADIAL*TSIZE:13" CASES=DYNO:ELECTR
N= 4 OUT OF 4 6.PATN VS. 4.HP

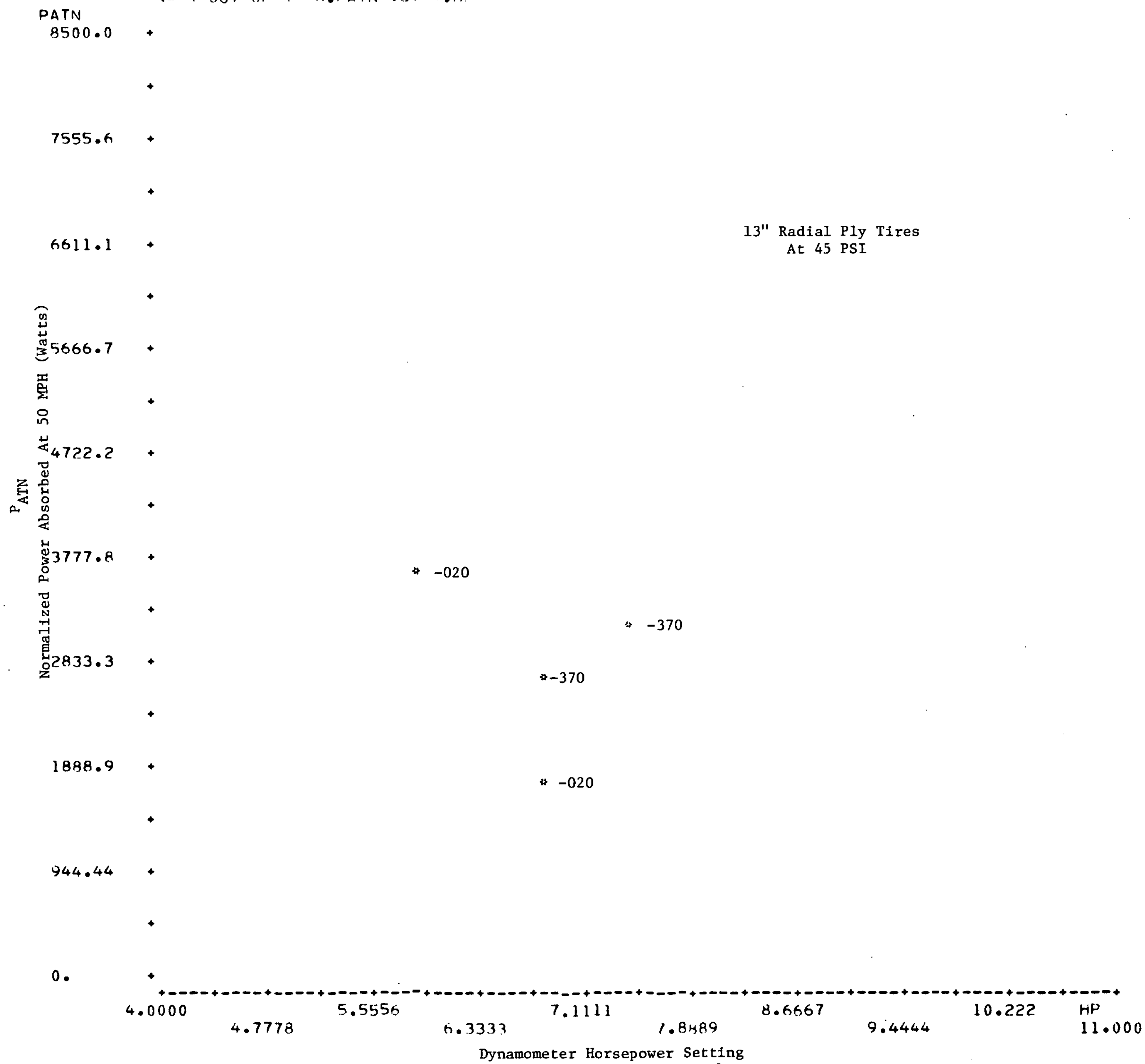

Figure F-2

Power Absorbed At 50 MPH As A Function Of Dynamometer Horsepower Setting For 13" Radial Ply Tires On The Single Large-Roll Dynamometer

<SCATTER BYSTRATA VAR=6:4 CASES=V3:1 STRAT=V2:1*V7:2 INTERVAL=(0,8500);(4,11)>

SCATTER PLOT <1> TTYPE:RADIAL*TSIZE:14" CASES=DYNO:CLAYTO
N= 13 OUT OF 13 6.PATN VS. 4.HP

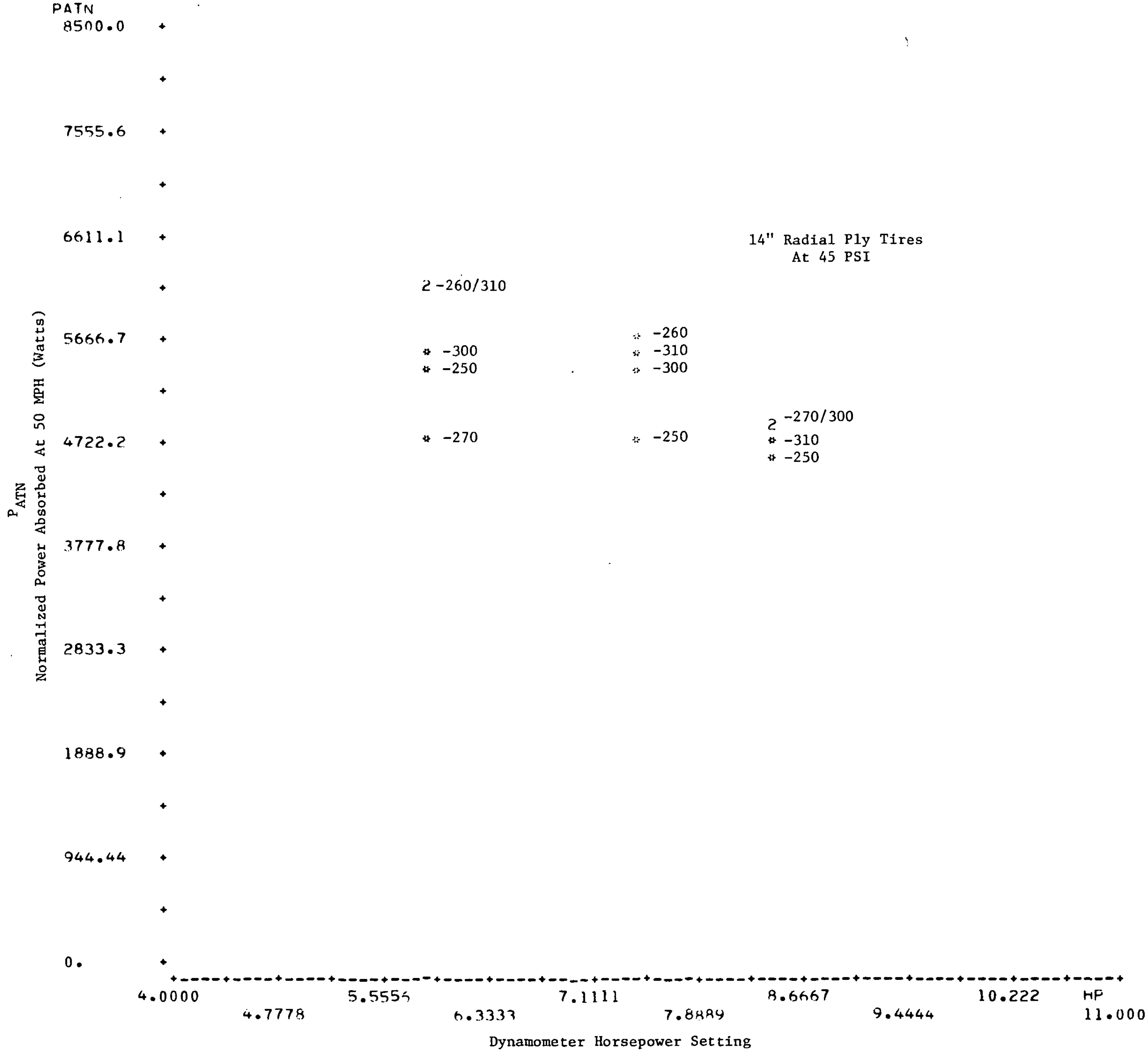

Figure F-3

Power Absorbed At 50 MPH As A Function Of Dynamometer Horsepower Setting For 14" Radial Ply Tires On The Twin Small-Roll Dynamometer

<SCATTER BYSTRATA VAR=6:4 CASES=V3:2 STRAT=V2:1*V7:2 INTERVAL=(0,8500);(4,11)>

SCATTER PLOT <1> TTYPE:RADIAL*TSIZE:14" CASES=DYNO:ELECTR
N= 15 OUT OF 15 6.PATN VS. 4.HP

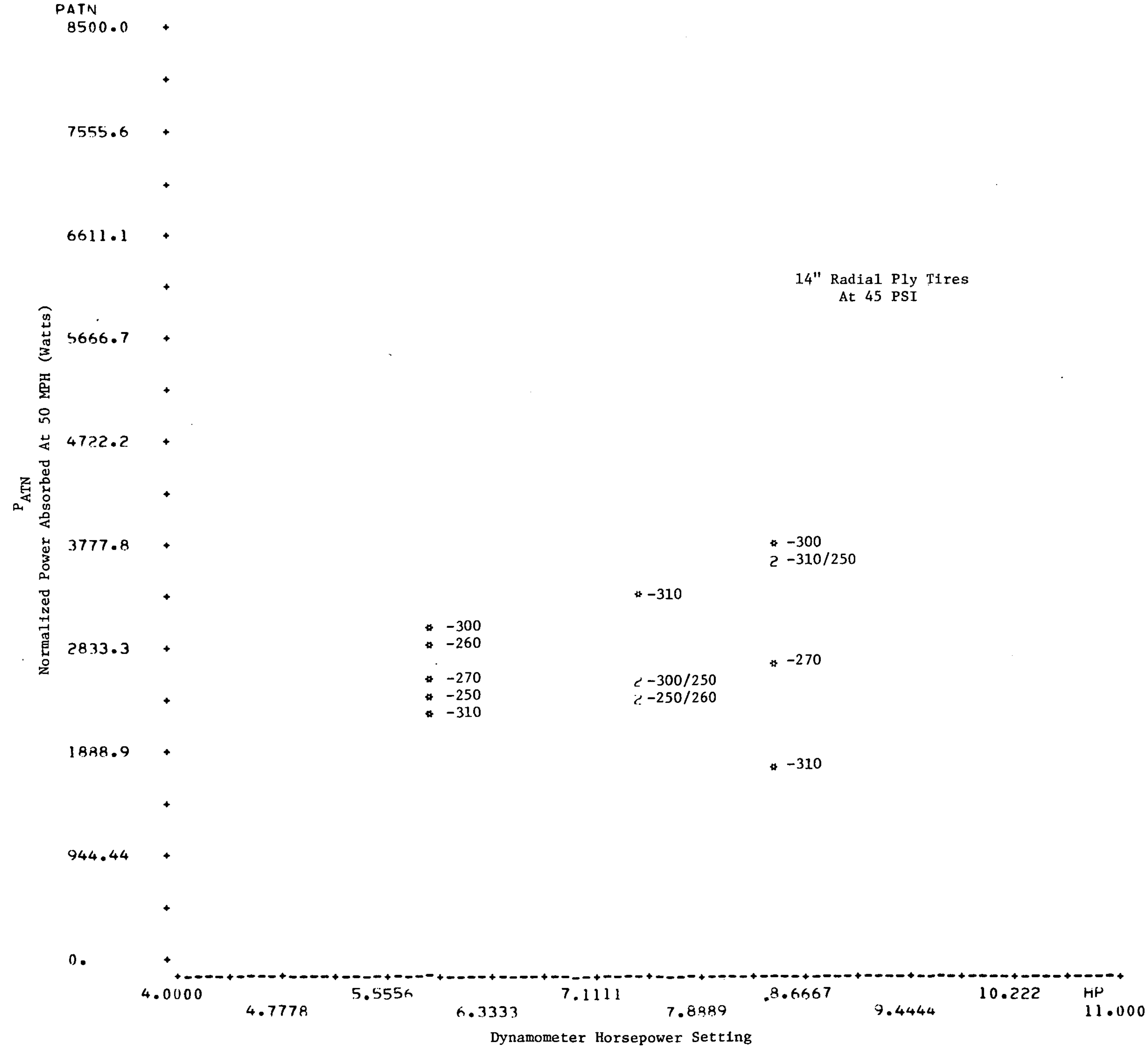

Figure F-4

Power Absorbed At 50 MPH As A Function Of Dynamometer Horsepower Setting For 14" Radial Ply Tires On The Single Large-Roll Dynamometer

<SCATTER BYSTRATA VAR=6:4 CASES=V3:1 STRAT=V2:1*V7:3 INTERVAL=(0,8500);(4,11)>

SCATTER PLOT <1> TTYPE:RADIAL*TSIZE:15" CASES=DYNO:CLAYTO
N= 22 OUT OF 22 6.PATN VS. 4.HP

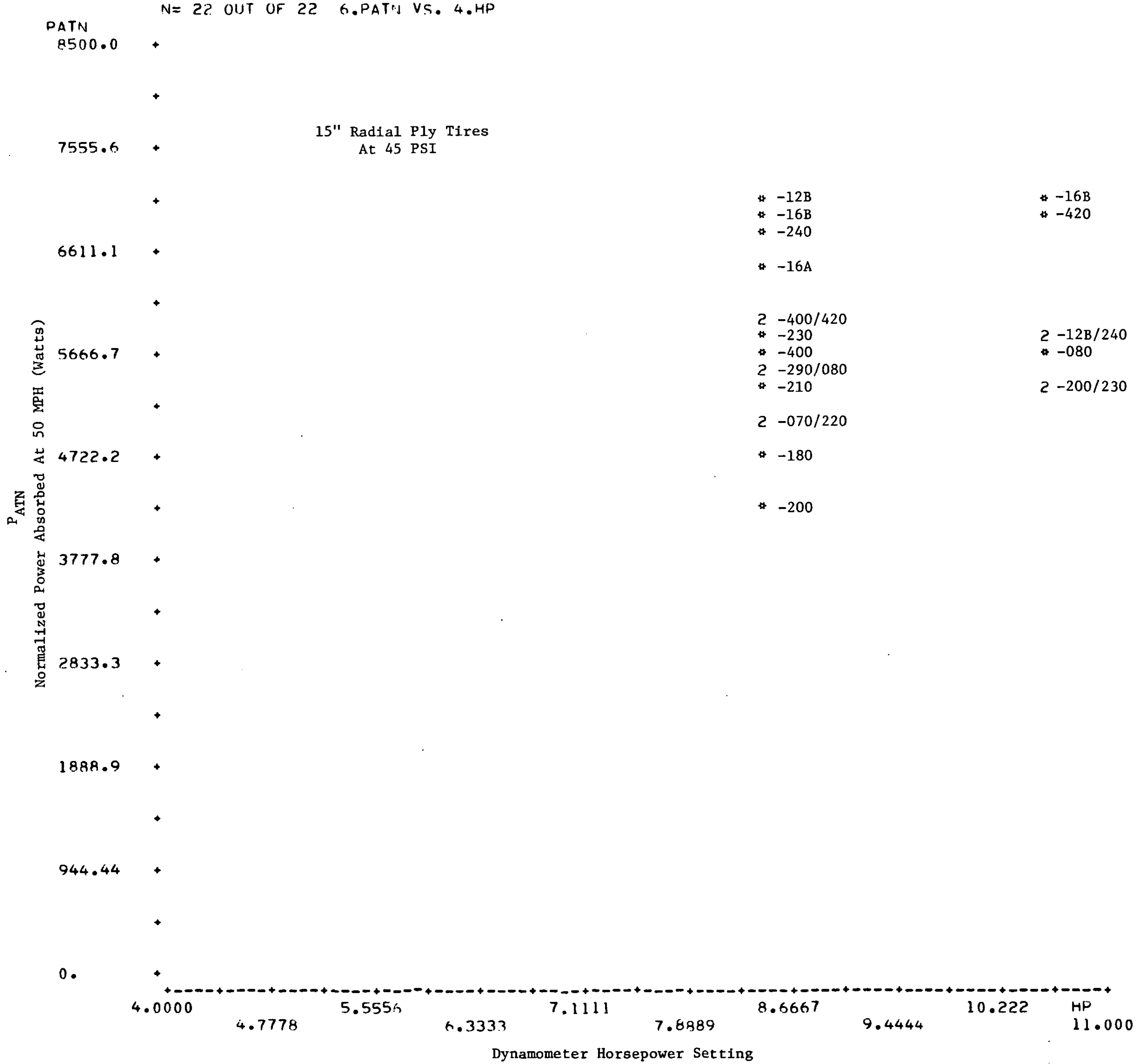

Figure F-5

Power Absorbed At 50 MPH As A Function Of Dynamometer Horsepower Setting For 15" Radial Ply Tires On The Twin Small-Roll Dynamometer

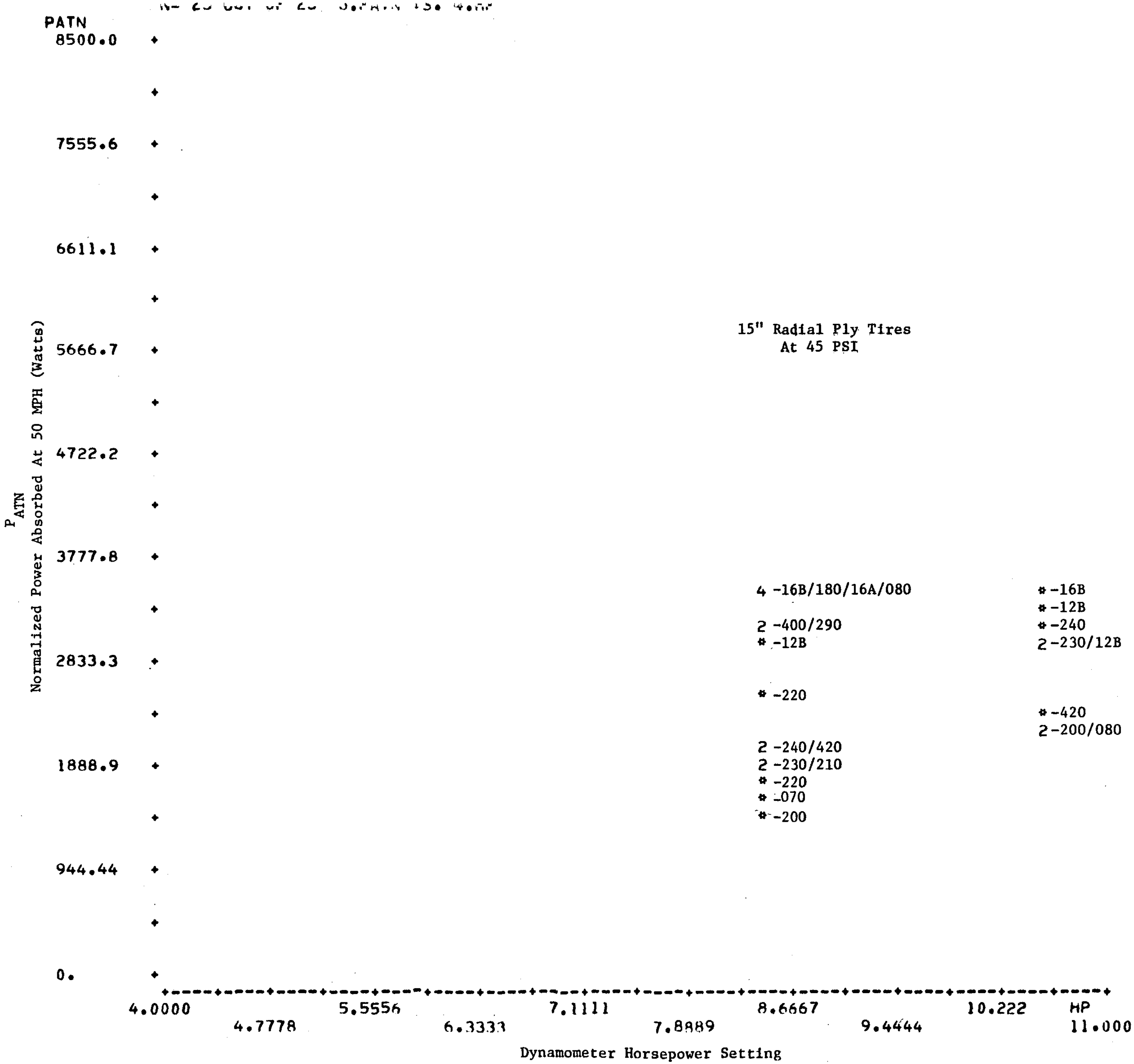

Figure F-6

Power Absorbed At 50 MPH As A Function Of Dynamometer Horsepower Setting For 15" Radial Ply Tires On The Single Large-Roll Dynamometer

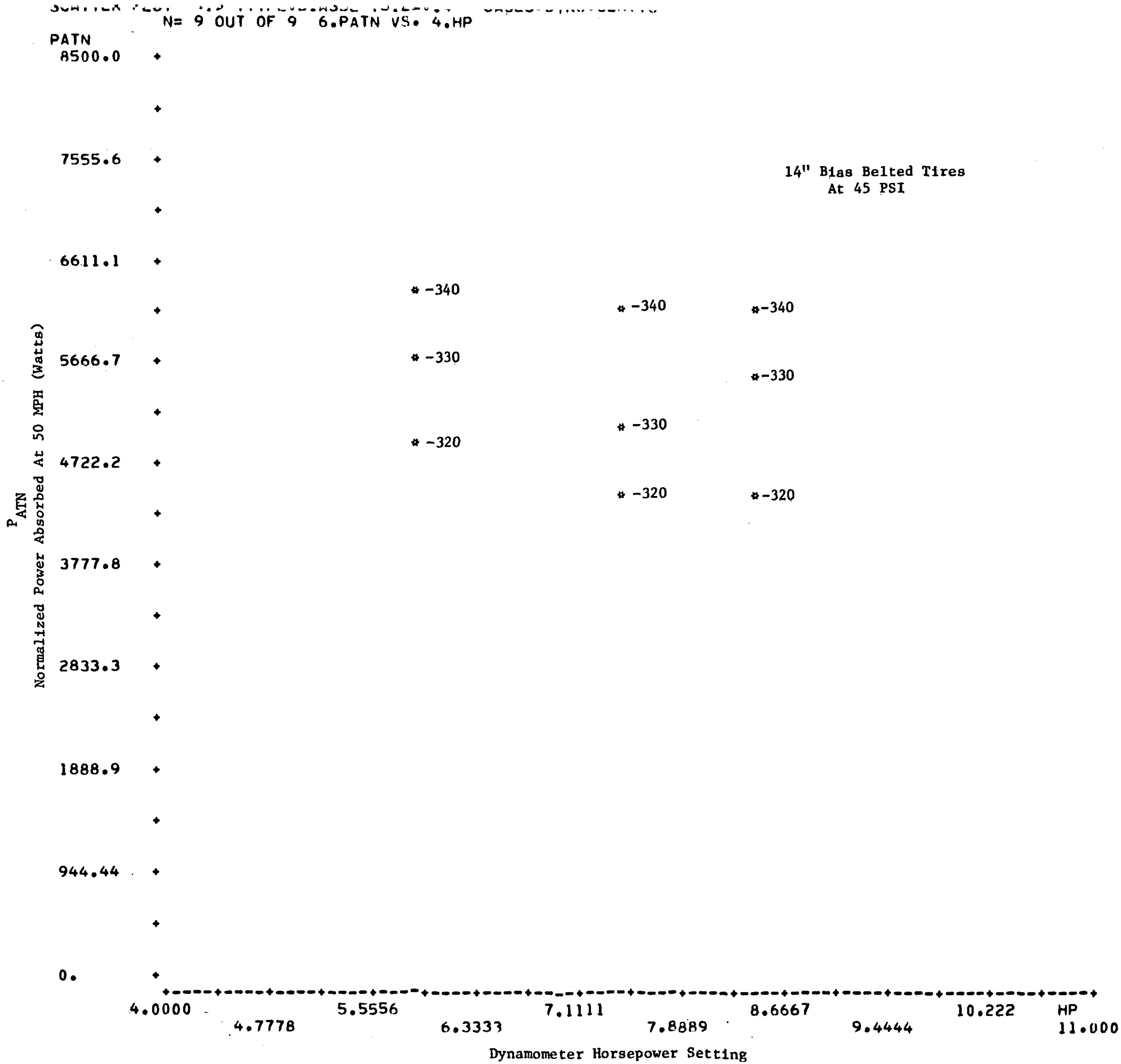

Figure F-7

Power Absorbed At 50 MPH As A Function Of Dynamometer Horsepower Settings For 14" Bias Belted Tires On The Twin Small-Roll Dynamometer

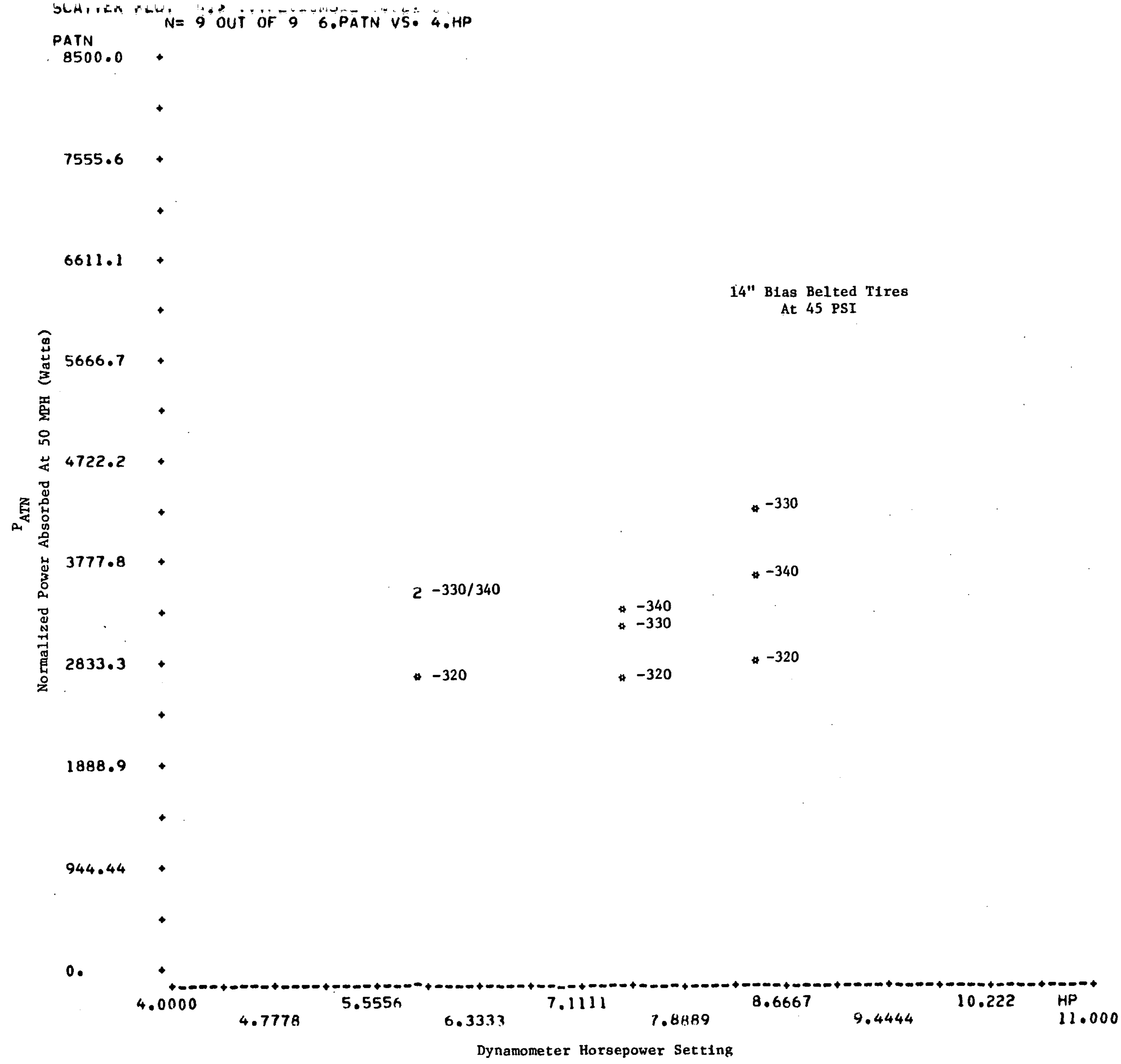

Figure F-8

Power Absorbed At 50 MPH As A Function Of Dynamometer Horsepower Setting For 14" Bias Belted Tires On The Single Large-Roll Dynamometer

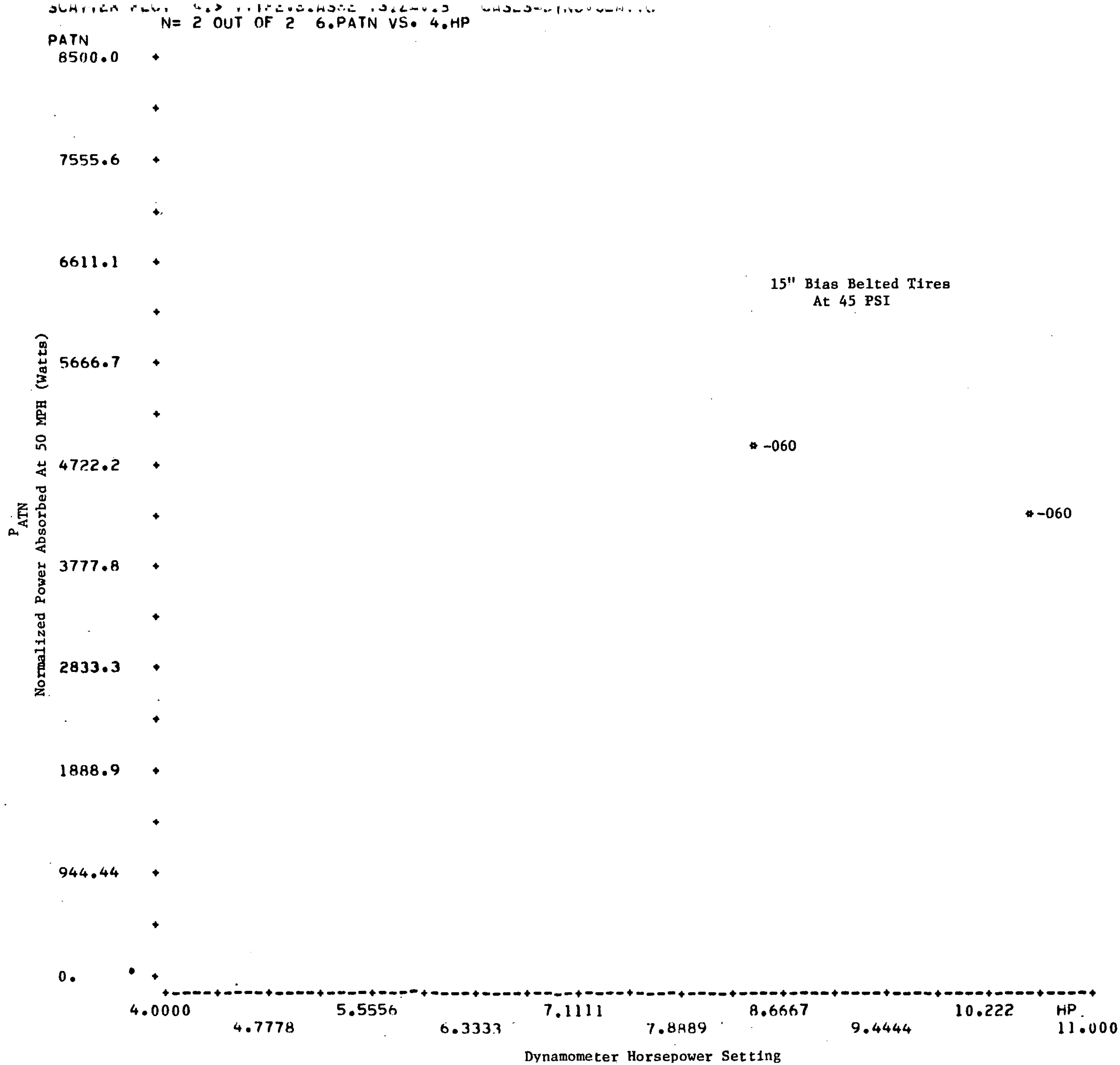

Figure F-9

Power Absorbed At 50 MPH As A Function Of Dynamometer Horsepower Setting For 15" Bias Belted Tires On The Twin Small-Roll Dynamometer

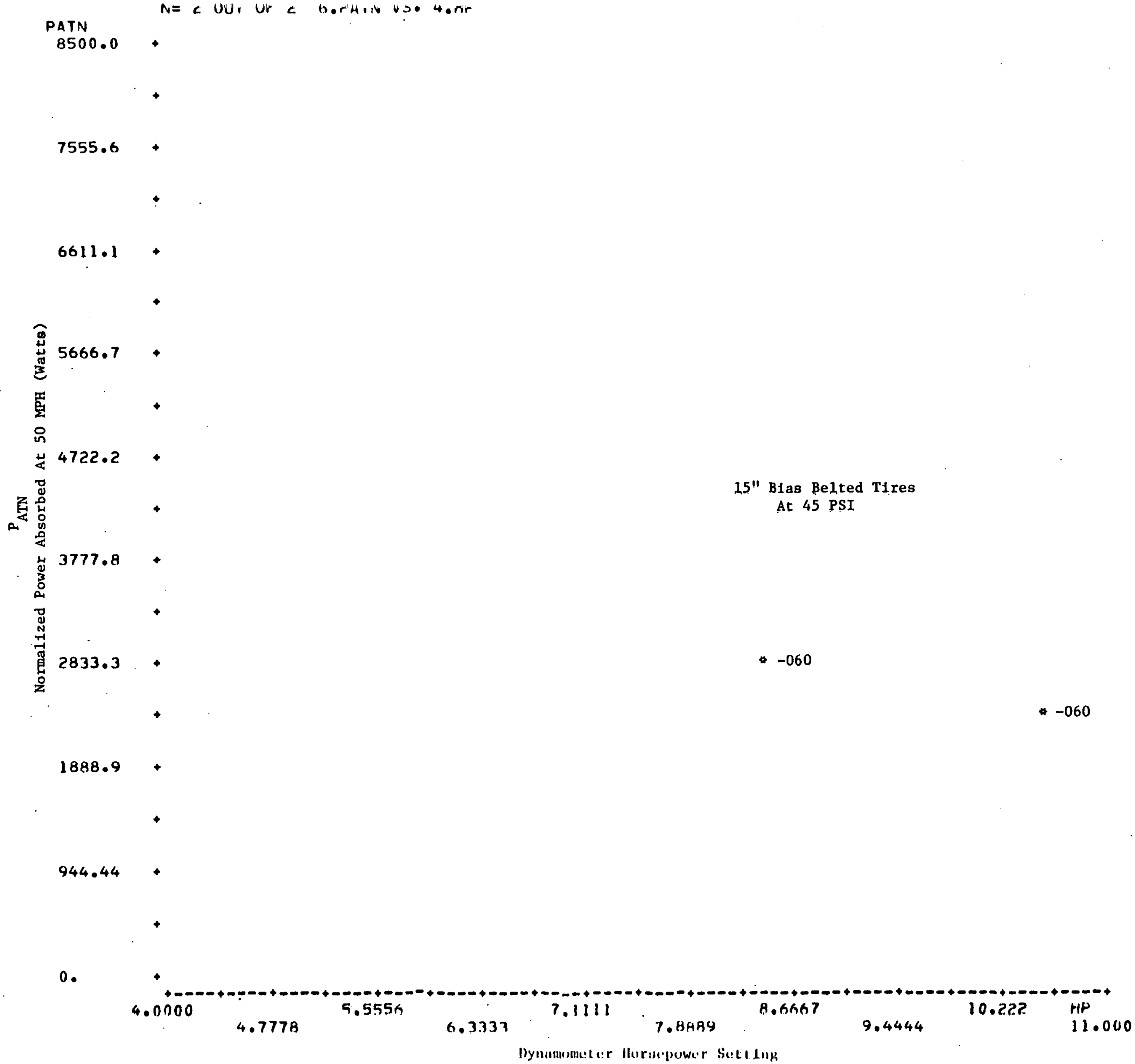

Figure F-10

Power Absorbed At 50 MPH As A Function Of Dynamometer Horsepower Setting For 15" Bias Belted Tires On The Single Large-Roll Dynamometer

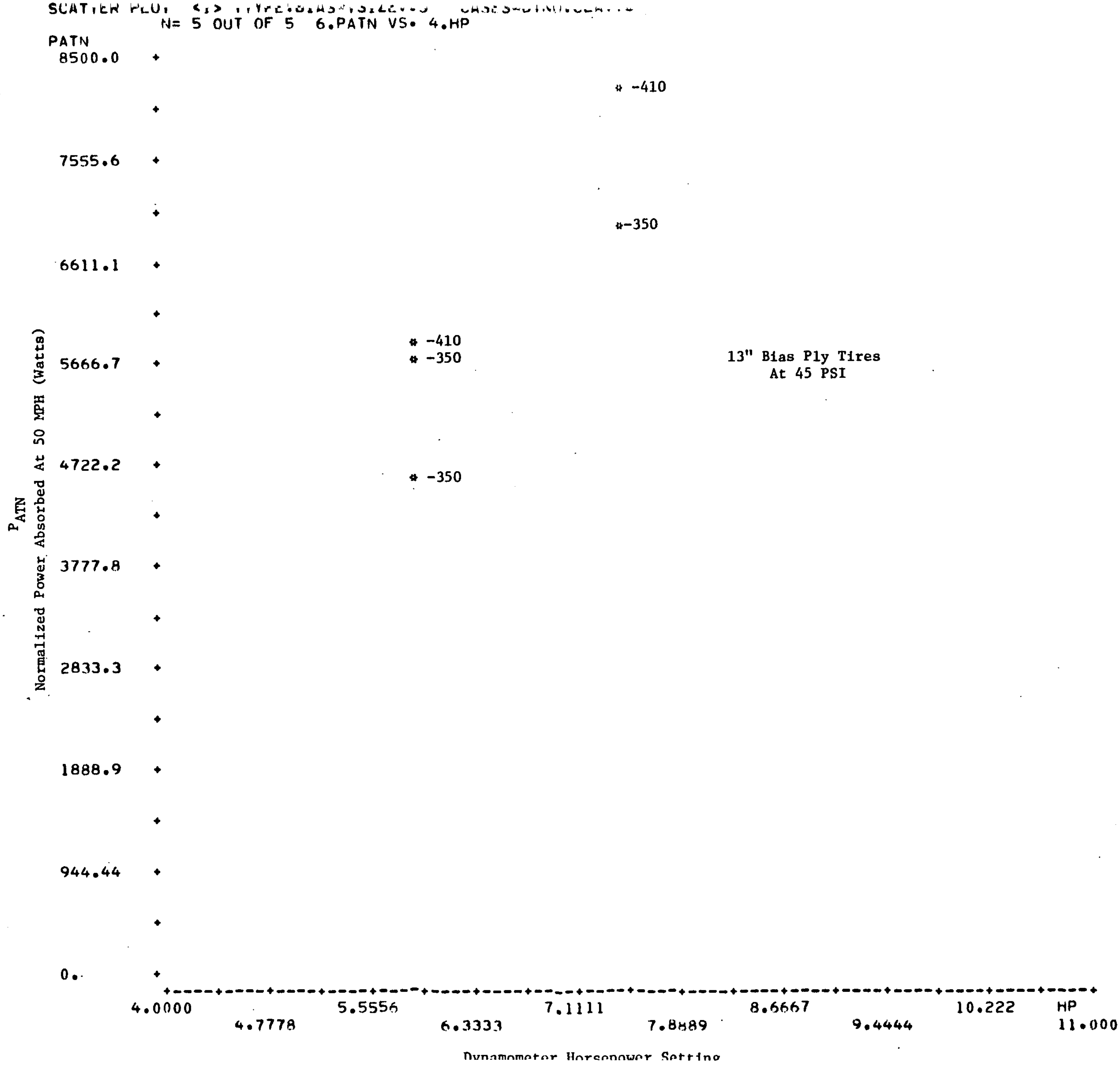

Figure F-11

Power Absorbed At 50 MPH As A Function Of Dynamometer Horsepower Setting For 13" Bias Ply Tires On The Twin Small-Roll Dynamometer

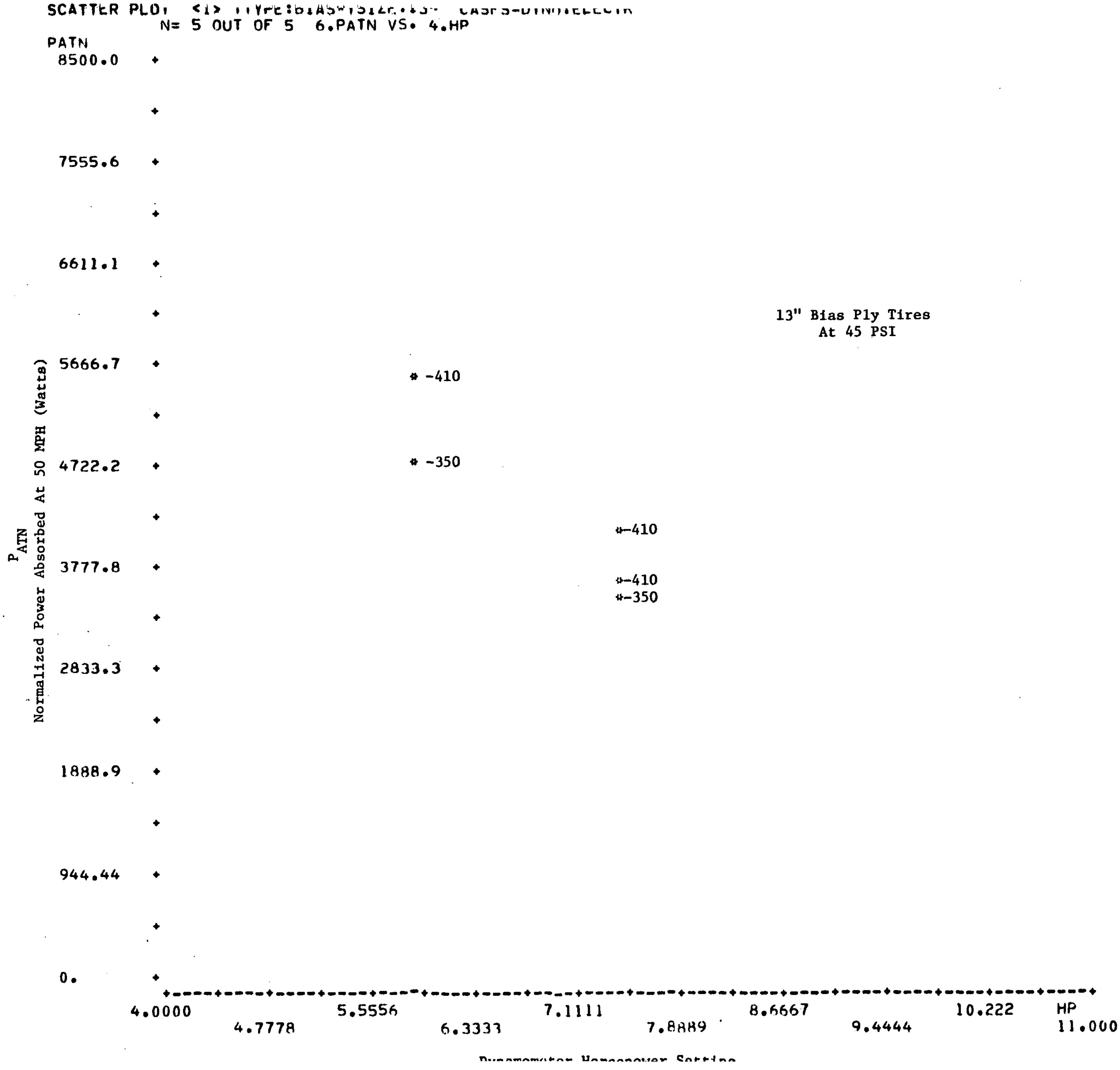

Figure F-12

Power Absorbed At 50 MPH As A Function Of Dynamometer Horsepower Setting For 13" Bias Ply Tires On The Single Large-Roll Dynamometer

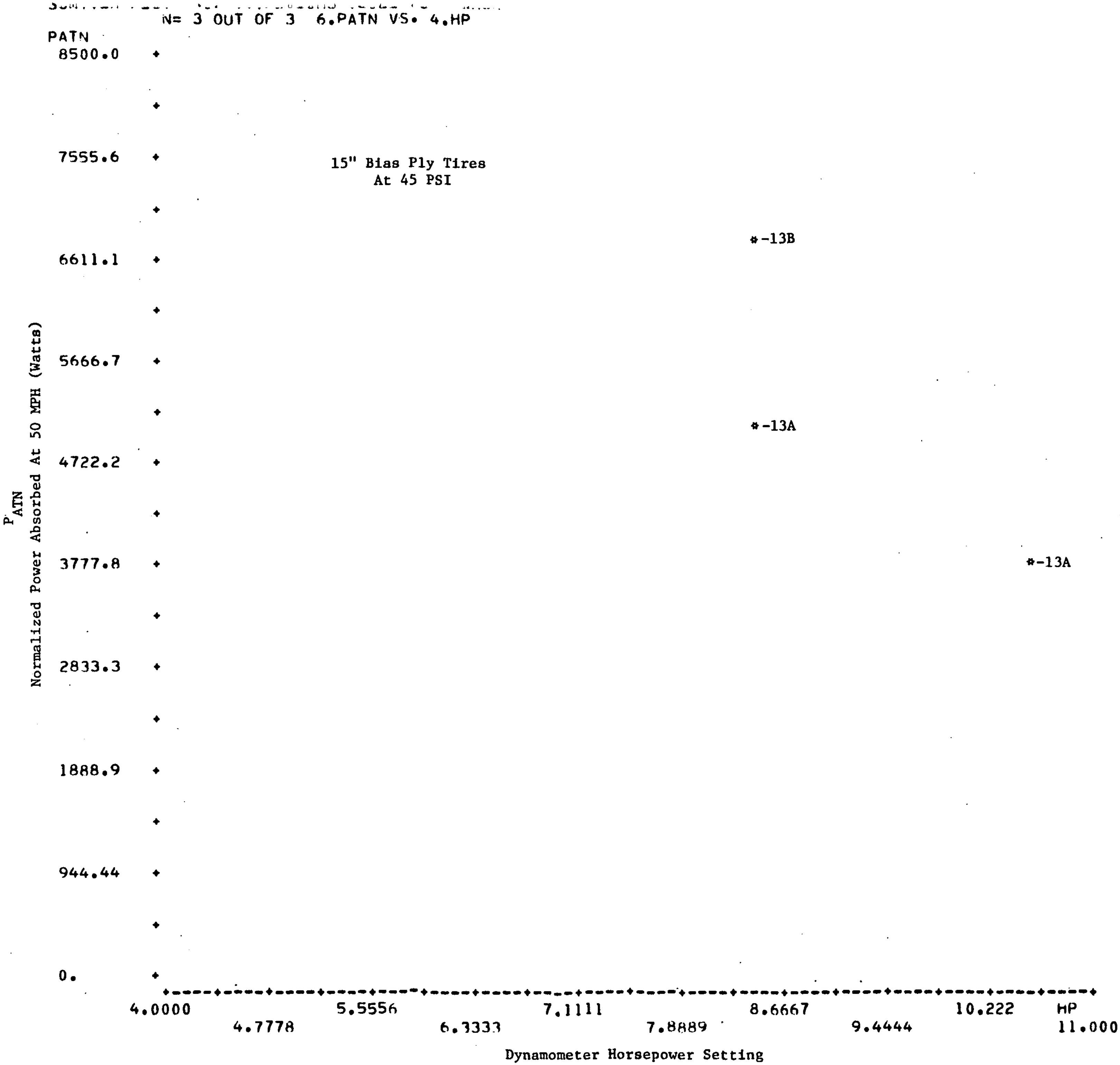

Figure F-13

Power Absorbed At 50 MPH As A Function Of Dynamometer Horsepower Setting For 15" Bias Ply Tires On The Twin Small-Roll Dynamometer

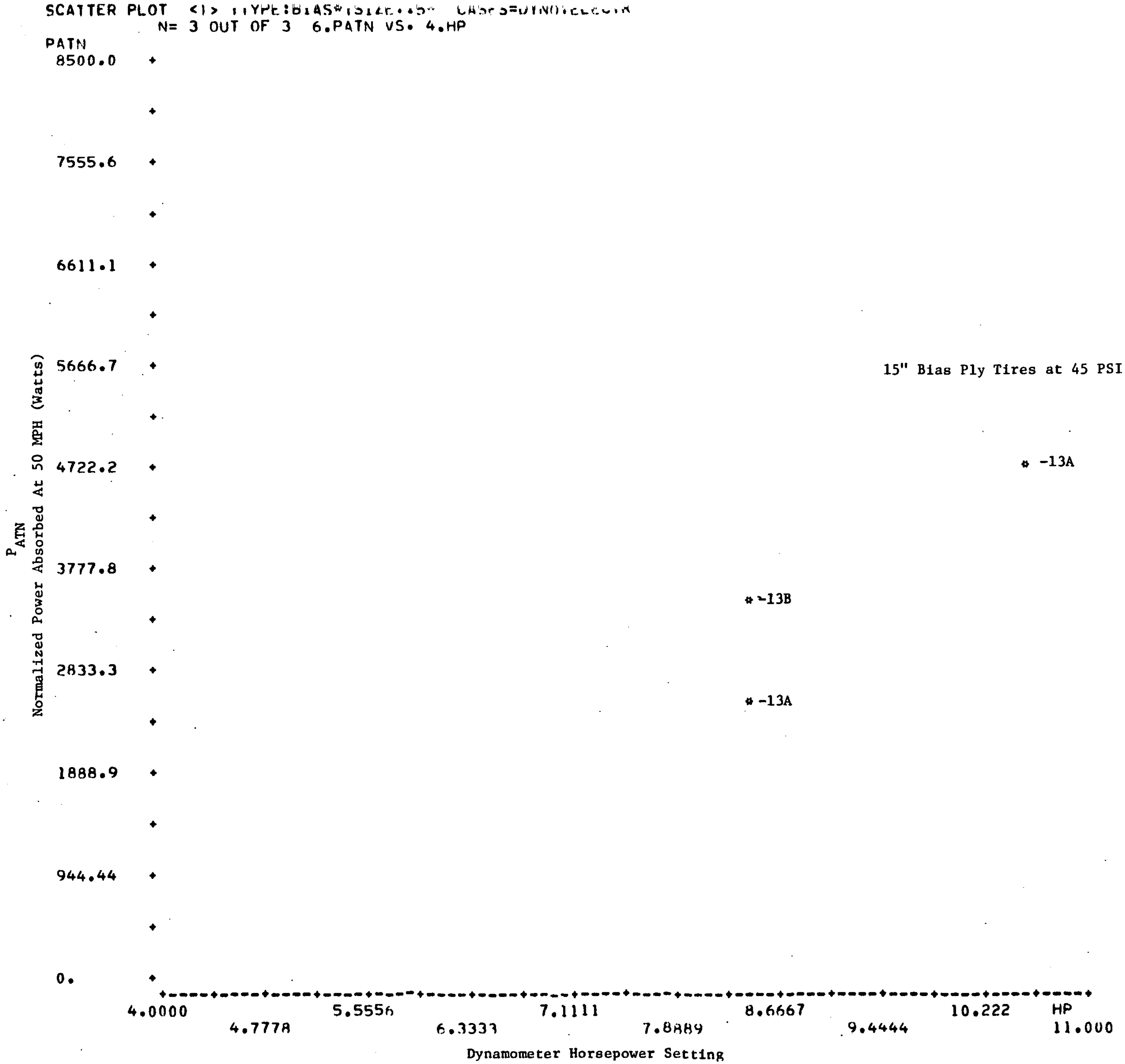

Figure F-14

Power Absorbed At 50 MPH As A Function Of Dynamometer Horsepower Setting For 15" Bias Ply Tires On The Single Large-Roll Dynamometer