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Ranking Tires Using a Transient Speed-Time Cycle

by

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NOTICE

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Abstract

The ability to rank passenger car tires according to their respective rolling resistance facilitates emission and fuel economy testing and can serve as a consumer buying aid. However, at the present time a single, universally accepted tire rolling resistance measurement method is not available. Current practices measure rolling resistance while the tire is operated at steady state conditions which are atypical of actual tire use.

ECTD is concerned that tires ranked according to typical steady state practices may perform differently when operated according to current emissions and fuel economy (transient) tests or in real life. This study was conducted to determine the difference in tire rolling resistance rankings from steady state and transient testing.

Tires and equipment used in previous ECTD tire rolling resistance experiments were utilized for this study. These consisted of two vehicles equipped with driveshaft torques and speed sensors, a single large-roll dynamometer and 13", 14" and 15" tires of various construction types (radial, bias belted and bias). The power transmitted by each vehicle was summed during its operation of accelerations and cruises of the Federal Test Procedure. Immediately following this transient operation, steady state rolling resistance measurements were conducted.

The results indicate that a significant correlation between the transient and steady state procedures exist but that test variability would not permit any concrete conclusions. In general, the data indicate that both procedures tend to rank tires in the same manner.

It is recommended that, due to the high test variability, the equipment used in this study not be used for future programs of this type. It is also recommended that further investigation be conducted as a part of a recently awarded tire testing contract (#68-03-2763).

I. Introduction

Since the advent of the coast down procedure to determine the road force on a vehicle, the role of the tire has become more and more important. In order to facilitate emission and fuel economy testing, for which the road force is determined, ECTD has sought a tire ranking system based on tire rolling resistance. This ranking system would be used in vehicle selection prior to emission and fuel economy testing and could be a consumer buying aid. However, no good, universally accepted method of measuring rolling resistance is available. Current methods tend to measure rolling resistance while the tire is at a steady state condition. ECTD has reservations about these techniques, since the tire is rarely used in this manner during emission and fuel economy (transient tests) testing or in typical consumer applications.

ECTD is concerned that tires during transient emission and fuel economy testing may perform differently from tires under a steady state condition. This report discusses the results of an experiment designed to determine the differences in tire rolling resistance rankings from transient and steady state tests.

II. Program Design

Two vehicles instrumented with driveshaft torque-transducers and speed-sensors were utilized for this study. Each vehicle was installed on a single large-roll dynamometer and operated at 50 mph for 30 minutes to stabilize both engine and drivetrain lubricant temperatures. Tires at ambient temperature (75°F) were then installed and the tire pressure was set to 26 psi. The vehicle was then operated according to the Federal Test Procedure speed-time cycle. The dynamometer was set for a nominal road load force with only system inertia applied (approximately 1,900 pounds).

The power expended by the vehicle during the acceleration and cruise modes of the speed-time cycle was monitored and recorded on a once-per-second basis. Upon completion of the transient speed-time cycle, the vehicle was accelerated to 50 mph and maintained at that velocity for a period of approximately 15 minutes while steady state tire rolling resistance measurements were conducted. The above procedure was repeated a minimum of two times for each pair of test tires for a total of 80 tests.

III. Analysis

In order to determine the power expended by the vehicle, the driveshaft torque and speed were monitored throughout the vehicle's operation. The instantaneous power was then computed and summed for all accelerations and cruises during the speed-time cycle according to the following equations:

$$P_i = T_i W_i \qquad (1)$$

where

P_i = ith output power point

T_i = ith driveshaft torque observation

W_i = The angular velocity of the driveshaft during the ith driveshaft torque measurement.

The total power was then computed as follows:

$$P_{TOT} = \sum_{i=1}^{n} P_i \qquad (2)$$

where

P_{TOT} = The total output power during accelerations and cruises

n = Total number of observations.

Since n and therefore P_{TOT} is dependent upon throttle perturbations, a weighted mean value was computed for all tests on the same pair of tires. The following equation illustrates this computation:

$$AVP_{TOT} = \frac{\sum_{k=1}^{m} n_k P_{TOT_k}}{N}$$

where

AVP_{TOT} = Average Output Power,

n_k = The number of observations in the kth test,

m = The number of tests on a particular pair of tires, and

N = The total number of observations.

The method utilized to determine the tire rolling resistance during the steady state portion of the test, was to measure the power transmitted by the vehicle and the power absorbed by the dynamometer. The difference was considered to be the power dissipated by the tire. From the tire power dissipation, a value for the tire rolling resistance, F_{RR}, was then derived. A more complete derivation for the computation of tire rolling resistance is contained in Appendix A. A mean tire rolling resistance value was then calculated for all tests on a particular pair of test tires.

IV. Results

The total vehicle output power, P_{TOT}, and the steady state tire rolling resistance, F_{RR}, data were analyzed to determine the relationship between the transient and steady state procedures. This analysis indicates that a significant correlation exists between the two procedures (i.e., the two procedures are not independent). Figure 1 presents P_{TOT} as a function of F_{RR} for each test. The general trend of increasing vehicle output power with increasing steady state rolling resistance can be easily discerned. A complete listing of these data by tire identification number is presented in Appendix B.

It should be noted that Figure 1 may be misleading. By computing the ratio P_{TOT} to F_{RR} and plotting these data versus tire identification number, the magnitude of the test variability for each tire tested may be realized. The causes of this variability could be numerous and are not easily identifiable. The general test methods and equipment used are considered to be the major contributors. Figure 2 presents these data.

As a method of reducing the variability, a weighted mean total vehicle output power, AVP_{TOT}, and a mean steady state rolling resistance value $\overline{F_{RR}}$ were computed. An analysis of variance was then performed on these data with respect to tire type within each of the nominal tire sizes tested (13", 14", and 15" tires). Significant differences between the various tire types could not be discerned due to data variability. The relative rankings of the tire types tested by the two procedures are presented in Table 1 below. Note that the general trends of the tire type mean values for each of the two procedures are the same.

TABLE 1

Rankings by Cycle and Tire Type Within Each Tire Size

Size	N	Tire Type	Ranking: Transient	Ranking: Steady State	Mean Value: Transient (watts)	Mean Value: Steady State (lb/k-lb)
13"	5	Radial	1	1	4478300	13.057
	1	Bias Belted	2	2	4748900	15.174
	3	Bias	3	3	4805100	15.558
14"	4	Radial	1	1	4649000	12.286
	3	Bias Belted	2	2	5192900	16.495
	-	Bias	-	-	-	-
15"	12	Radial	1	1	4978700	13.711
	2	Bias Belted	2	2	5500600	14.959
	2	Bias	3	3	5595800	17.152

N = Number of tires in the sample.

V. Conclusions/Recommendations

The results of this experiment indicate that, in general, either

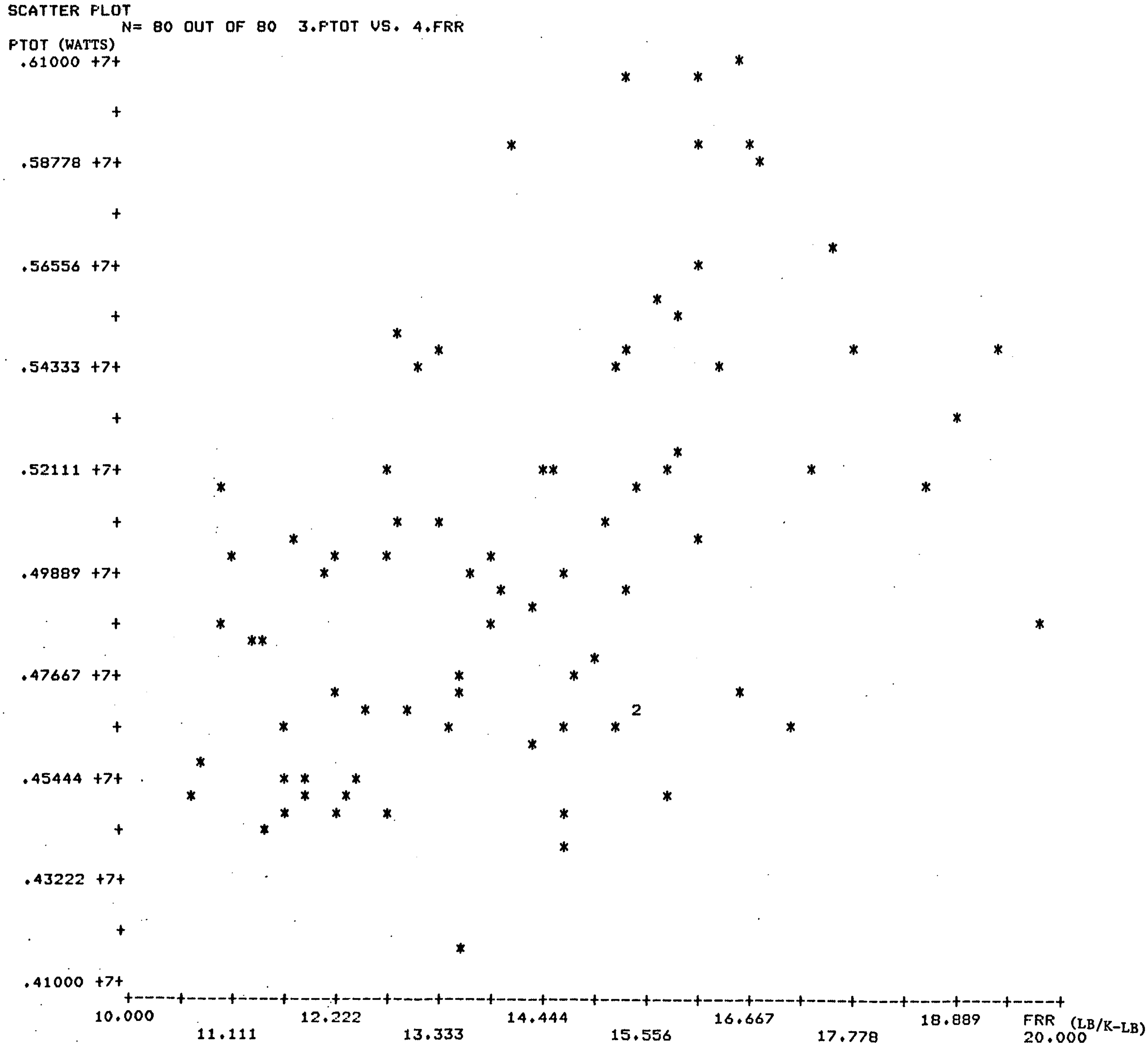

FIGURE 1

Total Vehicle Output Power, P_{TOT}, as a Function of Tire Rolling Resistance, F_{RR}

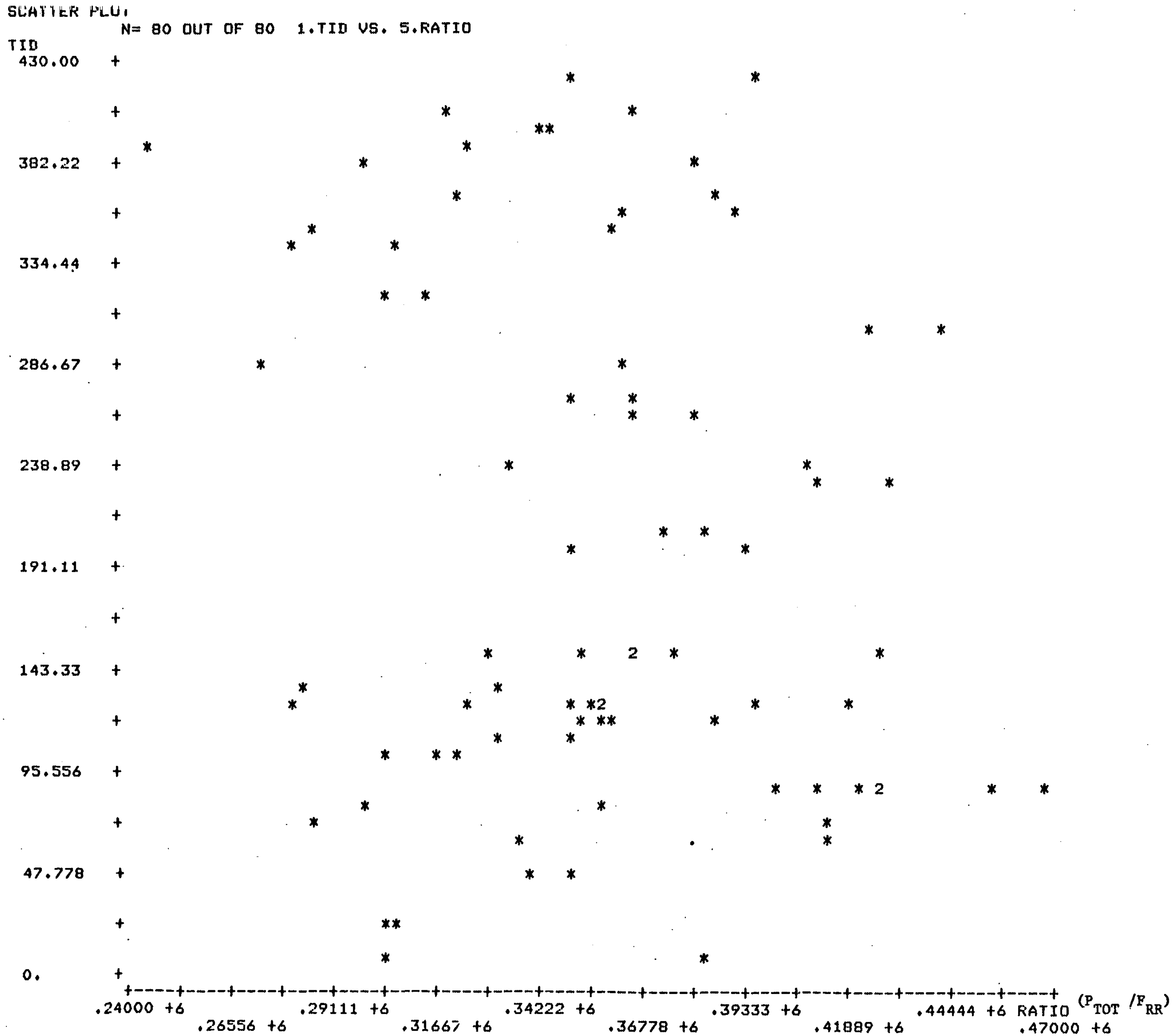

FIGURE 2

Tire Identification Number versus the Ratio of Total Vehicle Output Power to Tire Rolling Resistance procedure can be used to rank tires on the basis of tire rolling resistance. The significant correlation between the two procedures implies that the two parameters analyzed (P_{TOT} and F_{RR}) are interdependent (i.e., controlling variations of either parameter will affect the other parameter).

Several potential areas for concern to ECTD are revealed upon examination of the data presented above. Figure 1 indicates that several tires display the characteristic of having low steady state rolling resistance, F_{RR} and high vehicle output power, P_{TOT}, and some which have high F_{RR} and low P_{TOT}. These data points could be the result of test variability. However, the question "Do tires with these characteristics actually exist?" must be answered. If these data are representative of actual tire characteristics and not just a function of test variability, it behooves ECTD to require tire rolling resistance information obtained via a transient speed-time test procedure with each vehicle certification request. This type of information would also be of interest to the consumer when replacing existing tires.

It is therefore recommended that tests of a similar nature be conducted using more sophisticated equipment to confirm the results of this experiment. This area could be investigated as part of the recently awarded "Tire Energy Dissipation" contract (contract #68-03-2763).

It is also recommended that the equipment used for this experiment <u>not</u> be used for future tire rolling resistance investigations since it is a major source of variability.

References

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APPENDIX A

Methodology for Determining Tire Rolling Resistance

Methodology Utilized to Determine Tire Rolling Resistance

The power absorbed by the tire was computed each second of data collected according to the following equations:

$$P_{AT} = P_{engine} - P_{abs.\ diff.} - P_{bearing\ losses\ dyno} \quad (1)$$

$$= T_{eng} W_E - T_{diff} W_E - T_{LC} W_D - T_{BL} W_D \quad (2)$$

$$= (T_{eng} - T_{diff}) W_E - (T_{LC} + T_{BL}) W_D \quad (3)$$

where

P_{AT} = the power absorbed by the tire at the test speed

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: This quantity includes any effects due to brake drag.

T_{LC} = total torque measured by the dynamometer load cell

T_{BL} = torque due to bearing and frictional losses in the dynamometer

W_E and W_D = the angular velocities of the vehicle driveshaft and the dynamometer roll, respectively.

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

$$P_{AT} = T_T W_T \quad (4)$$

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:

$$T_T = F_R \times r \quad (5)$$

where F_R is the rolling force of the tire and r is the tire radius. Substituting equation 5 into 4 yields:

$$P_{AT} = (F_R \times r) W_T \quad (6)$$

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 6 produces:

$$P_{AT} = \frac{(F_R \times r)\, V_T}{r} = F_R\, V_T \qquad (7)$$

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 slip between the tire and the dynamometer roll occurs. Therefore, 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:

$$F_R = \frac{P_{AT}}{V_T} \qquad (8)$$

where V_T is the vehicle speed.

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 were 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:

$$F_{RR} = \frac{F_R}{F_{ZT}} \qquad (9)$$

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* Numbers in [] refer to references listed in the References section of this paper.

APPENDIX B

Test Data by Tire Identification Number

TABLE B-1

Total Vehicle Output Power and Tire Rolling Resistance by Tire Identification Number

TIRE ID	TIRE SIZE	TIRE TYPE	PTOT, TOTAL VEHICLE OUTPUT POWER (WATTS)	FRR, ROLLING RESISTANCE (LB/K-LB)	PTOT/FRR
010	13	RADIAL	4699607.70110	15.481	303572.618
010	13	RADIAL	4456460.98574	11.671	381840.544
020	13	RADIAL	4169058.63029	13.604	306458.294
020	13	RADIAL	4459429.52088	14.681	303755.161
050	14	RADIAL	4861544.48247	13.890	350003.202
050	14	RADIAL	4976103.17255	14.649	339688.933
060	15	BIASBE	5437440.26569	13.148	413556.455
060	15	BIASBE	5082784.62920	15.082	337009.987
070	15	RADIAL	4503038.11836	15.771	285526.480
070	15	RADIAL	5003666.10788	12.084	414073.660
080	15	RADIAL	5193074.84290	17.368	299002.467
080	15	RADIAL	5422514.44701	15.204	356650.516
090	15	RADIAL	4569432.59125	10.732	425776.425
090	15	RADIAL	4829152.70572	11.289	427775.065
090	15	RADIAL	4673362.90804	11.649	401181.467
090	15	RADIAL	4835103.88043	11.498	420516.949
090	15	RADIAL	5157718.88194	11.036	467354.012
090	15	RADIAL	5011721.31631	12.217	410225.204
090	15	RADIAL	5031882.96196	11.068	454633.444
100	13	BIASBE	4936358.72204	15.373	321105.752
100	13	BIASBE	4678714.39497	15.439	303045.171
100	13	BIASBE	4646476.97175	14.709	315893.465
110	14	BIASBE	5251387.67691	15.849	331338.739
110	14	BIASBE	5547526.54437	15.853	349935.441
121	15	RADIAL	5225096.70084	14.575	358497.201
121	15	RADIAL	4722578.47916	12.241	385800.055
122	15	RADIAL	4946343.12039	13.989	353588.042
122	15	RADIAL	5204202.99512	14.406	361252.464
131	15	BIAS	5880754.75908	16.810	349836.690
131	15	BIAS	5599430.11113	15.705	356538.052
131	15	BIAS	5487245.65375	15.363	357172.795
131	15	BIAS	5905336.77896	14.121	418195.367
131	15	BIAS	5332775.93030	18.912	281978.423
131	15	BIAS	5678084.85648	17.534	323832.831
131	15	BIAS	5897708.69109	16.622	354813.421
131	15	BIAS	6079214.81062	15.378	395318.950
132	15	BIAS	5434690.59457	16.369	332011.155
132	15	BIAS	5480499.63302	19.294	284052.018
151	15	BIASBE	5659061.59892	16.081	351909.807
151	15	BIASBE	5494032.17758	12.850	427551.142

TABLE B-1 (continued)

Total Vehicle Output Power and Tire Rolling Resistance by Tire Identification Number

TIRE ID	TIRE SIZE	TIRE TYPE	PTOT, TOTAL VEHICLE OUTPUT POWER (WATTS)	FRR, ROLLING RESISTANCE (LB/K-LB)	PTOT/FRR
151	15	BIASBE	6085531.48439	16.611	366355.516
151	15	BIASBE	5912991.88684	16.166	365767.159
151	15	BIASBE	5214041.40196	15.793	330148.889
151	15	BIASBE	6078585.89076	16.154	376289.829
200	15	RADIAL	5015769.50980	12.766	392900.635
200	15	RADIAL	4725925.94608	13.548	348828.310
210	15	RADIAL	4678619.58792	12.521	373661.815
210	15	RADIAL	5081775.55830	13.280	382663.822
230	15	RADIAL	5474233.67325	13.325	410824.291
230	15	RADIAL	5048233.57910	11.738	430076.127
240	15	RADIAL	5210731.75113	12.775	407885.069
240	15	RADIAL	5174624.18976	15.480	334278.048
260	14	RADIAL	4548570.03879	11.944	380824.685
260	14	RADIAL	4517766.91246	12.378	364983.593
270	14	RADIAL	4477099.54956	12.218	366434.732
270	14	RADIAL	4453785.67033	12.768	348824.066
290	15	RADIAL	5035755.49335	13.870	363068.168
290	15	RADIAL	4669527.44244	17.099	273087.750
300	14	RADIAL	4863804.01492	10.980	442969.400
300	14	RADIAL	4502121.83540	10.620	423928.610
320	14	BIASBE	4651382.81145	15.257	304868.769
320	14	BIASBE	5063672.56870	16.080	314905.010
340	14	BIASBE	5178608.69943	18.514	279713.120
340	14	BIASBE	5452987.08649	17.830	305832.142
350	13	BIAS	4734697.99628	16.508	286812.333
350	13	BIAS	4676142.38075	13.010	359426.778
360	13	RADIAL	4535218.38450	12.497	362904.568
360	13	RADIAL	4532181.99243	11.624	389898.657
370	13	RADIAL	4429162.46963	11.492	385412.676
370	13	RADIAL	4601722.82945	14.320	321349.360
380	13	RADIAL	4378467.70093	14.660	298667.647
380	13	RADIAL	4523452.27654	11.872	381018.554
390	13	BIAS	4862117.06838	19.736	246357.776
390	13	BIAS	4769476.88401	14.737	323639.607
400	15	RADIAL	4646382.52911	13.463	345122.375
400	15	RADIAL	4910079.64209	14.384	341357.039
410	13	BIAS	4982682.78344	13.680	364231.198
410	13	BIAS	4796418.02577	14.993	319910.493
420	15	RADIAL	4760031.74965	13.577	350595.253
420	15	RADIAL	5116505.39162	12.929	395738.680

TABLE B-2

Average Total Vehicle Output Power and Tire Rolling Resistance by Tire Identification Number

TIRE ID	TIRE SIZE	TIRE TYPE	AVPTOT, WEIGHTED MEAN VEHICLE POWER (WATTS)	$\overline{FRR}$, ROLLING RESISTANCE (LB/K-LB)	AVPTOT/$\overline{FRR}$
010	13	RADIAL	4574553.58600	13.576	336958.868
020	13	RADIAL	4317660.20300	14.143	305286.022
050	14	RADIAL	4917026.70500	14.270	344570.897
060	15	BIASBE	5259796.73000	14.115	372638.805
070	15	RADIAL	4754096.65100	13.928	341333.763
080	15	RADIAL	5305296.33200	16.286	325758.095
090	15	RADIAL	4870421.62000	11.356	428885.313
100	13	BIASBE	4748929.74100	15.174	312964.923
110	14	BIASBE	5404428.26600	15.851	340951.881
121	15	RADIAL	4968880.56700	13.408	370590.734
122	15	RADIAL	5076651.16900	14.198	357561.006
131	15	BIAS	5733699.06400	16.306	351631.244
132	15	BIAS	5457839.64500	17.832	306069.967
151	15	BIASBE	5741444.10400	15.609	367829.080
200	15	RADIAL	4871960.53500	13.548	359607.362
210	15	RADIAL	4878631.21600	12.901	378159.152
230	15	RADIAL	5261616.49000	12.532	419854.492
240	15	RADIAL	5192475.11900	14.128	367530.798
260	14	RADIAL	4532920.80200	12.161	372742.439
270	14	RADIAL	4465615.76600	12.493	357449.433
290	15	RADIAL	4852751.44600	15.484	313404.253
300	14	RADIAL	4680605.99100	10.800	433389.444
320	14	BIASBE	4859595.21900	15.668	310160.532
340	14	BIASBE	5314678.63300	18.172	292465.256
350	13	BIAS	4706746.25600	14.759	318906.854
360	13	RADIAL	4533676.37600	12.061	375895.562
370	13	RADIAL	4515774.67800	12.906	349897.310
380	13	RADIAL	4449849.60300	13.266	335432.655
390	13	BIAS	4816153.46700	17.236	279424.081
400	15	RADIAL	4778466.39000	13.924	343182.016
410	13	BIAS	4892407.22500	14.337	341243.442
420	15	RADIAL	4933726.12700	13.253	372272.401

APPENDIX C

Tire Description by Identification Number

Tire Description

ID Number	Manufacturer	Size	Model
010	Goodyear	BR 70 X 13	Polyglass Radial WT
020	Goodyear	BR 70 X 13	Polyglass Radial
050	Goodyear	HR 78 X 14	Polyglass Radial WT
060	Goodyear	H 78 X 15	Custom Power Cushion Polyglass
070	Goodyear	HR 78 X 15	Polyglass Radial
080	Goodyear	HR 70 X 15	Polyglass Radial WT
090	Goodyear	HR 78 X 15	Custom Polysteel Radial
100	Goodyear	B 78 X 13	Cushion Belt Polyglass
110	Goodyear	H 78 X 14	Cushion Belt Polyglass
121	B. F. Goodrich	HR 78 X 15	Silvertown Steel Radial
122	B. F. Goodrich	HR 78 X 15	Silvertown Steel Radial
131	B. F. Goodrich	H 78 X 15	Custom Long Miler
132	B. F. Goodrich	H 78 X 15	Custom Long Miler
151	B. F. Goodrich	HR 78 X 15	Silvertown Belted
200	Goodyear	HR 78 X 15	Steel Belted Radial Custom Tread
210	Uniroyal	GR 78 X 15	Steel Belted Radial PR6
230	General	GR 78 X 15	Dual Steel II Radial
240	Uniroyal	LR 78 X 15	Steel Belted Radial PR6
260	Uniroyal	FR 78 X 14	Steel Belted Radial
270	Firestone	FR 78 X 14	Steel Belted Radial
290	Firestone	HR 78 X 15	Steel Belted Radial
300	Uniroyal	ER 78 X 14	Steel Belted Radial
320	Goodyear	E 78 X 14	Custom Power Belted Cushioned Polyglass
340	Firestone	E 78 X 14	Sup-R-Belted Champion
350	Uniroyal	B 78 X 13	Fastrak Belted
360	Goodyear	BR 78 X 13	Steel Belted Radial
370	Firestone	BR 78 X 13	Steel Belted Radial
380	Uniroyal	BR 78 X 13	Steel Belted Radial
390	Firestone	B 78 X 13	Deluxe Champion
400	Uniroyal	HR 78 x 15	Steel Belted Radial
410	B. F. Goodrich	B 78 X 13	Silvertone Bias
420	B. F. Goodrich	GR 78 X 15	Lifesaver 78 Steel Belted Radial