EPA-460/3-79-010
July 1979

CALSPAN ADVANCED TECHNOLOGY CENTER

COMPARISON BETWEEN A DOUBLE-ROLL AND A FLAT-BED DYNAMOMETER CONFIGURATION IN REGARDS TO PASSENGER-CAR TIRE POWER CONSUMPTION, FUEL ECONOMY AND EXHAUST EMISSIONS

by

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July 1979
Contract No. 68-03-2534

Project Officer
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FOREWORD

This report is submitted in fulfillment of EPA Contract No. 68-03-2534. The report has been reviewed by the Emission Control Technology Division, U. S. Environmental Protection Agency, and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the U. S. Environmental Protection Agency, nor does the mention of trade names or commercial products constitute endorsement or recommendation for use.

ABSTRACT

The purpose of this research program was to achieve a quantitative comparison between a conventional double-roll chassis dynamometer and an experimental prototype of a flat-bed dynamometer as regards tire power losses, fuel economy and exhaust emissions. Design and fabrication of the special dynamometer, partially funded under this contract, were based on the use of a power absorption unit and an inertia unit from a conventional Clayton dynamometer.

Two 1977-model vehicles, one in the 2250-lb. inertia class (a Chevette) and one in the 4500-lb. class (an Oldsmobile 98) were used for test purposes. Each vehicle was supplied with complete sets of bias-ply, bias-belted and radial-ply tires. Rear-wheel rims on each vehicle incorporated torque transducers.

Test operations included: (1) the measurement of wheel torque and wheel horsepower during steady-state operation of the vehicles on a test track, (2) the measurement of the rolling resistance of the individual tires on the Calspan Tire Research Facility and (3) the measurement of emissions, fuel economy, tire power loss and wheel torque for dynamometer tests using the Federal Test Procedure, the Highway Fuel Economy Test and steady-state velocity tests. Dynamometer tests were made only on the 4500-lb. inertia class vehicle.

In terms of fuel economy, the flat-bed dynamometer correctly ranks the different tire constructions showing the radial-ply tires are superior to the bias-type tires. The roll dynamometer, however, reverses the order and yields data that show the bias-type tire affords better fuel economy than the radial-ply tire. For radial-ply tires, the differences in measured fuel economies on the two dynamometers were relatively minor for all tests. Some differences in exhaust emissions were noted between results from identical tests performed on the two dynamometers. The significance of these differences is questionable because of the nominally large variability in these measurements, a paucity of replicate data and the presence of certain small differences in ambient conditions at the dynamometer test sites.

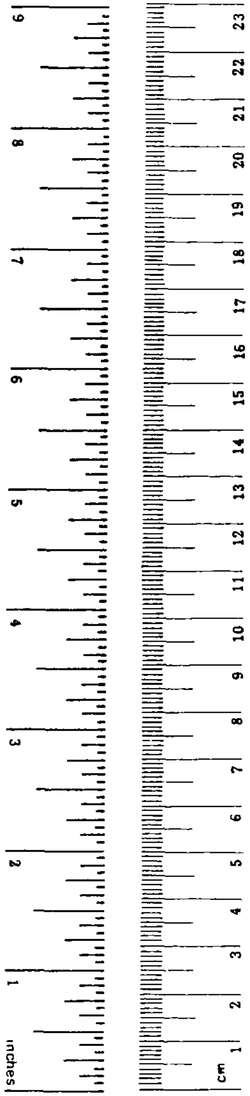
This report was submitted in fulfillment of Contract No. 68-03-2534 by the Advanced Technology Center, Calspan Corporation under sponsorship of the U. S Environmental Protection Agency. This report encompasses the time period March 11, 1977 to April 24, 1979, and work was completed as of June 29, 1979.

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

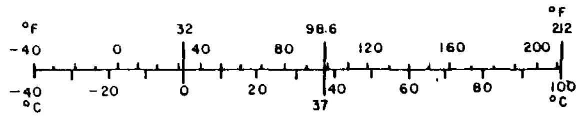
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	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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ACKNOWLEDGEMENT

Significant conceptual and design contributions to the flat-bed dynamometer were made by G. R. Duryea, I. Gusakov and S. D. Smith. Dynamometer checkout tests as well as the maintenance and repair of the unit throughout the entire program were performed by A. J. LaPres.

General Motors Corporation supplied the test vehicles, the personnel and the test facilities at its Milford, Michigan Proving Ground free of cost. All vehicular testing and data acquisition was performed by GM personnel who supplied reduced data to Calspan. Operations at the Milford Emissions Laboratory were directed by D. D. Horchler, J. A. Tysver and C. E. VanAcker.

SECTION 1.0

INTRODUCTION

The validity of laboratory test procedures for the measurement of vehicle fuel economy and exhaust emissions depends on the accuracy with which the energy transfer and power losses that occur on the road are reproduced. Current practice involves the operation of the vehicle on a roll-type of chassis dynamometer. Using inertia fly-wheels coupled to the dynamometer rolls, the transfer of engine power to kinetic energy equivalent to that of the moving vehicle can be accurately simulated. Energy lost within the vehicle system can also be readily simulated.

Power losses, such as those caused by aerodynamic drag, are simulated by the use of various types of power absorption devices that also are coupled to the dynamometer rolls. A device commonly used for this application is a water-brake type of power absorber which characteristically approximates a cubic variation of power with velocity as does the aerodynamic drag loss of automotive vehicles. Federal Test Procedures require that the dynamometer power dissipation is set to equal the vehicular "road load" at 50 mph*. Except for the presence of power losses associated with the rolling resistance of tires, losses which vary approximately linearly with velocity, the dynamometer simulation of vehicle "road load" at other velocities would be reasonably accurate. A further complication results from the fact that tires operating on rolls undergo large deflections of the carcass resulting in excessively high tire temperatures. Federal Test Procedures permit the use of cold tire inflation pressures to 45 psi to preclude tire damage. Thus the tire power consumption that is experienced on a roll-type dynamometer is expected to differ from that experienced on a flat roadway.

The experimental study reported here was undertaken principally to evaluate the differences in fuel economy and exhaust emissions as measured for identical tests performed on a dual-roll chassis dynamometer and special flat-bed type of chassis dynamometer that duplicated a straight and level roadway surface. Other objectives included the measurement of vehicular road load power and tire horsepower consumption and the characterization of the dynamometer frictional and true horsepower loading. Bias-ply, bias-belted and radial-ply tire constructions were used in tests performed on vehicles representative of the 2250-lb.**and 4500-lb. inertia classes.

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* The use of the English system of units was approved by the Project Officer. A conversion table is included in the report.

** For road tests this vehicle was ballasted to a weight of 2500 lb.

The flat-bed dynamometer was assembled as an experimental prototype making use of the basic loading components of a Clayton-type chassis dynamometer. Two Calspan-developed simulated roadway units (SRU) were the basic building blocks of this dynamometer to which the Clayton water brake and inertia units were connected.

A cost-sharing contractual arrangement was entered into by the EPA, General Motors and Calspan, with General Motors in a subcontractor role to Calspan. By this agreement General Motors provided, without cost, the test vehicles, tires, facilities and personnel required to perform the specified road tests and dynamometer evaluation tests at its Milford, Michigan Proving Ground (GMPG). Calspan provided, without cost, the engineering, design and development effort required to adapt the SRU to the basic Clayton dynamometer components.

This report describes the accomplishments of the program, the tests that were performed, the results that were obtained and the significance of these results. The tests that were performed and the data analyses that were made were in accordance with the explicit requirements of the contractual Statement of Work.

To provide an overview of the sequence of events as they occurred during the course of the project, which continued over a span of more than two years, a chronology of the significant milestones is itemized in Table 1.

Table 1

CHRONOLOGY OF MAJOR PROJECT EVENTS

	EVENT	DATE
1.	Program initiated	March 1977
2.	Test vehicles and tires procured (GMPG)	June 1977
3.	Design of the flat-bed dynamometer completed	September 1977
4.	Vehicle road tests completed (GMPG)	October 1977
5.	Delivery of Simulated Roadway Unit (SRU) accepted	November 1977
6.	Fabrication of flat-bed dynamometer and water system completed	February 1978
7.	Tire rolling resistance tests completed on TIRF	February 1978
8.	Checkout tests of the flat-dynamometer at Calspan completed	March 1978
9.	Delivery of the flat-bed dynamometer accepted by GMPG	August 1978
10.	Installation and checkout of the flat-bed dynamometer completed (GMPG)	November 1978
11.	Dynamometer testing begins (GMPG)	January 1979
12.	All test activity terminated	March 1979
13.	Draft of final report submitted	June 1979

SECTION 2.0

CONCLUSIONS

The following itemized conclusions are drawn from the test results obtained during the performance of the test program and the analyses to which these results were subjected. There is no significance to be attached to the ordered sequence of these conclusions.

- Friction horsepower losses for the flat-bed dynamometer that was used in this study were significantly larger than those for the Clayton roll dynamometer. At a speed of 50 mph, the friction horsepower for the flat-bed unit was 11.1 as compared with 2.8 for the roll unit.

- The absorbed-horsepower/velocity characteristic curve of the flat-bed dynamometer matches the road-horsepower/velocity characteristic curve of the 1977 Oldsmobile 98 test vehicle much more closely than the Clayton dynamometer.

- The flat-bed dynamometer correctly rank orders tires in terms of fuel economy showing the radial-ply construction superior to that of the bias-ply.

- The roll dynamometer incorrectly rank orders tires in terms of fuel economy showing the bias-ply construction superior to that of the radial-ply.

- In comparing data means, the most significant differences, in a statistical sense, occurred between tests on (1) bias-ply tires on the flat-bed and the roll dynamometers and (2) radial-ply and bias-ply tires on the flat-bed dynamometer. The least significant differences occurred between tests on radial-ply and bias-ply tires on the roll dynamometer. The foregoing remarks apply to exhaust emissions (FTP tests)*, fuel economy and positive wheel torque (FTP, HFET and SS tests)*.

- Exhaust emissions data (FTP tests) generally are not conclusive in a statistical sense although the CO and NO_x levels are consistently higher on the flat-bed dynamometer than on the roll dynamometer for comparable test conditions.

*FTP - Federal Test Procedure, HFET - Highway Fuel Economy Test, SS - Steady Speed

- Differences in tire power consumption (SS tests) among radial-ply, bias-belted and bias-ply constructions operating on the roll dynamometer generally are not statistically significant.

- The flat-bed dynamometer requires further development to improve (1) belt life, (2) water-bearing seal durability and (3) belt tracking. Friction horsepower losses need to be reduced also.

SECTION 3.0

RECOMMENDATIONS

Based on the conclusions resulting from this experimental study, the desirability of conducting additional programs to further quantify the differences between fuel economy and exhaust emission data as measured on conventional roll-type chassis dynamometers and flat-bed-type dynamometers would seem to be justified. It is recommended that follow-on effort should include:

(1) The design and fabrication of a production-type flat-bed dynamometer that would incorporate such features as:

- a programmable, electrical-type power absorption unit that would overcome the relatively high frictional power loss and simulate, to a high level of accuracy, a wide spectrum of road load power versus velocity functions
- a direct means for determining friction horsepower
- roadway belts with improved durability
- improved water-bearing seals
- a convenient and rapid way to vary the track width
- a compact and efficient heat exchanger to control water temperature

(2) A test schedule with a significantly increased level of replication. The wide variability in HC and CO emissions measurements necessitates more than the three replicate tests that were conducted in this program if meaningful statistical analyses are to be performed. The confidence with which the population mean can be defined for a set of data is improved by approximately a factor of two when replication is increased from three tests to ten.

(3) Tests on other sizes and brands of vehicles as well as on low-inertia class vehicles to ascertain how different size tires affect the differences in fuel economy, emissions and tire power loss between the flat-bed and roll-type dynamometers.

SECTION 4.0

DISCUSSION

4.1 THE FLAT-BED DYNAMOMETER

The flat-bed dynamometer consists of two distinct systems, the dynamometer itself and its associated water supply system. A description of the salient features of the entire assembly will be presented in this section of the report. Additional detailed information is included in Appendix A.

The description of the dynamometer that follows will be rendered more meaningful by reference to the simple sketch of Figure 1 which shows a plan view of the unit. Basically, the system can be considered as a chassis-type dynamometer similar to one manufactured by Clayton whose rolls have been replaced by simulated roadway units (SRU) (1)* which provide flat and level surfaces for the vehicle's driving wheels to operate on. Each SRU consists of two parallel, vertical frame members that support two crowned drums on which the endless belt operates. One drum, the lower one shown in the sketch, operates in bearings that are fixed in the frame of the SRU. The other drum is so mounted that belt-tension and belt-tracking adjustments can be made by a repositioning of the drum. Each drum is 19.25 inches in diameter and 15 inches wide while the belt is 15.75 inches wide and 0.024 inches thick.

A hydrostatic water bearing is located midway between the axes of rotation of the drums and provides the physical support for the belt and its load. Spring-loaded, wiper-type seals are used to control water leakage at the bearing which operates at a supply pressure of approximately 200 psi. The water bearing is designed to accommodate tire contact pressures up to 100 psi and has an active bearing size that is about 10 inches in width and 12 inches in length. Except for differences in shaft lengths and shaft termination details, the two SRU units are identical in all other respects.

The nonadjustable drums are coupled directly through a pair of flex-type rubber couplings joined by a floating shaft. With this arrangement, the dynamometer accommodates the rear-track of the larger test vehicle. By removing the floating shaft and translating the left-hand SRU**and the power absorption

* Numbers in parentheses designate references listed at the end of the report.
** As shown in the sketch.

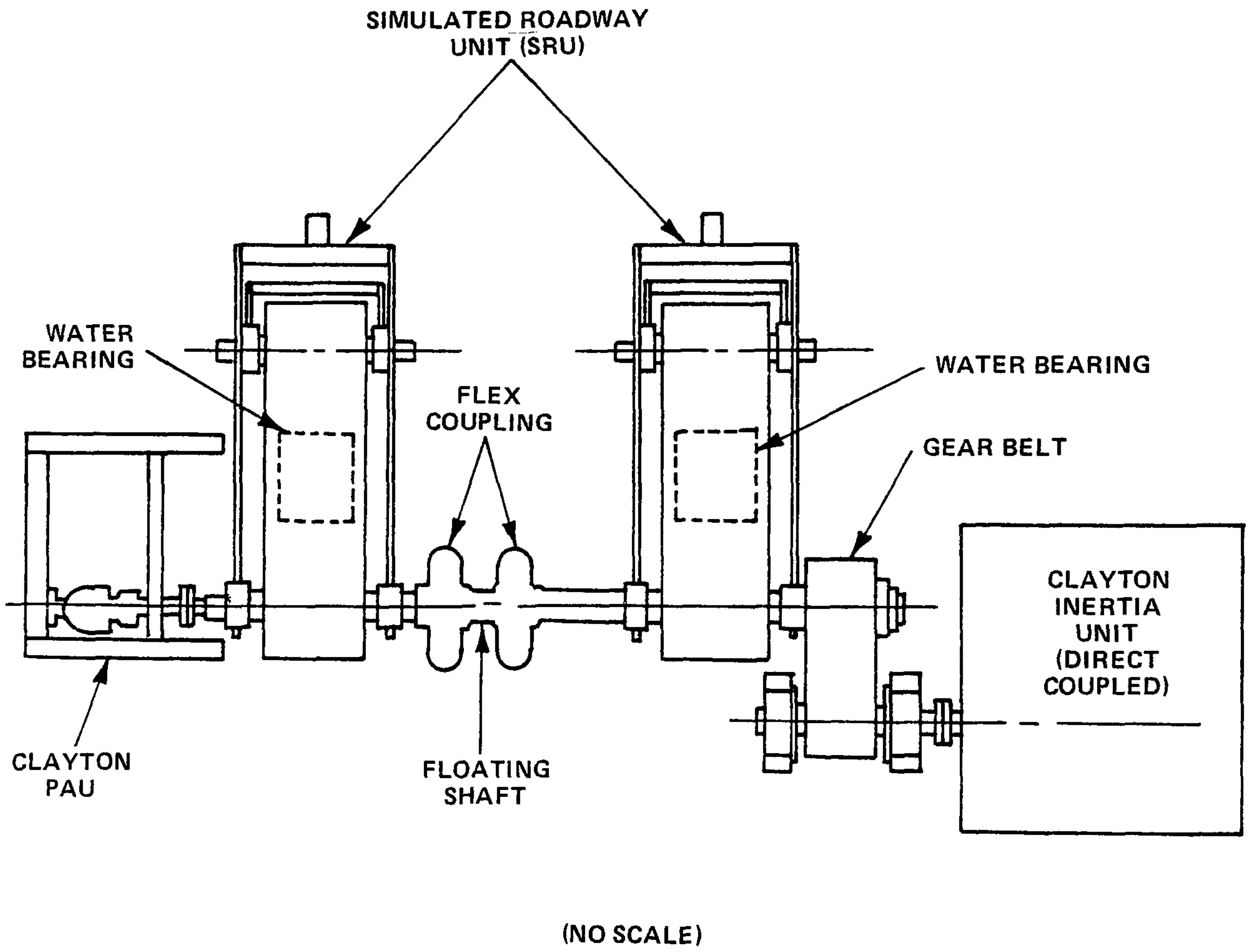

Figure 1 Flat-bed dynamometer plan-view sketch.

unit (PAU), the spacing between the SRU's will satisfy the rear-wheel track requirements of the smaller test vehicle. To facilitate this adjustment, both the SRU and the PAU are mounted on a common base plate which can translate as well as rotate. This latter feature permits setting a small slip angle at the vehicle's right rear wheel, if necessary, to stabilize the vehicle's lateral position at the belts*.

A direct-coupled, five-wheel, Clayton inertia unit was coupled to the SRU's through a step-up speed ratio using a gearbelt-pulley combination. Because of the large difference in the diameters of the SRU drums and the Clayton rolls (8.65 inches, diameter), the rotational speed of the SRU drums was much slower at any given vehicle speed than the Clayton rolls. As a consequence, the effectiveness of the flywheel inertia in simulating vehicle weight at the roadway surface had to be augmented by a step-up ratio (1:1.875).

All dynamometer components were mounted on a steel-beam support base allowing the system to be transported as a single unit with the component parts in an aligned condition. Dynamometer design envelope was dictated by the requirement that the unit fit a standard (3 ft x 8 ft x 15 ft) pit at the GM Proving Ground.

The water supply system consists of a high-pressure, high-volume pump (≈200 gpm at 200 psi), a sump, a low-pressure, high-volume pump (300 gpm), a 500-gallon reservoir (polyethylene), particulate filters and sundry valves, switches, motor controls, etc. With the exception of the reservoir, all of the water system components were mounted on the dynamometer support base.

Following the assembly of the complete dynamometer system, the belts on the SRU's were covered with a medium-grit, adhesive-backed abrasive material sold under the tradename of "Safety-Walk"**. This same material is used on the Calspan TIRF machine and satisfactorily simulates the texture and skid resistance of typical highway surfaces when a "stoning" operation is performed on the as-delivered material.

4.2 TEST PLAN DETAILS

The overall test plan required that two vehicles be obtained for test operations; one in the 5000-lb. inertia class and one in the 2500-lb inertia class. Three sets of tires were to be provided for each vehicle representing bias-ply, bias-belted and radial-ply constructions. Vehicle rear wheels were

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* It was not necessary to use this feature during this test program

** 3-M Company

to be instrumented to permit the measurement of rear-wheel torque during all testing operations.

Testing operations included the measurement of rear-wheel torque during a series of steady velocity runs on an outdoor test track with the vehicles equipped with each of the three sets of tires. From these data the wheel horsepower variation with velocity could be established. Subsequent to these road tests, laboratory measurements were to be made to determine the rolling resistance of each of the tires on the Calspan flat-bed tester (TIRF) under the same normal load conditions as each tire experienced on the test vehicle. Data from these tests were to be used in establishing road load power settings for the dynamometer tests. Dynamometer tests were to be conducted on both the flat-bed and roll-type units for the purpose of measuring fuel economy, exhaust emissions, wheel horsepower, tire power loss and other dependent variables. Vehicles were to be operated in accordance with the Federal Test Procedure (FTP), the Highway Fuel Exonomy Test (HFET) and a series of steady velocity tests (SS). The foregoing comments represent a statement of intentions. The succeeding comments present the events that actually transpired.

Vehicle down-sizing for the 1977 model year did not permit fulfillment of a 5000-lb. inertia class requirement with a high-volume production vehicle. As a compromise, General Motors selected an Oldsmobile 98 as a 4500-lb. inertia class vehicle and the Chevrolet Chevette as a 2250-lb inertia class vehicle. These choices still preserved the desired factor-of-two ratio between vehicle inertias. To minimize variation in tire dimensions with construction differences, all tires in a given size were obtained from one manufacturer. Bias-belted tires in the 13-inch size used by the Chevette are not normally fabricated, however, the General Tire and Rubber Company did supply GM with a set of these tires.

Road tests were performed on each vehicle following a test schedule that exceeded in scope the requirements of the contract as tabulated below:

ROAD TEST SCHEDULE

Run No.	Tire Construction	Tire Pressure (cold)	Speed, mph
1-10	Radial	MRP*	20,30,40,50,60 60,50,40,30,20
11-13	Bias-belted	MRP*	50,50,50
14-16	Bias	MRP*	50,50,50

*Tire manufacturer's recommended pressure (24 psi)

The full set of runs specified on the radial-ply tires was completed for the bias-belted and bias-ply tires as well. An in-depth discussion of the road tests and the resultant data is included in Section 4.3.

Following the completion of the road tests, Calspan performed laboratory tests to measure the equilibrium rolling resistance force of the tires at a constant velocity of 50 mph (rolling resistance is essentially independent of speed up to about 65 mph). Since data on each of the tires were not required in performing the dynamometer tests, only 20 of the 24 tires were tested in the interests of minimizing costs. Section 4.4 elaborates on the details of these tests and presents a summary of the measured data. Since only the front tires are free-rolling (on a rear-wheel drive vehicle), the applicability of free-rolling data to rear tires may be questioned. Test data show that for even sizable levels of steady wheel torque, tire rolling resistance remains substantially constant. (2) In fact there is evidence that minimum rolling resistance can occur at a positive (driving) torque and not in the free-rolling condition.

The bulk of the testing was performed on the dynamometers, faithfully following a test plan which was outlined in the contractual statement of work. FTP, HFET and steady-speed tests were performed, with replication, on both radial-ply and bias-ply tires. Bias-belted tires were only tested at steady-speed conditions. Replication was limited to only two repeat tests as a maximum. In some instances, only one repeat test was made. For all tests, wheel torques and exhaust emissions were measured. The effects of changes in inflation pressure and dynamometer load settings on measured data were investigated for the case of the flat-bed dynamometer only. Specific details of the dynamometer test schedule are given in Appendix B. Test results are presented in Section 4.5 which also includes the results of dynamometer calibration tests.

4.3 VEHICLE ROAD TESTS

4.3.1 Test Details

The purpose of the road tests on the Chevette and the Oldsmobile 98 vehicles was to obtain rear-wheel torque measurements at various steady-state velocities on a flat and level roadway. Tests were performed on each vehicle which was equipped alternately with sets of radial-ply, bias-belted and bias-ply tires. Both test vehicles were equipped with automatic transmissions and used an oxidizing catalytic converter as part of its emission control system.

Each vehicle was fitted with torque rims on the rear wheels to permit the measurement of wheel torque. These rims were specially built to maintain the same vehicular wheel track as existed with standard rims. The reason for this requirement was that the flat-bed dynamometer had been designed to accommodate, within a small tolerance, the standard rear track of the Chevette and the Oldsmobile 98.

Electronic equipment was carried on board the vehicles to log and to display the data. This equipment, designated by GM as the Total Torque Tester (TTT), totalizes and digitally displays time, torque and distance. Distance measurements were made using a trailing-wheel device which incorporated an optical encoder permitting an accuracy of 0.1 ft. to be realized. A description of this test instrumentation is included in Appendix D. Velocity, therefore, is a calculated quantity based on time and distance measurements.

Tests were conducted in dry weather only and test procedures employed for each vehicle were identical. Prior to each test day, the fuel tank was filled, the vehicle weight at each wheel was recorded and the tires were set to the manufacturer's recommended pressure (24 psi). The vehicle was operated for 30 minutes at 50 mph to stabilize tire temperatures. Wind velocity and direction, barometric pressure, weather conditions and ambient temperature were recorded. The vehicle was then operated for two laps, at each test speed, on the Proving Ground north-south straightaway which is a flat, level test track that incorporates high-speed turn loops at either end.

Data were collected for one mile in each direction with four miles of data taken at each speed on each day. A minimum of three days of test data were collected for each vehicle and tire-type combination. Wheel torque and wheel horsepower measurements were made at average steady speeds of 20, 30, 40, 50 and 60 mph. Test data were logged manually from the digital displays.

Road tests took place during September/October, 1977. Ambient temperature varied from 48^{o}F to 67^{o}F for these tests with barometric pressure ranging from 28.40 to 29.70 in Hg. Data shown in the next section were not corrected for these changes in ambient conditions which would affect the retarding forces experienced by the vehicles due to aerodynamic drag and tire rolling resistance.

4.3.2 Results

A tabular summary of the numerical data resulting from the road tests on the Oldsmobile is shown in Table 2. Velocity, wheel torque and wheel horsepower are tabulated for each tire construction. Details of the wheel horsepower calculation are shown as step 4.1.12 of Appendix C. Corresponding data for the Chevette are shown in Table 3.

Least-squares curves of the form $(a + bV^2)$ were calculated to fit the wheel torque data for each vehicle as tested with each of the three sets of tires. Similarly, least-squares curves of the form $(cV + dV^3)$ were fitted to the wheel horsepower data. A listing of the least-squares equations that apply to the test data appears in Table 4. A measure of the goodness of fit of the data to these equations is indicated by the magnitude of the quantity "s"

Table 2

STEADY-STATE MEASUREMENTS OF WHEEL TORQUE AND WHEEL HORSEPOWER AT VARIOUS SPEEDS ON A 1977 OLDSMOBILE 98 (TEST WEIGHT = 4561 LB) EQUIPPED WITH BIAS, BIAS-BELTED AND RADIAL-PLY TIRES (ROAD-TEST DATA)

TIRE SIZE	TIRE CONSTRUCTION	ROAD SPEED, MPH	WHEEL TORQUE, FT-LB	WHEEL HP
G78-15	Bias Ply	19.86	96.26	4.64
		29.91	112.64	8.14
		40.07	134.44	12.98
		50.15	166.47	20.06
		60.29	201.99	29.19
G78-15	Bias Belted	19.99	104.27	4.99
		30.05	124.41	8.92
		40.05	148.05	14.09
		50.23	181.96	21.65
		60.40	218.87	31.19
GR78-15	Radial Ply	19.86	80.62	3.86
		29.87	94.02	6.78
		39.95	114.11	10.95
		50.19	142.98	17.19
		60.29	177.48	25.68

NOTE:
- Vehicle operated for a distance of 10 miles at each constant speed.
- Values shown represent the average of three test points.

Table 3

STEADY-STATE MEASUREMENTS OF WHEEL TORQUE AND WHEEL HORSEPOWER AT VARIOUS SPEEDS ON A 1977 CHEVETTE (TEST WEIGHT = 2491 LB)* EQUIPPED WITH BIAS, BIAS-BELTED AND RADIAL-PLY TIRES (ROAD-TEST DATA)

TIRE SIZE	TIRE CONSTRUCTION	ROAD SPEED, MPH	WHEEL TORQUE, FT-LB	WHEEL HP
P155/80D13	Bias Ply	19.99	46.97	2.72
		29.92	59.11	5.11
		40.06	75.73	8.74
		50.11	98.76	14.21
		60.24	127.34	21.97
P155/80D13	Bias Belted	19.93	49.73	2.91
		29.86	61.87	5.41
		39.72	78.00	9.04
		49.82	101.12	14.67
		59.77	126.23	21.91
P155/80R13	Radial Ply	20.18	43.27	2.54
		30.04	55.73	4.87
		40.04	72.07	8.39
		49.92	93.87	13.62
		59.67	121.55	21.08

NOTE:
- Vehicle operated for a distance of 10 miles at each constant speed.
- Values shown represent the average of three test points.

* Vehicle was ballasted to ≃2500 lbs. for these tests.

Table 4

SUMMARY OF LEAST-SQUARES CURVE FITS TO WHEEL TORQUE AND WHEEL HORSEPOWER DATA FOR THE CHEVETTE AND THE OLDSMOBILE 98 (ROAD-TEST DATA)

TIRE CONSTRUCTION	T (torque) = f(V) CHEVETTE	OLDS 98
Bias Ply	$T = 36.61 + 0.0249V^2$ $s = 0.54$ ft-lb	$T = 83.09 + 0.0327V^2$ $s = 0.82$ ft-lb
Bias Belted	$T = 40.23 + 0.0242V^2$ $s = 0.51$ ft-lb	$T = 91.59 + 0.0352V^2$ $s = 1.29$ ft-lb
Radial Ply	$T = 33.01 + 0.0247V^2$ $s = 0.58$ ft-lb	$T = 67.54 + 0.0300V^2$ $s = 1.02$ ft-lb
TIRE CONSTRUCTION	**HP = f(V) CHEVETTE**	**OLDS 98**
Bias Ply	$HP = 0.1033V + 7.209 \times 10^{-5}V^3$ $s = 0.065$ hp	$HP = 0.2019V + 7.782 \times 10^{-5}V^3$ $s = 0.088$ hp
Bias Belted	$HP = 0.1208V + 6.899 \times 10^{-5}V^3$ $s = 0.079$ hp	$HP = 0.2236V + 8.069 \times 10^{-5}V^3$ $s = 0.13$ hp
Radial Ply	$HP = 0.0943V + 7.245 \times 10^{-5}V^3$ $s = 0.074$ hp	$HP = 0.1602V + 7.287 \times 10^{-5}V^3$ $s = 0.088$ hp

s = Unbiased estimate of the standard deviation of the test data.

$$s = \left[\frac{\Sigma(X_m - X_c)^2}{n - 1}\right]^{\frac{1}{2}}$$

X_m = measured value of T or HP

X_c = calculated value of T or HP from equation

n = number of test points (speeds) = 5

associated with each equation. The letter "s" denotes the unbiased estimate of the standard deviation of the test data with respect to the least-squares curve. The equation used to calculate "s" is shown at the bottom of Table 4. The curves fit the data quite well with the largest percentage deviations occurring at the lowest velocity where the torque and horsepower levels are the smallest. For wheel torque, one standard deviation corresponds to a deviation of about 1% while for horsepower this deviation is about 3%.

Power absorption units on Clayton dynamometers are designed to absorb horsepower in proportion to the velocity raised to the 2.8 power (approximately). This implies that the velocity/torque relationship for a passenger car is characterized by velocity to the 1.8 power. To test whether the road data were better described by an equation of the form $(\alpha + \beta V^{1.8})$, the data obtained for the Chevette equipped with radial-ply tires were employed to calculate the coefficients α and β. The "s" value obtained for this equation was 1.34 and compares unfavorably with the corresponding value of 0.58 shown in Table 4. It was concluded that measured wheel torque data are better described by a second order equation in velocity.

The road test data show that wheel horsepower required to sustain a constant speed is least when the vehicles are operating on radial-ply tires and largest when operating on bias-belted tires. For the Chevette the maximum difference among tire constructions is less than one hp while for the Oldsmobile it is 5.5 hp (both at 60 mph) reflecting the large disparity in tire rolling resistances. To the extent that all other test conditions remained constant, these horsepower differences can be ascribed to differences in the tire power losses.

Assuming that the velocity-cubed term in the wheel horsepower equations (Table 4) is entirely the result of aerodynamic losses, the coefficients of this term should be independent of the tire construction use in the tests. The tabulated results support this assumption reasonably well.

Graphical presentations of the test results are given in Figures 2 through 5. On all figures, the curves drawn represent graphically the least-squares equations of Table 4 while the plotted symbols represent measured data. Plots were made on an expanded vertical scale to emphasize the excellent conformity of the fitted curves to the measured data.

4.4 TIRE ROLLING RESISTANCE MEASUREMENT

A measurement of the tire rolling resistance was required so that the road load horsepower settings for certain of the dynamometer tests could be determined. Specifically, these tests required that the dynamometer setting of road load horsepower, as measured from vehicle road tests on radial-ply tires, be augmented by the difference in power loss (at 50 mph) between the front bias-

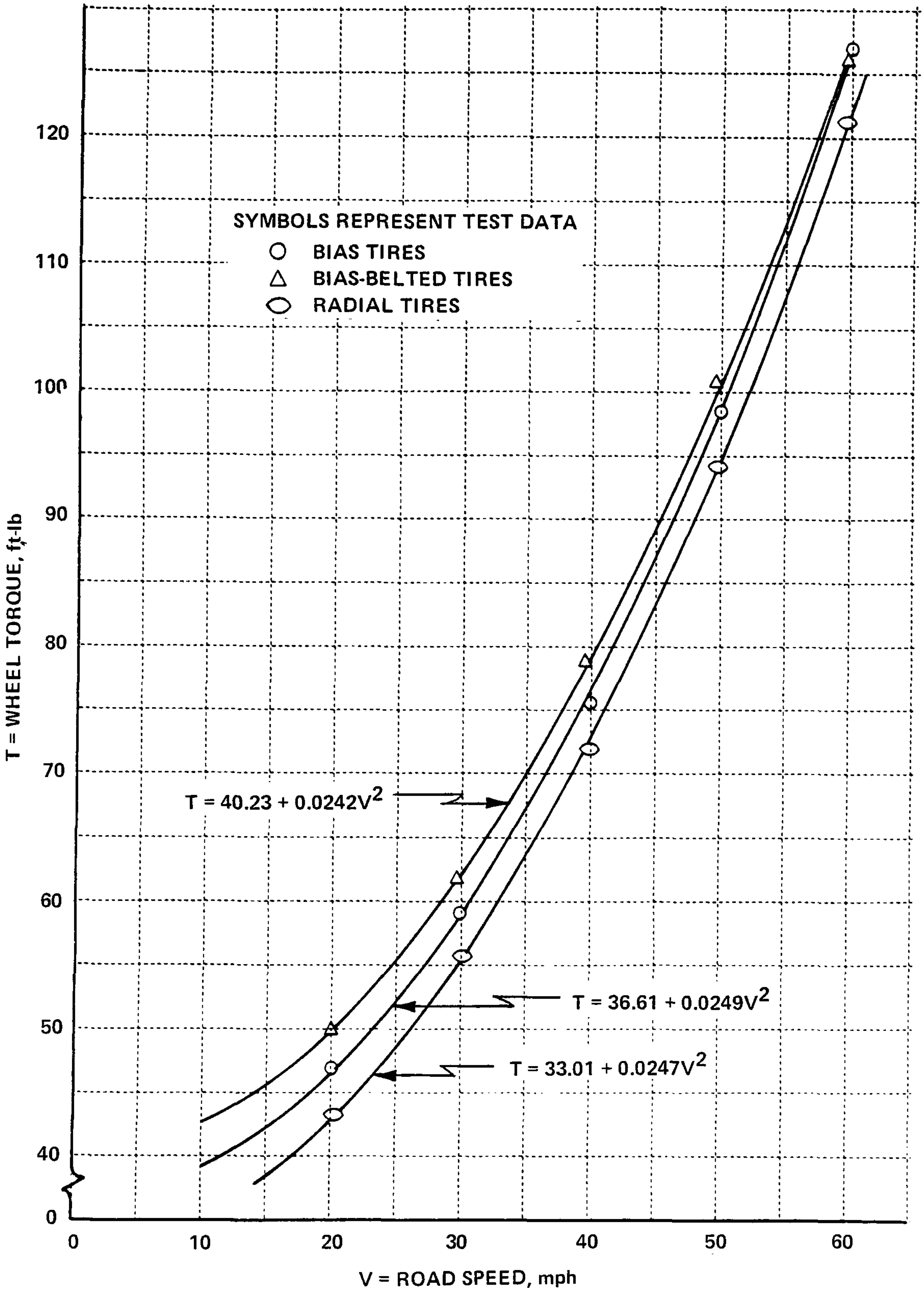

Figure 2 Least-squares curves fitted to wheel-torque data for 1977 Chevette equipped with bias, bias-belted and radial tires.

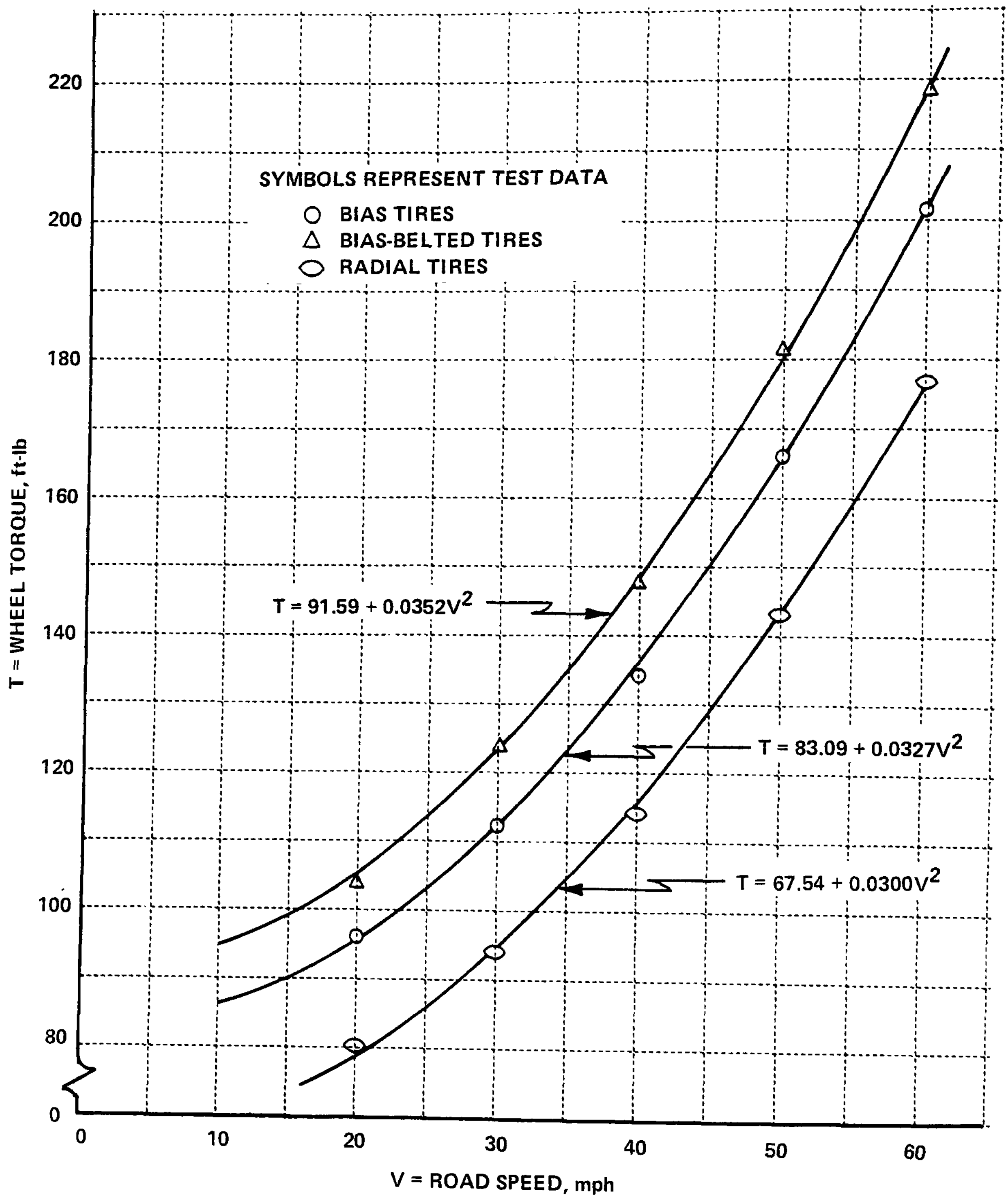

Figure 3 Least-squares curves fitted to wheel-torque data for 1977 Oldsmobile 98 equipped with bias, bias-belted and radial tires.

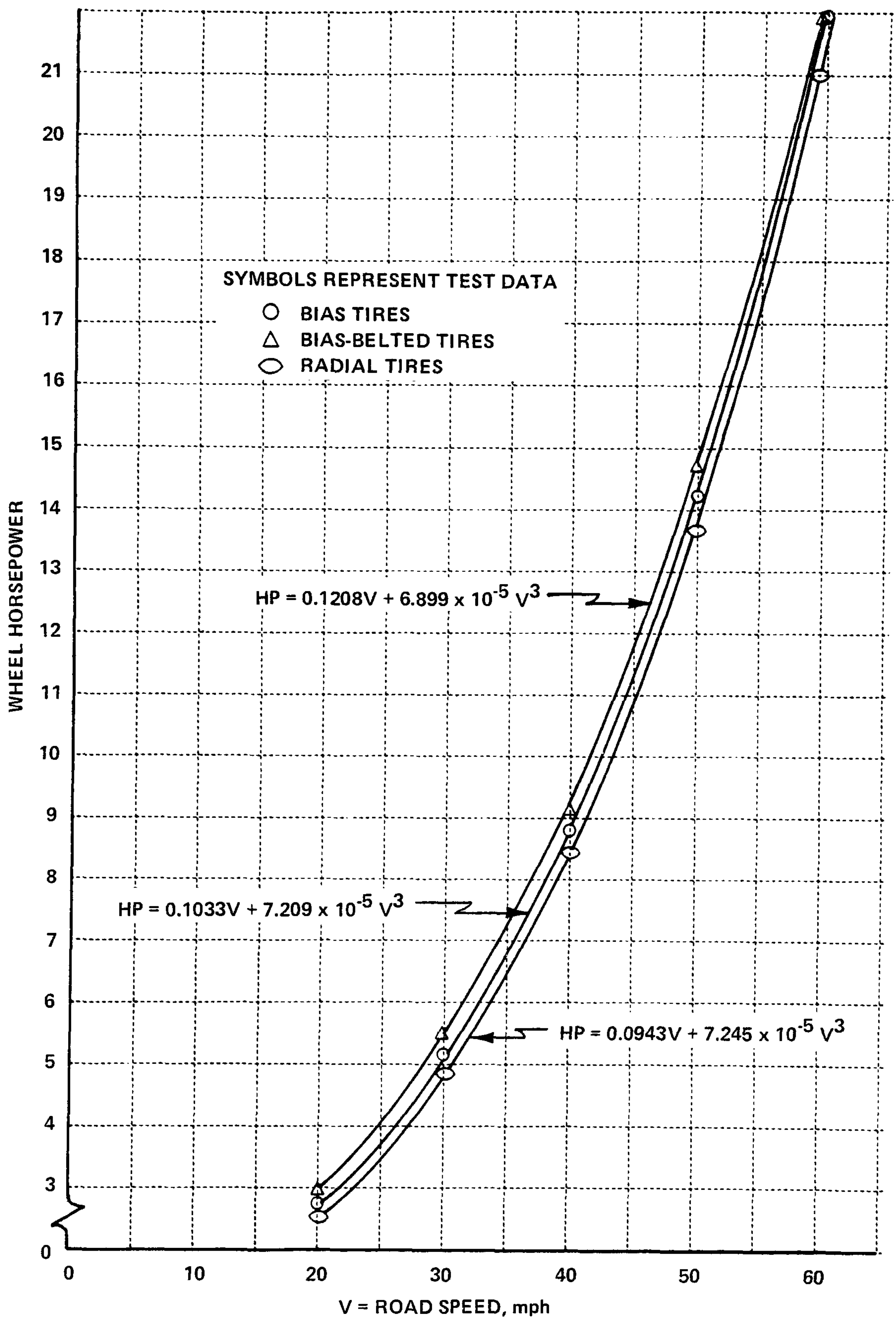

Figure 4 Least-squares curves fitted to wheel-horsepower data for 1977 Chevette equipped with bias, bias-belted and radial tires.

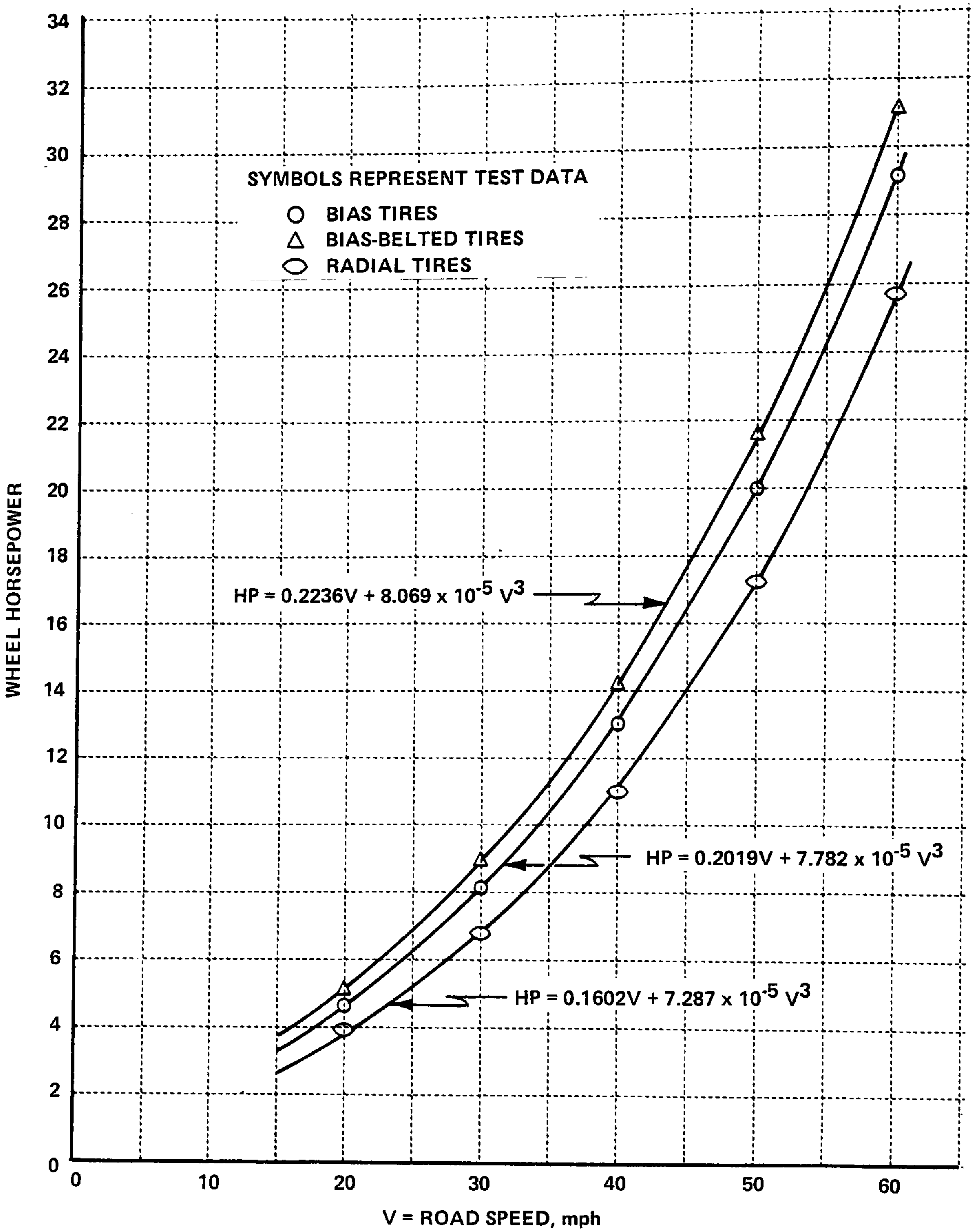

Figure 5 Least-squares curves fitted to wheel-horsepower data for 1977 Oldsmobile 98 equipped with bias, bias-belted and radial tires.

ply and front radial-ply tires. This difference is calculable from a knowledge of the rolling resistance of these tires.

Tests were performed on all of the bias-ply and the radial-ply tires. Since rolling resistance data were not required for the bias-belted tires, only the rear tires in this type construction were tested to provide comparative results.

4.4.1 Methodology

The measurement of tire rolling resistance on the Calspan Tire Research Facility (TIRF) (see Appendix E) is routine procedure (3). In the present case, the tires were received from GM mounted on individual rims following the completion of the road tests. Each tire was marked according to its location on the vehicle. Each tire was demounted and then mounted on TIRF rims of the same width as the original rims*. Each tire/rim assembly was mounted on the shaft of the TIRF metric balance which measures the three orthogonal forces and moments produced by the tire. The tires were operated on the textured surface of the flat roadway at a speed of 50 mph. Tires were free rolling and operating at zero degrees camber and slip angle. GM supplied data on the actual normal load experienced at each tire position on each vehicle in its test configuration. Within the tolerance limits (<10 lbs.) of the machine, each tire was tested at its designated load. Cold inflation pressures of 24 psi (165 kPa), the same as used in road and most flat-bed dynamometer tests, were used.

Each test was of a 30-minute duration which was sufficient to attain an equilibrium state in tire temperature, tire pressure and rolling resistance force. TIRF machine operation and data sampling are computer controlled.

4.4.2 Results

Rolling resistance force (FR, lb.) is calculated from measured values of longitudinal force (FX), bearing friction torque (BFT, ft-lb) and tire loaded radius (RL, in.) according to the following equation.

$$FR = -FX + \frac{BFT(12)}{RL}$$

* Tires and rims were carefully marked and the tires were remounted as originally received.

The FX and BFT values are corrected for any instrumentation zero shifts experienced during the course of the tests and represent the average of the final 20 data points* taken during a test. A summary of the test results is presented in Table 5. A perusal of the data will show that the rolling resistance for a given size tire correlates with the normal force (rolling resistance varies approximately linearly with normal force). One replicate run was made and the data are typical of the repeatability achieved on TIRF tests.

These rolling resistance data confirm the results obtained from the road tests presented in Section 4.4.2 which showed that in order of increasing power loss the tire constructions rank in the following order: radial, bias and bias-belted.

4.5 DYNAMOMETER CHECK TESTS

By contractual requirement, the operational integrity of the flat-bed dynamometer was to be demonstrated at Calspan by performing steady-state runs to 65 mph and duplicating the accelerations/decelerations of the FTP test cycle using a 4500-lb. inertia class vehicle. In addition to demonstrating the structural adequacy of the dynamometer, the tests would answer the question of vehicle stability on the flat surfaces of the SRU's and the criticality of vehicle/dynamometer alignment. On a dual-roll type of dynamometer, the cradling of the drive wheels automatically aligns the vehicle laterally and provides a fore-and-aft centering stability.

Lacking a pit which would place the belt surfaces at floor-level, it was necessary to perform the tests with the dynamometer base resting on the floor (belt surfaces about 3 feet above floor level). Testing was performed using a 1978 Chevrolet Impala sedan which was placed on the dynamometer with a fork-lift truck. After aligning and leveling the vehicle, the front wheels of which rested in hollows formed in massive wooden blocks, the rear of the vehicle was tethered loosely to the dynamometer base with chains to provide lateral restraint.

A series of steady-speed tests to 75 mph and several complete FTP velocity/time schedules were completed without difficulty. For all tests, the vehicle exhibited no perceptible lateral movement. Also, there was no evidence of any belt motion relative to the drums. Water retention at the bearing seals was satisfactory with only minor seepage being observed.

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* Data were sampled at a rate of one per second.

Table 5

SUMMARY OF EQUILIBRIUM VALUES OF THE ROLLING RESISTANCE FORCE FOR THE TEST TIRES

TIRE SIZE	TYPE OF CONSTRUCTION	POSITION ON VEHICLE	TIRE LOADED RADIUS, IN.	NORMAL FORCE, LB.	ROLLING RESISTANCE FORCE, LB.
GR78-15	Radial Ply	LR	12.72	-1073	11.69
		RR	12.74	-1077	11.53
		RF	12.58	-1192	12.68
		LF	12.57	-1239	13.56
G78-15	Bias Ply	LR	13.10	-1081	13.87
		RR	13.16	-1078	13.97
		RF	13.04	-1192	15.61
		LF	13.03	-1236	16.26
G78-15	Bias Belted	LR	13.30	-1078	14.74
		RR	13.31	-1077	14.58
P155/80R13	Radial Ply	LR	10.69	-603	7.96
		RR	10.70	-602	7.81
		RF	10.70	-601	8.00
		RF*	10.69*	-600*	7.94*
		LF	10.61	-676	8.87
P155/80D13	Bias Ply	LR	11.00	-601	8.47
		RR	10.97	-600	8.16
		RF	11.00	-597	8.64
		LF	10.90	-673	10.17
P155/80B13	Bias Belted	LR	10.97	-600	9.49
		RR	10.91	-607	9.57

* Repeat Run

All 15-inch tires are by Uniroyal.
All 13-inch tires are by General.

Following these tests, personnel from the GM Proving Ground requested the opportunity to perform coastdown tests on the dynamometer at Calspan. The purpose of these tests was to obtain a true horsepower versus indicated horsepower calibration of the unit. These tests are performed by driving the dynamometer up to a speed of $\approx$65 mph, rapidly lifting the vehicle free of the unit and measuring the velocity-time coastdown curve. Excessively large quantities of water leaked past the water-bearing seals as soon as the vehicle load was removed from the bearings. Even if the water leakage problem were resolved, the validity of such a coastdown calibration would be questionable since the viscous losses in the bearing may be a function of load.

As an alternative approach, GM personnel performed vehicle-on-dyno tests on a Clayton unit at Milford using an Impala sedan which was equipped with the same drivetrain and tires as was the Calspan vehicle. Coastdown tests were made with the vehicle's transmission in neutral and the vehicle resting on the dynamometer. GM personnel then visited Calspan and a similar series of coastdown tests was performed on the flat-bed unit using the Calspan Impala vehicle. Equivalent loads of 2250 and 4500 lb. were used.

Correcting for measured vehicle power loss from the tests on the roll dynamometer, a frictional horsepower loss of approximately 10 hp was found for an equivalent load of 4500 lb. at a velocity of 50 mph and the water bearings under load. Comparable friction losses for the roll dynamometer are about 3 hp. Other findings from these tests were:

- With dynamometer horsepower settings identical at 50 mph, the flat-bed unit imposed larger power loadings at the lower speeds and smaller loadings at the higher speeds than the roll dynamometer.

- At an equivalent weight setting of 4500 lb. and dynamometer load equal to vehicle road load at 50 mph, the flat-bed unit exhibited a horsepower/velocity characteristic that more closely duplicated the road-measured* characteristic for the Oldsmobile than did the roll dynamometer.

- At an equivalent weight setting of 2250 lb. and a velocity of 50 mph, the flat-bed unit provides a power loading, with the PAU completely unloaded, equal to the measured road load horsepower for the Chevette at 50 mph.

- Repeatability of the test data for the flat-bed/vehicle combination was very good.

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* Vehicle road tests (Section 4.3) preceded these tests in a chronological sense.

These data demonstrated the inherent differences in the horsepower/velocity characteristic for each type of dynamometer.

Following these preliminary checks at Calspan, the flat-bed dynamometer system was shipped to the Vehicle Emissions Laboratory at the Milford Proving Ground. Since there was no pit available in which the dynamometer could be installed, it was necessary to operate the unit above floor level as had been done at Calspan. With the aid of a hydraulically actuated platform, large enough to accommodate the test vehicle, the vehicle could be raised to the level of the SRU belt surfaces and either pushed or driven onto the dynamometer.

Figure 6 shows an annotated picture of the flat-bed dynamometer installation at the GM Proving Ground. The aluminum channel tracks lying on the belts are required to span the unsupported lengths of the SRU belts between the water bearings and the drums whenever a vehicle is moved on or off the dynamometer. The unsupported belts cannot sustain the loads imposed by the test vehicles.

In concluding this section of the report, it is appropriate to identify two operational factors related to the PAU used with the flat-bed dynamometer. This PAU was an early Clayton model not equipped with the automatic road load power control used on later models. The early models are known to have sizable hysteresis characteristics which can adversely affect measurements made in cyclic type tests (4). Such a unit was not available for this test program.

As stated earlier (Section 4.1), the PAU was coupled directly to the SRU drum shaft despite the fact that at any speed the PAU rpm would be lower than that of the PAU used on the roll dynamometer. This was done for reasons of economy after it had been demonstrated, using Clayton data, that the same PAU horsepower versus dynamometer velocity characteristic could be obtained over different ranges of the shaft rpm (within limits). Clayton personnel verified this fact*.

4.6 VEHICLE DYNAMOMETER TESTS

At the time the flat-bed dynamometer was received at the GM Proving Ground, the Emissions Laboratory did not have a dyno pit available for the installation. Consequently, the dynamometer was operated above floor level in the manner described in Section 4.5 and Appendix A. Ambient temperature and humidity were not controlled in this area as they were in areas where the permanent dynamometer installations are located.

In order to avoid biases in the test data which might result from making all the tests in sequence on the flat-bed dynamometer and then on the Clayton dynamometer, tests between the two units were performed in a randomized manner.

* Telephone conversation with Max Moore, Clayton Manufacturing Co., El Monte, California, May 2, 1977.

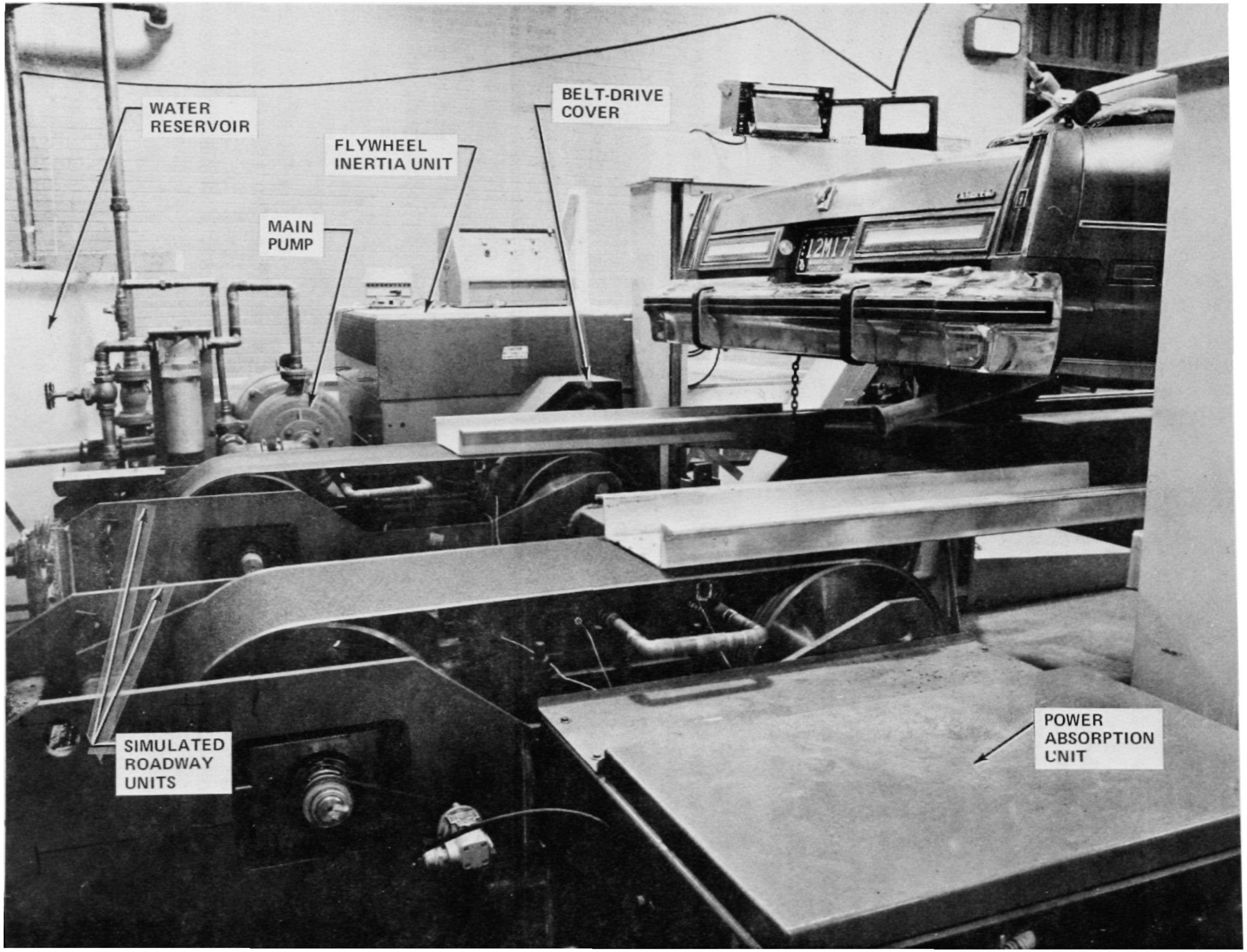

Figure 6 **Flat-bed dynamometer installation at the GM Proving Ground at Milford.**

As a result, tests were made on whatever Clayton dynamometer site was available at the time. As many as four different dynamometers were used in completing the sequence of tests whose results are discussed in this section. Each dynamometer was calibrated and maintained to EPA certification standards.

Testing began on the Oldsmobile 98 because the differences in wheel torque/horsepower among the tire constructions used on this vehicle were larger than for those used on the Chevette (see Section 4.3). These larger differences would make it easier to detect any differences in fuel economy and emissions, measured on the two types of dynamometers, ascribable to tire construction. All tests adhered to current certification rules requiring a repeat of the entire test if any vehicle or equipment malfunction occurred. About 60% of the test runs were repeated for this and other reasons. A considerable number of the runs on the flat-bed unit had to be repeated because of an incorrect inertia setting*.

Operational difficulties developed with the flat-bed dynamometer. With useage, the leakage at the water seals increased to the extent that it caused a curtailment of testing. A major reason for the seal problems appeared to be abrasive wear caused by rust and dirt particles,from the chassis of the test and dyno warm-up vehicles, getting onto the inner surface of the SRU belts. New seals were fabricated and installed to correct this problem. Also belt-tracking instabilities were encountered at times with the belts tending to drift off the drums. During steady-speed tests, the direction of the drift changed with speed. A belt-tracking adjustment on the moveable drum was used to stabilize the belt drift.

A total of five belt failures occurred during the test period from December 1978 to March 1979 with three of these experienced in the last month. In all cases, lateral cracks developed in the belt to a length of several inches. The first four cracks occurred in belts used on the same SRU and in each case the crack started at the edge of the belt. One of these failures was attributable to damage sustained by the belt during installation when rapid migration during belt run-in and adjustment caused one edge to come in contact with the SRU frame. Despite no visible damage, this belt shortly thereafter developed a series of lateral cracks along the damaged edge of the belt. The last belt failure was experienced on the remaining original belt. This crack was located in the central portion of the belt. With this belt failure the available stock of replacement belts was exhausted.

Belt fatigue failures are felt to be related to manufacturing problems and not to design deficiencies. Belts for TIRF and the SRU's have been obtained from two sources. To date, all belt fatigue failures on TIRF and the flat-bed

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* The inertia unit selector switch for the Oldsmobile vehicle was set for 4500-lb. instead of 5500-lb. (see Appendix A).

dynamometer have occurred in belts made by the same manufacturer*.

A review of the project status from the standpoint of time schedule, costs, objectives and test results obtained, led to the mutual decision that all experimental work would cease at this point. The major consideration was that the test results that had been acquired were sufficient to demonstrate the differences in measurements made on the two types of dynamometers. Thus all dynamometer tests on the Chevette vehicle were eliminated as well as two steady-speed tests on the flat-bed unit with the Oldsmobile equipped with the bias-ply tires.

To place the cited operational problems experienced with the flat-bed dynamometer in perspective, it is necessary to point out that the two SRU's were the initial prototypes and that these were expected to see limited use. Even though no tests were performed on the Chevette vehicle, dynamometer operating time considerably exceeded original estimates.

4.6.1 Dynamometer Calibration

Different procedures were used in calibrating the two types of dynamometers. That used for the Clayton dynamometers will be described first. With the knowledge that several different Clayton units would be used in the course of the test program, the performance of the conventional coastdown tests to measure friction horsepower and true horsepower as a function of velocity on any one unit was unreasonable. Instead, a partly experimental and partly analytical method was used to determine an average true absorbed horsepower. Three calibrated Clayton units were selected randomly and the Oldsmobile vehicle** was operated on each at a speed of 50 mph. The road load power on each unit was adjusted until the measured wheel torque equaled that measured during the road tests at this speed (142.98 ft-lb.). The true dynamometer hp in each case was noted and the three values averaged to yield 11.60 hp with the measured values within $\pm$0.2 hp of the mean. Note that the corresponding indicated hp corresponds to the setting PR specified in Table B-1 of Appendix B. From prior coastdown tests on these dynos with the PAU's disconnected, the average friction hp values were calculated:

Speed, mph	Friction, hp
20	0.581
30	1.104
40	1.814
50	2.830
60	4.167

* The only exception involved the belt that was damaged in installation.

** Equipped with radial tires inflated to 45 psi.

Thus the PAU average absorbed power at 50 mph is 8.77 hp (11.60-2.83) and since the hp/velocity relationship for the Clayton automatic road load power control unit is described by the following equation: $hp = k\,[V(mph)]^3$, the value of k is found to be 7.016×10^{-5}. With the value of k known, the PAU hp at other speeds can be calculated. Thus summing the experimentally-determined friction hp and the calculated PAU hp at each speed, the true dynamometer horsepower at each speed was obtained. The Clayton dynamometer data are summarized below:

Speed, mph	Average Friction hp		Average PAU hp		Average True hp
20	0.581	+	0.561	=	1.142
30	1.104	+	1.894	=	2.998
40	1.814	+	4.489	=	6.303
50	2.830	+	8.768	=	11.598
60	4.167	+	15.151	=	19.318

As discussed in Section 4.5, coastdown tests on the flat-bed unit could not be performed because the unloaded water bearing leaked water excessively. Consequently, steady-speed tests were performed with the vehicle on the unit and the PAU disconnected. The Oldsmobile was equipped with the radial tires inflated to 24 psi. At each steady speed the vehicle was driven for four miles. Data were collected during the last two-mile portion of each run. Two sets of tests were made, one with the speeds in increasing sequence and one with the speeds in decreasing sequence. Resultant data were averaged and used to calculate wheel horsepower according to the following equation.

$$\text{Wheel HP} = 2\pi \times R_{int} \times \frac{HP_{int}}{t_{int}} \times \frac{R_T}{d_{int}}$$

Where:

HP = integrated HP measured with the TTT (HP-sec.)

t_{int} = integrated time (sec.)

d_{int} = integrated distance* (ft.)

R_{int} = integrated revolutions, vehicle wheel

R_T = constant (1.1484) built into the TTT corresponding to a tire rolling radius (ft.)

* Measured with a calibrated wheel operating on the roadway, see Appendix D.

A summary of the average wheel horsepower data and friction horsepower for the flat-bed dynamometer is tabulated below. Note that the friction horsepower data were obtained by subtracting tire power consumption from the wheel horsepower using TIRF-measured rolling resistance for the two rear radial-ply tires*.

Speed, mph	Average Wheel hp	Tire hp	Friction hp
20	3.570	1.238	2.332
30	6.010	1.858	4.152
40	9.081	2.477	6.604
50	14.231	3.096	11.135
60	19.572	3.715	15.857

A plot of the friction horsepower as a function of velocity for the flat-bed and the Clayton dynamometers is shown in Figure 7 while the true absorbed horsepower as a function of velocity for the Clayton unit is shown as Figure 8. Wheel horsepower versus velocity for the Oldsmobile equipped with radial-ply tires operating on the flat-bed dynamometer, with the PAU disconnected, is presented in Figure 9. The plots of the dynamometer friction loss dramatically illustrate the large differences that characterize these two particular types of dynamometers.

A fuller account of the detailed procedures employed in performing these tests is included in Appendix C.

4.6.2 Test Procedures

The test design (Appendix B) specified tests on both dynamometers using each of the three different types of tire constructions. In general a test day began with a cold start FTP (non-evaporative) test followed by a HFET test and then by the steady speed (SS) tests with tests between the dynamometers types performed on a randomized basis. Vehicle and dynamometer preparation for the nonevaporative FTP or HFET tests followed standard certification procedures.

FTP tests followed the 1976 Federal Emission Testing Procedure without evaporative testing. Fuel drain, fuel system pressure checks and diurnal heat build prior to each test were not required. Measurements of wheel torque and total integrated values of the positive and negative torque were obtained.

* 23.22 lbs. total for two tires, see Table 5 in Section 4.4.2.

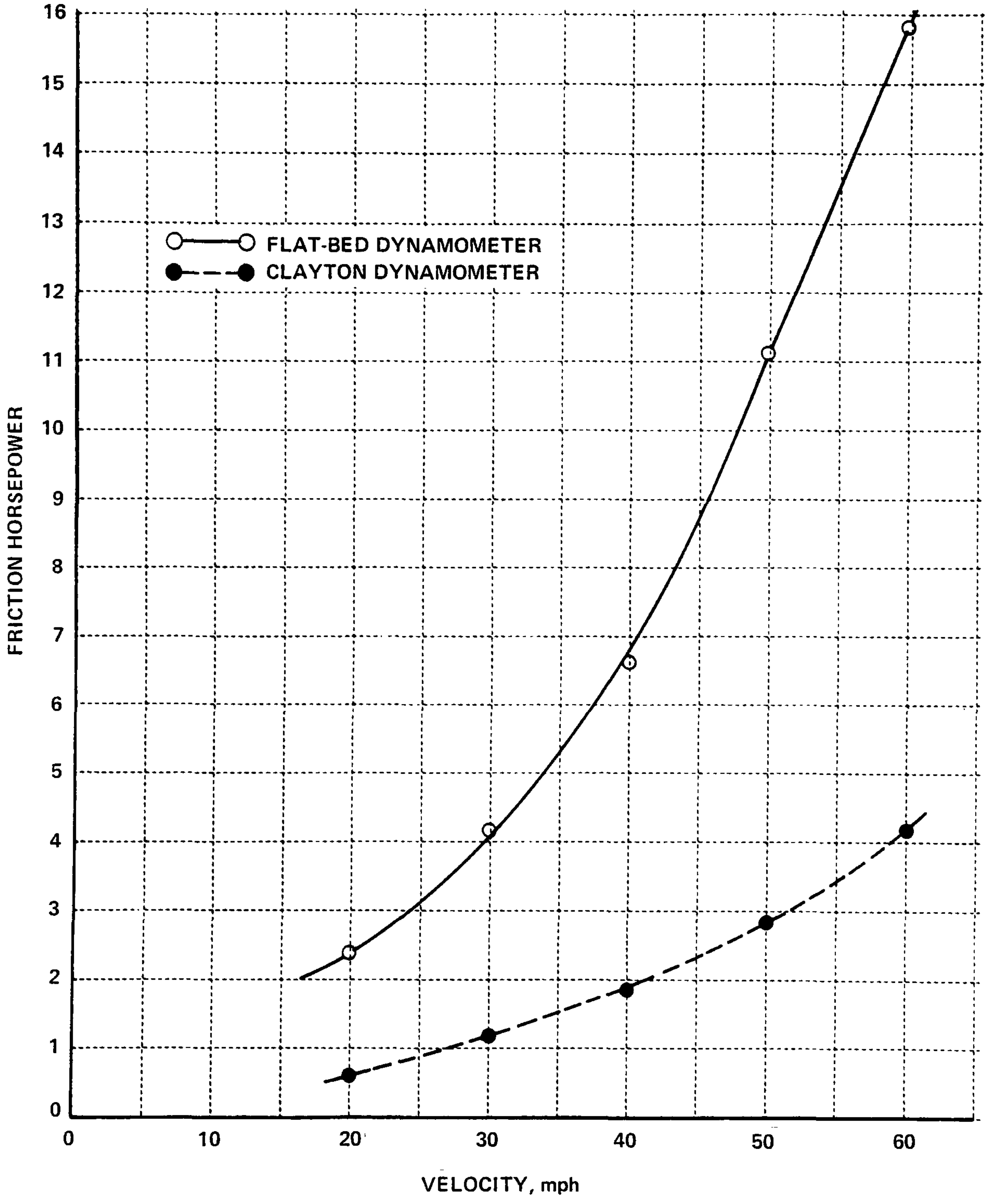

Figure 7 Friction horsepower versus velocity for the flat-bed and Clayton dynamometers (PAU disconnected).

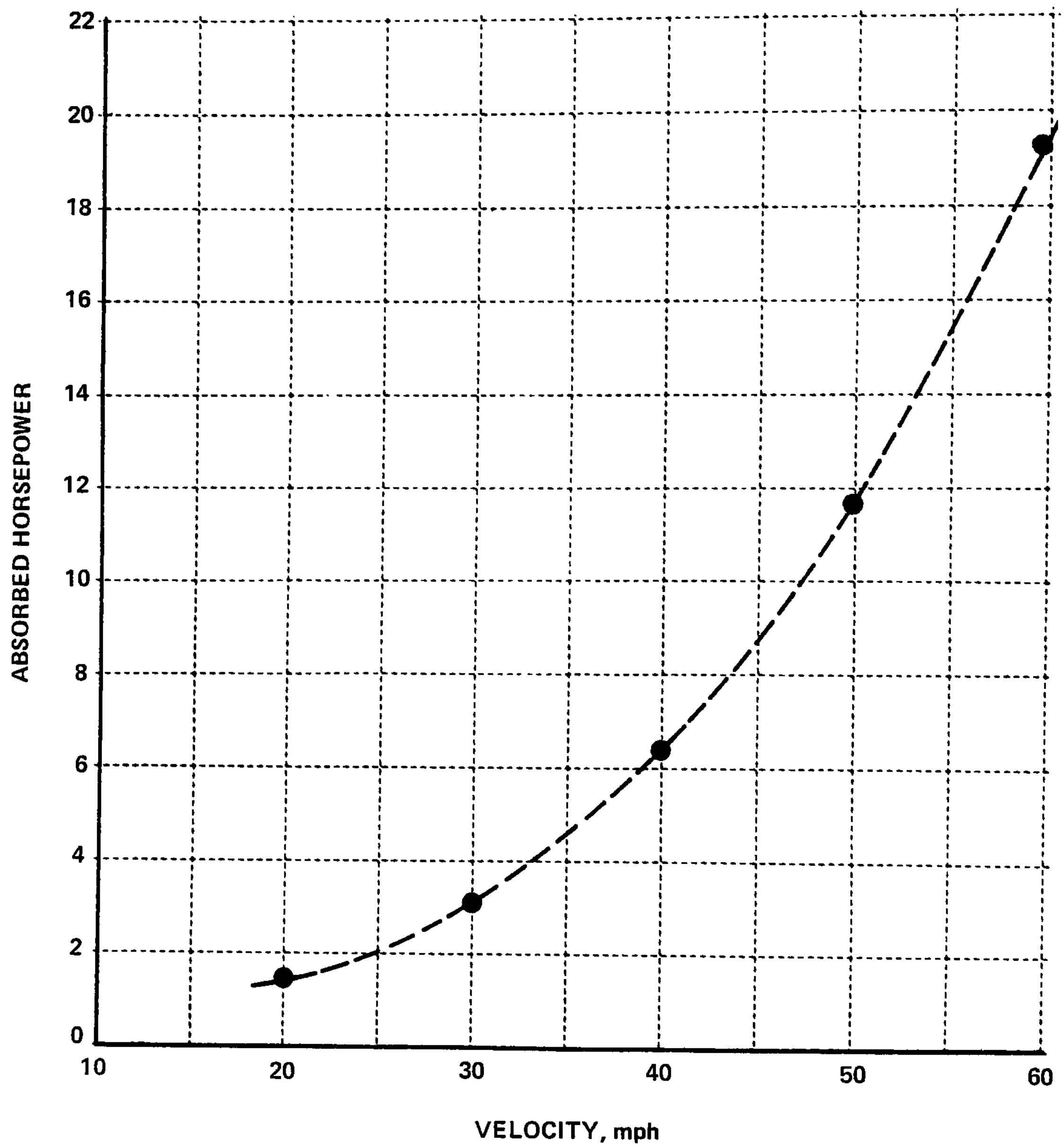

Figure 8 True absorbed horsepower for the Clayton dynamometer as a function of velocity; dyno indicated HP = PR.

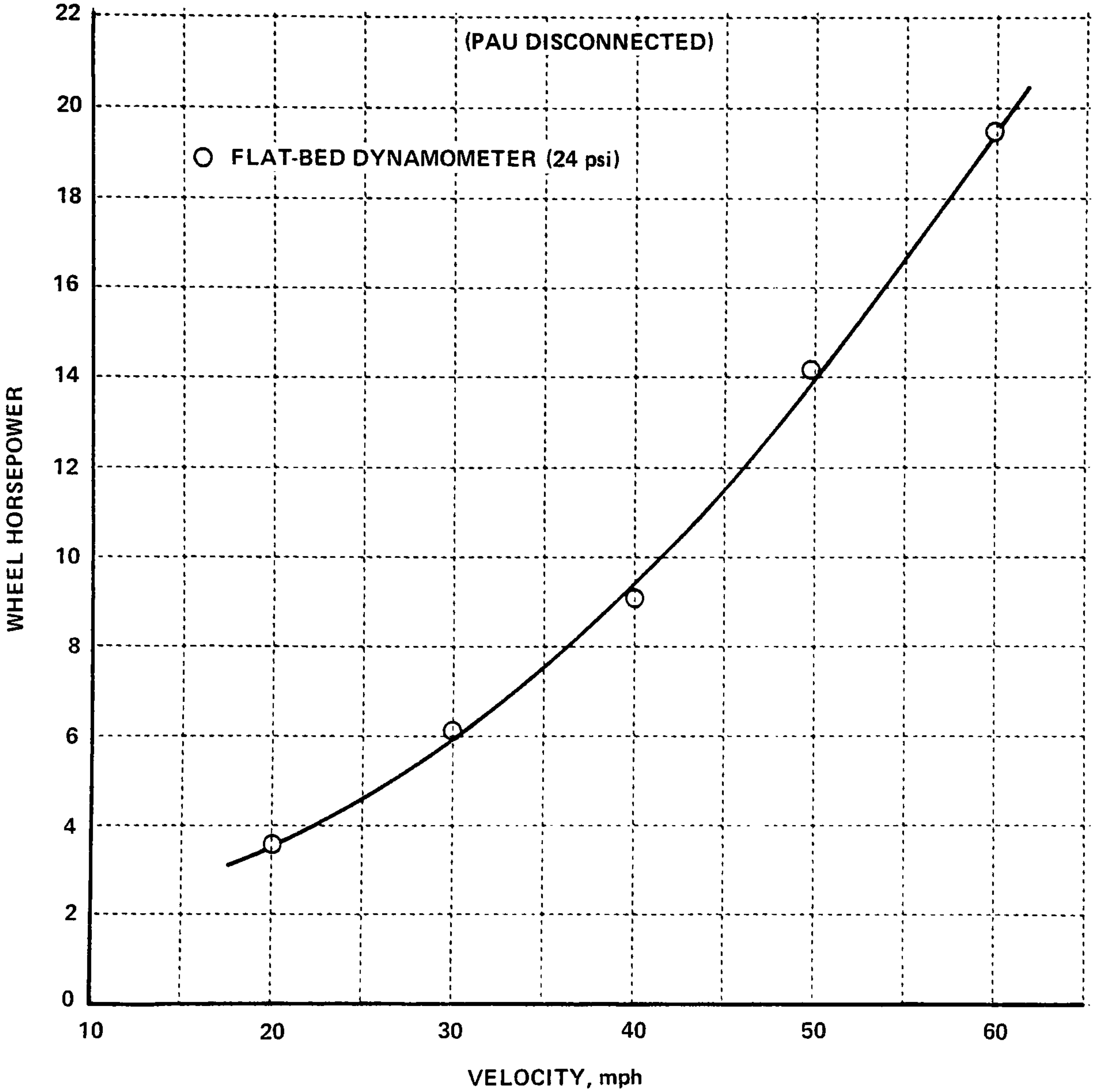

Figure 9 Wheel horsepower versus velocity, Oldsmobile 98 with radial-ply tires (GR78-15) on the flat-bed dynamometer.

The HFET tests were performed in accordance with the "EPA Recommended Practice for Conducting Highway Fuel Economy Tests". Thus if the HFET followed within three hours of an FTP, a preconditioning HFET cycle was performed. Fuel economy as well as the integrated values of the positive and negative wheel torques were measured. Although not required by the Statement of Work, emissions were also measured. Just prior to the preconditioning HFET cycle, the vehicle was operated for one minute at 50 mph and the dynamometer indicated hp was recorded and, if necessary, adjusted to the proper setting. Steady speed tests were made at the following speeds and in the order listed: 60, 50, 40, 30, and 20 mph. At each speed the run duration was ten minutes with wheel torque and exhaust emissions (HC, CO, CO_2 and NO_x) measured. The original test plan specified a ten-mile run at each speed but a waiver was obtained from the Project Officer to use ten-minute runs to permit the completion of an FTP/HFET/SS sequence within one day's testing.

All tests were performed with the dynamometer indicated horsepower set at either PR or PRA. PR corresponds to that indicated horsepower that was obtained when the Oldsmobile vehicle, equipped with radial-ply tires inflated (cold) to the specified pressure*, was operated on the dynamometer at 50 mph and the PAU was adjusted so that the rear-wheel torque was equal to that measured at 50 mph during the road tests on these same tires on the same vehicle. The value of PRA was obtained by adding to PR the difference in front-tire power loss at 50 mph between the bias-ply and the radial-ply tires as calculated from TIRF measurements of the rolling resistance of the individual tires. For the Oldsmobile, this difference amounted to 0.75 hp. PRA settings were only used for tests on the bias-ply tires on the flat-bed dynamometer.

Detailed step-by-step procedures which were used in performing the dynamometer tests and obtaining the test data are included in Appendix C.

4.6.3 Summary of Test Results

4.6.3.1 FTP Tests

The principal purpose of the FTP tests was to measure exhaust emissions (HC, CO, NO_x and CO_2 on a grams-per-mile basis), fuel economy (mpg) and integrated (positive as well as negative) wheel torques for the radial-ply and bias-ply tires on each dynamometer at an indicated hp setting equal to PR. In addition, tests on the bias tires on the flat-bed dynamometer were repeated using an indicated hp equal to PRA. Each test was performed three times for replication purposes. A summary of the data means and standard deviations is presented in Table 6 where the Block number designation for each data set corresponds to that shown in the contractual Statement of Work. Block numbers

* 24 psi on the flat-bed unit and 45 psi on the Clayton unit

TABLE 6. EXHAUST EMISSIONS, FUEL ECONOMY AND WHEEL TORQUE DATA FOR THE FTP TESTS

1977 OLDSMOBILE, 4500 lb INERTIA WEIGHT													
Block No.	Dynamometer	Type Test	No. of Tests	Tire Type	Inflation Pressure	Indicated hp	HC (gm/mi) $\bar{x}$ / s	CO (gm/mi) $\bar{x}$ / s	NO_x (gm/mi) $\bar{x}$ / s	CO_2 (gm/mi) $\bar{x}$ / s	F.E. (mpg) $\bar{x}$ / s	Avg. + Torq. (lb-ft) $\bar{x}$ / s	Avg. - Torq. (lb-ft) $\bar{x}$ / s
1	Flat Bed	FTP	3	Radial	MRP	PR	0.632 0.046	5.31 0.248	1.527 0.091	631.5 4.52	13.82 0.085	165.30 4.85	76.49 1.42
2	Flat Bed	FTP	3	Bias	MRP	PR	0.849 0.087	9.11 0.600	1.669 0.091	693.2 15.4	12.49 0.272	178.03 4.84	73.59 2.53
11	Flat Bed	FTP	3	Bias	MRP	PRA	0.678 0.015	5.81 0.640	1.809 0.081	706.9 14.2	12.31 0.266	185.42 5.44	71.71 2.92
14	Clayton	FTP	3	Radial	45 psi	PR	0.654 0.124	3.70 0.318	1.189 0.0093	611.5 13.7	14.33 0.315	150.67 4.10	78.95 1.52
15	Clayton	FTP	3	Bias	45 psi	PR	0.689 0.024	5.23 0.472	1.190 0.057	599.4 21.3	14.70 0.531	144.26 2.34	80.61 2.21

$\bar{x}$ = SAMPLE MEAN
s = SAMPLE STANDARD DEVIATION
MRP = MANUFACTURER'S RECOMMENDED PRESSURE (24 psi)

provide a convenient way to designate data sets when the differences between pairs of data means are analyzed for statistical significance in Section 4.6.3.4. The wheel torque data are presented as average torque values rather than integrated values since ft-lb-sec is not a meaningful quantity. An average torque for the FTP test cycle was obtained by summing the average for the first 1372 seconds of the test with that for the last (hot-transient portion) 505 seconds of the test.

Fuel economy data show that for a given tire construction, tests conducted on the Clayton dynamometer yield a higher level of fuel economy than do similar tests on the flat-bed unit. Further, on the roll dyno the bias-ply tires yield a larger miles-per-gallon figure than do the radial-ply tires. On the other hand, the flat-bed dynamometer ranks the tires in the reverse order in terms of fuel economy and in agreement with fuel economy data measured for vehicles operated on test tracks where the radial-ply tires show a pronounced and consistent advantage over bias-ply tires.

Fuel economy data correlate inversely with CO_2 emissions levels. This result is inevitable as CO_2 is the major factor in the carbon-balance equation employed to calculate fuel economy from exhaust emissions measurements. With the indicated horsepower set at PRA, an increase of 0.75 hp, the fuel economy is slightly lower than that at the PR condition. This result is consistent with expectations.

There are no obvious trends apparent in the HC and CO emission levels. Since the measurements of these two parameters are known to be characterized by a large variability (5), the inconclusiveness of data means calculated from only three tests is not surprising. Data variability is illustrated by the results shown for Blocks 2 and 11 where the only difference in test conditions is a 0.75 hp change in indicated hp. HC and CO levels show large differences which cannot be explained on the basis of the small change in the hp setting. Comparable tests (Blocks 1-14 and Blocks 2-15) do show that the NO_x levels measured on the flat-bed dynamometer are consistently larger than those measured on the roll dynamometer. In all cases, these data correlate directly with the levels of the positive wheel torque which is a measure of the power expended in driving the dynamometer. In Section 4.6.4, reference is made to ambient environmental factors that also could have affected these data.

The positive-torque data are seen to be smaller for the roll dynamometer than for the flat-bed unit. This is the result of the differences in the hp/velocity characteristics between the two units. At speeds below 50 mph, the flat-bed dynamometer has a consistently higher hp loading. Dynamometer test data illustrating these differences are included in Section 4.6.3.3.

Negative-torque data are a measure of the power expended in decelerating the dynamometer. They are inversely correlated with the positive torque data. This relationship seems logical. Since the same test is being repeated and the system inertias remain the same, it follows that the more power that is expended in accelerating a system, the less power is required in decelerating it. Consider data Blocks 1 and 2 in which the only test difference is in tire construction. The larger average positive torque for the bias-tire case compared to that of the radial-tire case is the result of the higher rolling resistance of the former relative to the latter. When braking traction is required, the higher rolling loss of the bias-ply tire necessitates a lower negative torque for a given braking traction force than for a radial-ply tire. Hence, the negative torque level for Block 2 data is smaller than that for Block 1.

4.6.3.2 HFET Tests

HFET tests were performed to measure fuel economy and the positive as well as negative torque. These data are shown in Table 7 as the means for three tests and the associated sample standard deviations. Emissions data were measured and these are also included.

Fuel economy data show the same trends as were found for the FTP tests. On the flat-bed dynamometer the radial-ply tires yield a better fuel economy than do the bias-ply tires. On the roll dynamometer, the reverse trend is found. In addition, the fuel economy data are higher for the roll dynamometer tests than they are for tests on the flat-bed unit. To a large extent, this difference is the result of the fact that, on the average, the flat-bed unit imposes a larger horsepower loading on the vehicle than does the roll-type unit.

Positive torques correlate inversely with fuel economy as do the FTP tests. On the other hand, the negative torques do not correlate as well with the positive torques as was the case previously. Because of the large differences between the FTP and the HFET cycles in terms of accels/decels, the absolute magnitudes of the negative torques are much smaller and hence experimental variability factors could affect the data to a much greater extent. As before, the average torque values are listed. Integrated torque can be calculated by multiplying the data by 765 seconds.

The emissions data again are characterized by considerable scatter as evidenced by the ratio of the standard deviation to the mean*. Emissions data for CO especially show a large scatter. For comparable test conditions, CO and NO_x emissions show consistently higher levels for tests performed on the flat-bed dynamometer when compared with those performed on the roll dynamometer.

* Also referred to as the coefficient of variation

TABLE 7. EXHAUST EMISSIONS, FUEL ECONOMY AND WHEEL TORQUE DATA FOR THE HFET TESTS

1977 OLDSMOBILE, 4500 lb INERTIA WEIGHT													
Block No.	Dynamometer	Type Test	No. of Tests	Tire Type	Inflation Pressure	Indicated hp	HC (gm)	CO (gm)	NO_x (gm)	CO_2 (gm)	F.E. (mpg)	Avg. + Torq. (lb-ft)	Avg. - Torq. (lb-ft)
							$\bar{x}$ / s	$\bar{x}$ / s	$\bar{x}$ / s	$\bar{x}$ / s	$\bar{x}$ / s	$\bar{x}$ / s	$\bar{x}$ / s
3	Flat Bed	HFET	3	Radial	MRP	PR	0.818	8.510	14.30	4543.3	19.92	160.89	18.29
							0.033	4.88	1.43	54.02	0.201	2.71	1.34
4	Flat Bed	HFET	3	Bias	MRP	PR	1.041	17.28	18.47	5037.4	17.93	183.59	19.10
							0.091	6.37	0.860	66.90	0.254	2.69	1.64
12	Flat Bed	HFET	3	Bias	MRP	PRA	0.953	17.88	18.31	5094.0	17.72	187.80	16.93
							0.039	2.80	0.491	46.44	0.146	4.15	0.345
16	Clayton	HFET	3	Radial	45 psi	PR	0.883	1.314	12.79	4470.2	20.27	160.00	17.51
							0.113	0.997	0.789	46.01	0.159	9.41	1.28
17	Clayton	HFET	3	Bias	45 psi	PR	0.873	4.057	13.32	4349.0	20.85	149.68	18.45
							0.019	2.75	0.509	83.49	0.406	3.84	0.502

$\bar{x}$ = SAMPLE MEAN
s = SAMPLE STANDARD DEVIATION
MRP = MANUFACTURER'S RECOMMENDED PRESSURE

4.6.3.3 Steady-State Tests

As in all of the earlier tests, emissions and wheel-torques were measured at each of the five steady state velocities that consituted a test run. In contrast to the other tests, the schedule provided for only two runs at each condition and, in some cases, only for one run. When possible, data means and standard deviations were calculated. From these measured data, such other parameters as fuel economy, wheel horsepower, true dynamometer absorbed horsepower and tire horsepower consumption were calculated for each velocity. A summary of the numerical results appears in Table 8. Emissions of CO were so low as to be on the threshold of detection and therefore do not appear in the Table. A discussion of the results follows together with graphical presentations of selected data.

Emissions data generally are in agreement with those obtained during the FTP and HFET tests. With even fewer replicate data available, the significance that can be attached to the numerical results is questionable. A series of computer-prepared plots, Figures 10 through 13, shows the variation of HC and NO_x emissions, on a total weight basis, as a function of velocity for the radial-ply and bias-ply tires tested on the flat-bed and roll-type dynamometers. In all these plots, the curves represent second-order, least-squares fits to the data. HC emissions tend to decrease with velocity for the roll dynamometer tests and show a peaked response for the flat-bed tests with a maximum at about 45 mph. The NO_x emissions data show that the levels are consistently higher for the flat-bed unit for both tire constructions. The difference between the emissions levels for comparable tests on the two dynamometers appears to be in the form of a bias.

Tests on the bias-belted tires were scheduled only in the steady-state sequence of tests. Fuel economy results are plotted against the type of tire construction involved in Figure 14 at each of the constant velocities. Data at the 20 mph speed could not be used since the vehicle was operated in second gear at this speed. This figure dramatically illustrates the reversal in tire ranking, according to fuel economy, that occurs between the two dynamometers. For the flat-bed unit tests, the tire ranking in order of increasing fuel economy is: bias, bias-belted and radial ply. For the roll dynamometer the order is reversed. The intermediate position occupied by the bias-belted tires is surprising, especially for the flat-bed tests, considering the fact that this construction produced the largest wheel horsepower levels in the road tests and the highest rolling-resistance levels in TIRF test. Consequently, it would be expected that this construction would produce the lowest fuel economy data in the flat-bed tests.

TABLE 8. EXHAUST EMISSIONS, FUEL ECONOMY, WHEEL TORQUE AND TIRE POWER CONSUMPTION DATA FOR STEADY SPEED TESTS -- 1977 OLDSMOBILE, 4500 LB INERTIA WEIGHT

Block No.	Dynamometer	Type Test	No. of Tests	Tire Type	Inflation Pressure	Indicated hp	Velocity (mph)	HC (gms) $\bar{x}$ / s	NO_x (gms) $\bar{x}$ / s	CO_2 (gms) $\bar{x}$ / s	F.E. (mpg) $\bar{x}$ / s	Wheel hp $\bar{x}$ / s
5	Flat Bed	SS	2	Radial	MRP	PR	60	0.494	18.72	4423.1	20.12	25.24
								0.0028	0.354	54.1	0.205	0.636
							50	0.560	8.008	3380.8	22.13	16.82
								0.0064	0.130	20.00	0.467	0.0778
							40	0.558	4.117	2597.0	22.82	11.42
								0.0559	0.0523	17.61	0.247	0.276
							30	0.450	2.546	1857.7	23.70	7.10
								0.0120	0.315	15.41	0.0566	0.0212
							20	0.354	1.604	1480.2	19.88	3.88
								0.0396	0.261	12.87	0.304	0.0212
6	Flat Bed	SS	2	Bias - B	MRP	PR	60	0.622	20.08	4692.0	18.87	26.30
								0.0417	0.757	102.2	0.488	0.290
							50	0.668	8.136	3620.1	20.33	17.86
								0.0113	0.0926	17.25	0.156	0.0990
							40	0.662	4.386	2753.2	21.40	11.84
								0.0233	0.139	1.34	0.0141	0.0990
							30	0.634	2.662	2024.2	21.74	7.64
								0.0205	0.170	2.90	0.0707	0.269
							20	0.447	1.682	1581.0	18.60	4.26
								0.123	0.0672	33.09	0.382	0.0071
7*	Flat Bed	SS	1	Bias	MRP	PR	60	0.543	22.24	4980.8	17.76	27.67
							50	0.720	8.479	3778.9	19.47	18.44
							40	0.770	4.227	2819.4	20.89	12.54
							30	0.601	2.818	2106.1	21.08	8.155
							20	0.396	1.766	1629.9	18.19	4.350
8	Flat Bed	SS	1	Radial	45 psi	PR	60	0.523	17.56	4868.5	19.60	24.69
							50	0.631	6.839	3487.5	21.26	16.23
							40	0.791	3.159	2508.4	23.69	11.02
							30	0.626	2.123	1855.1	24.27	6.44
							20	0.646	1.297	1471.3	19.57	3.32
9	Flat Bed	SS	1	Bias - B	45 psi	PR	60	0.603	18.74	4637.4	18.97	25.59
							50	0.675	7.143	3518.2	20.88	16.96
							40	0.642	3.751	2646.5	22.18	11.16
							30	0.657	2.589	1932.5	22.89	6.96
							20	0.440	1.589	1525.8	19.29	3.98
10	Flat Bed	SS	1	Bias	45 psi	PR	This Run Not Completed - Belt Failure					

Note: All 20 mph runs were made in 2nd gear; CO emissions were too low to measure
*A repeat run was not completed - Belt Failure

(Continued)

TABLE 8. (Continued)

Block No.	Dynamometer	Type Test	No. of Tests	Tire Type	Inflation Pressure	Indicated hp	Velocity (mph)	HC (gms)	NO_x (gms)	CO_2 (gms)	F.E. (mpg)	Wheel hp	Tire Power Consumption
								$\bar{x}$ / s	$\bar{x}$ / s	$\bar{x}$ / s	$\bar{x}$ / s	$\bar{x}$ / s	$\bar{x}$ / s
13	Flat Bed	SS	2	Bias	MRP	PRA	60	0.554	24.10	5004.7	17.64	28.67	–
								0.0184	1.14	3.96	0.0849	0.523	–
							50	0.666	9.254	3779.6	19.36	18.77	–
								0.0219	0.0622	26.94	0.290	0.198	–
							40	0.629	4.698	2845.1	20.71	12.49	–
								0.0255	0.115	5.74	0.283	0.0566	–
							30	0.598	2.818	2101.0	20.97	8.32	–
								0.0170	0.0778	25.10	0.0141	0.177	–
							20	0.552	1.580	1627.9	18.02	4.43	–
								0.140	0.0156	22.34	0.389	0.0566	–
18	Clayton	SS	2	Radial	45 psi	PR	60	0.673	17.09	4573.1	19.33	25.58	6.262
								0.0910	2.14	80.0	0.368	0.651	0.651
							50	0.814	6.494	3417.5	21.60	16.66	5.067
								0.109	0.659	119.4	0.757	0.120	0.120
							40	0.984	2.910	2562.8	23.02	10.18	3.872
								0.0926	0.0849	20.72	0.184	0.389	0.389
							30	0.986	1.956	1832.4	24.31	5.76	2.757
								0.0976	0.262	18.10	0.156	0.247	0.247
							20	0.766	1.121	1456.0	20.13	3.04	1.903
								0.0191	0.126	20.64	0.212	0.346	0.346
19	Clayton	SS	2	Bias - B	45 psi	PR	60	0.549	17.96	4462.5	19.86	24.34	5.017
								0.0240	1.237	14.2	0.0282	0.799	0.799
							50	0.721	6.600	3351.2	22.06	15.75	4.152
								0.0509	0.0544	16.33	0.0283	0.283	0.283
							40	0.963	3.114	2490.2	23.78	9.67	3.367
								0.119	0.0742	5.02	0.184	0.226	0.226
							30	1.408	1.966	1803.1	24.56	5.78	2.782
								0.0177	0.156	19.80	0.0636	0.325	0.325
							20	1.005	1.038	1436.9	20.56	2.84	1.693
								0.0346	0.0933	6.08	0.0495	0.134	0.134
20	Clayton	SS	2	Bias	45 psi	PR	60	0.519	18.33	4331.9	20.50	24.32	5.002
								0.0601	0.113	74.60	0.438	0.198	0.198
							50	0.672	6.700	3150.1	23.18	15.67	4.072
								0.0262	0.350	74.67	0.827	0.156	0.156
							40	0.827	3.198	2401.4	24.60	9.62	3.322
								0.109	0.426	99.07	1.01	0.120	0.120
							30	1.236	1.734	1707.4	25.86	5.41	2.412
								0.0651	0.211	23.26	0.364	0.0849	0.0849
							20	1.108	0.976	1402.2	21.08	2.60	1.453
								0.129	0.0856	38.33	0.785	0.0212	0.0212

Note: All 20 mph runs were made in 2nd gear; CO emissions were too low to measure

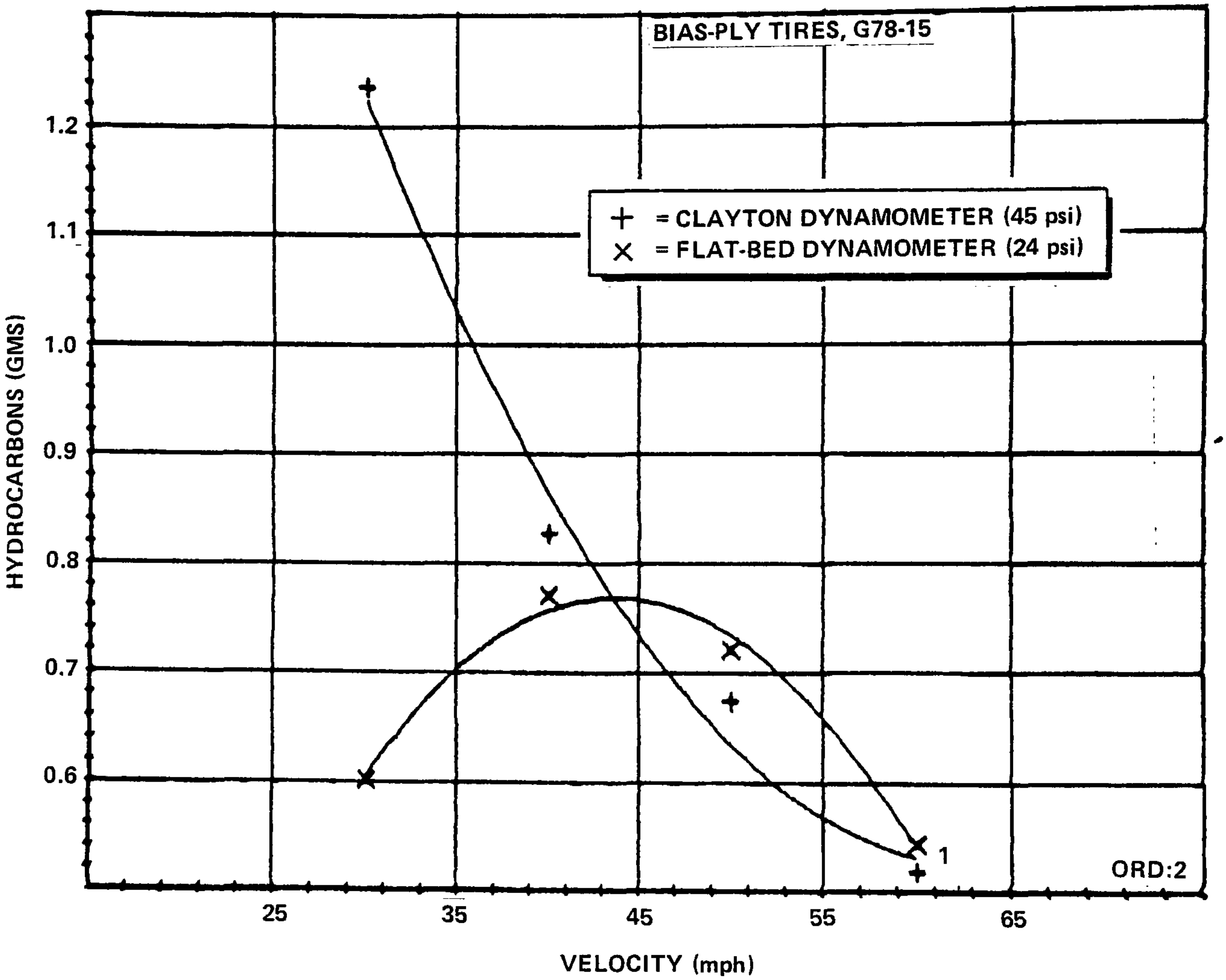

Figure 10 Hydrocarbon emissions as a function of velocity, steady-state tests on bias-ply tires.

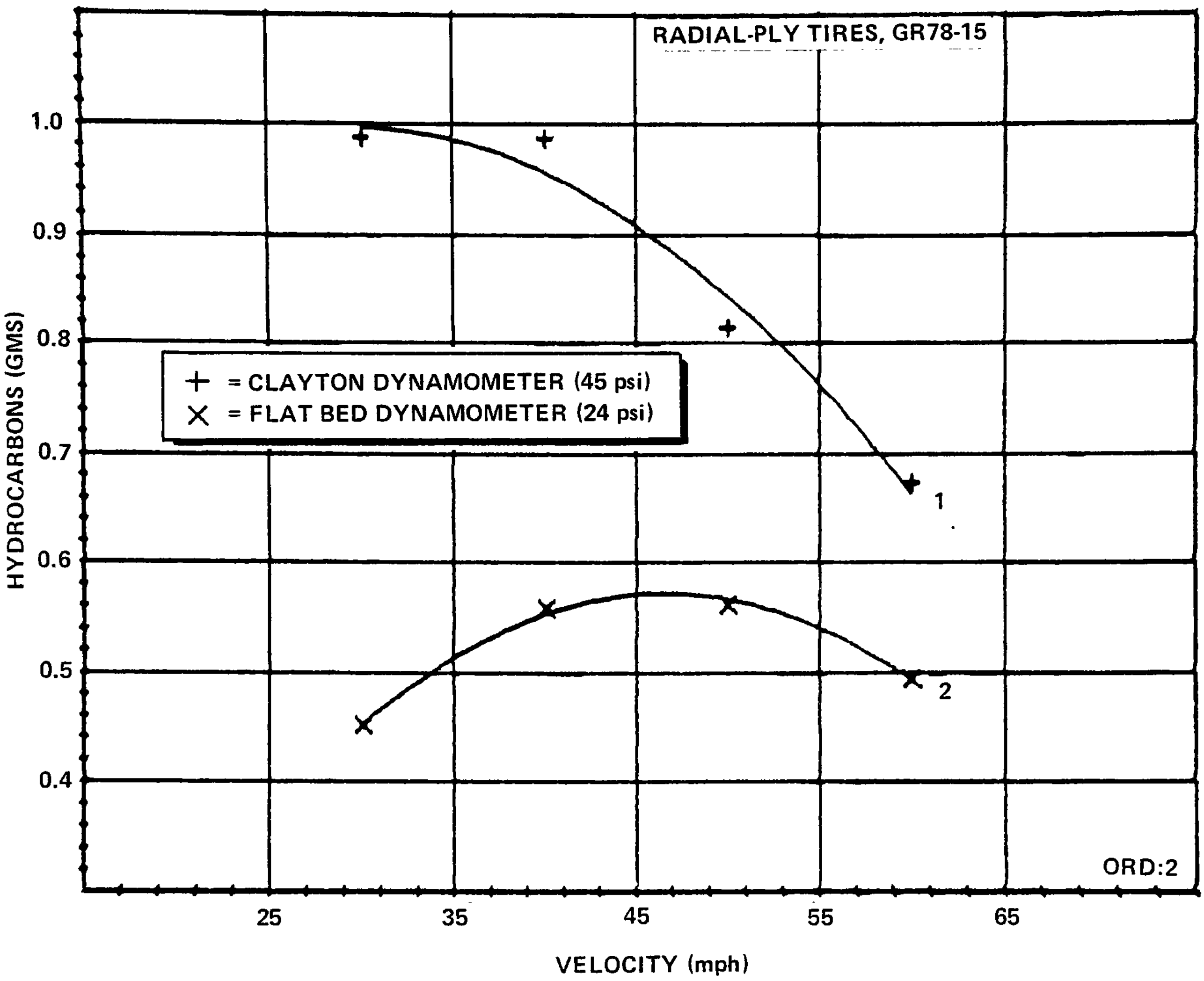

Figure 11 Hydrocarbon emissions as a function of velocity, steady-state tests on radial-ply tires.

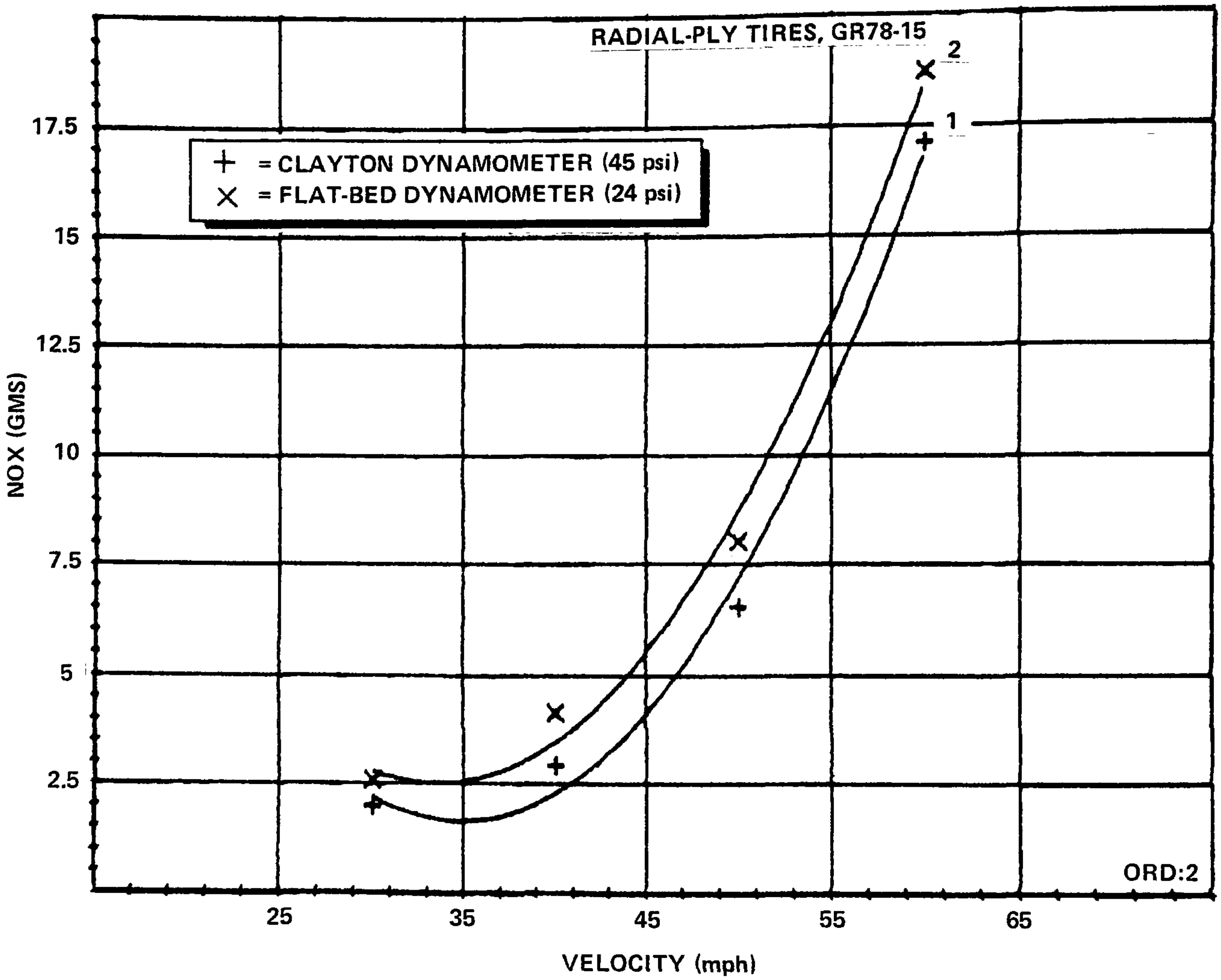

Figure 12 Oxides of nitrogen emissions as a function of velocity, steady-state tests on radial-ply tires.

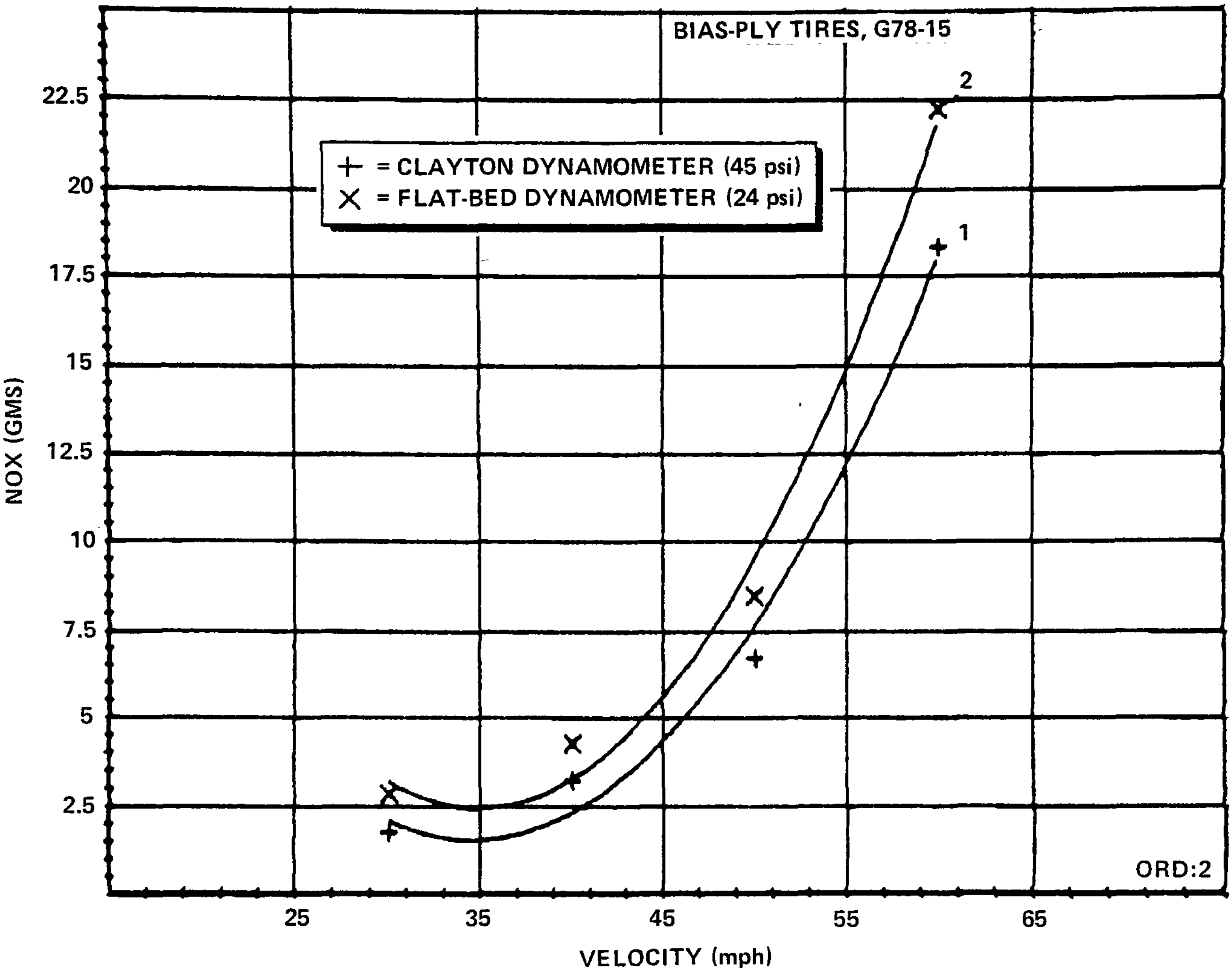

Figure 13 Oxides of nitrogen emissions as a function of velocity, steady-state tests on bias-ply tires.

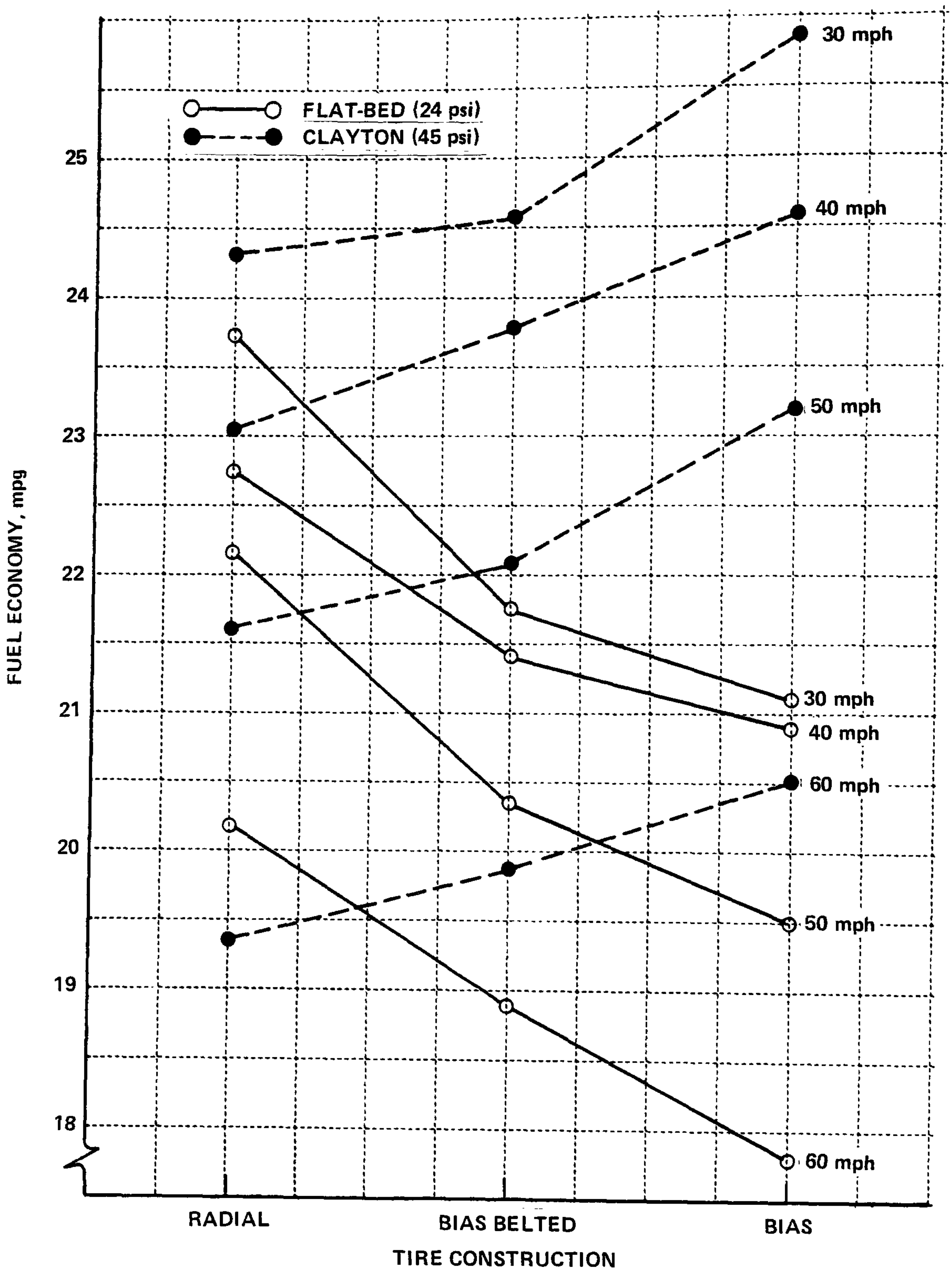

Figure 14 Dynamometer steady-state tests, fuel economy versus tire construction.

A comparison of the fuel economy data for the radial-ply tires obtained from tests on the two dynamometers is presented in Figure 15. These results show that differences in the measured fuel economy are quite small; a fact borne out by the FTP and HFET fuel economy data as well. Figure 16 shows similar data for the bias-ply tires where the fuel economy data obtained from the two dynamometers show larger differences with the roll-dynamometer tests yielding the higher numerical values.

Wheel horsepower was calculated for each velocity of each steady-state run using the relation given in Section 4.6. Figures 17 through 19 show plots of wheel horsepower as a function of steady-state velocity for each tire construction on both the flat-bed and roll-type dynamometers. Also shown on each plot are the data obtained during vehicle road tests. Since the dynamometer indicated hp, in each case, was set with respect to the wheel torque at 50 mph as measured for the radial-ply tires during the road tests, all the wheel horsepower data plotted for the radial-ply tires at 50 mph should be substantially identical. Figure 17 bears out this fact. For the other tire constructions, the data at 50 mph diverge as expected. The graphical presentations show that tests on the flat-bed dynamometer closely duplicate the wheel horsepower curve established by vehicle road tests on both the radial-ply and bias-ply tires. For the bias-belted tires, the road test data lie well above those measured on the flat-bed dynamometer.

The wheel horsepower data measured on the roll dynamometer are consistently lower than those measured on the flat-bed unit for a number of reasons peculiar to these tests. Firstly, all tests were performed using one dynamometer indicated hp that was established by duplicating the road-test wheel torque as measured with the vehicle operating on radial-ply tires. It is a proven fact that the rolling loss of a radial-ply tire is less than that of a bias-ply tire when both are operated on a flat surface, see data in Table 5, for example. Hence, for tests on the flat-bed unit, the wheel horsepower for the bias constructions would be larger than for the radial construction. On the other hand, the rolling loss for the radial-ply tire is larger than that for the bias tire when both are operated on a dual-roll configuration* (see Tire Power Loss Data, Table 8). Thus, for the case of the Clayton dynamometer tests, the wheel horsepower for the bias constructions would be smaller than for the radial construction. Secondly, the Clayton dynamometer absorbs less horsepower at velocities below 50 mph than the flat-bed unit if both are set to the same indicated hp at 50 mph.

A close examination of the wheel horsepower data measured during tests on each dynamometer shows that the results for the bias-belted tires lie between those of the other two constructions. This fact explains why this

* One reason for this result is the use of increased inflation pressures for the Clayton dynamometer tests and the relatively high sensitivity of bias-tire rolling loss to inflation pressure.

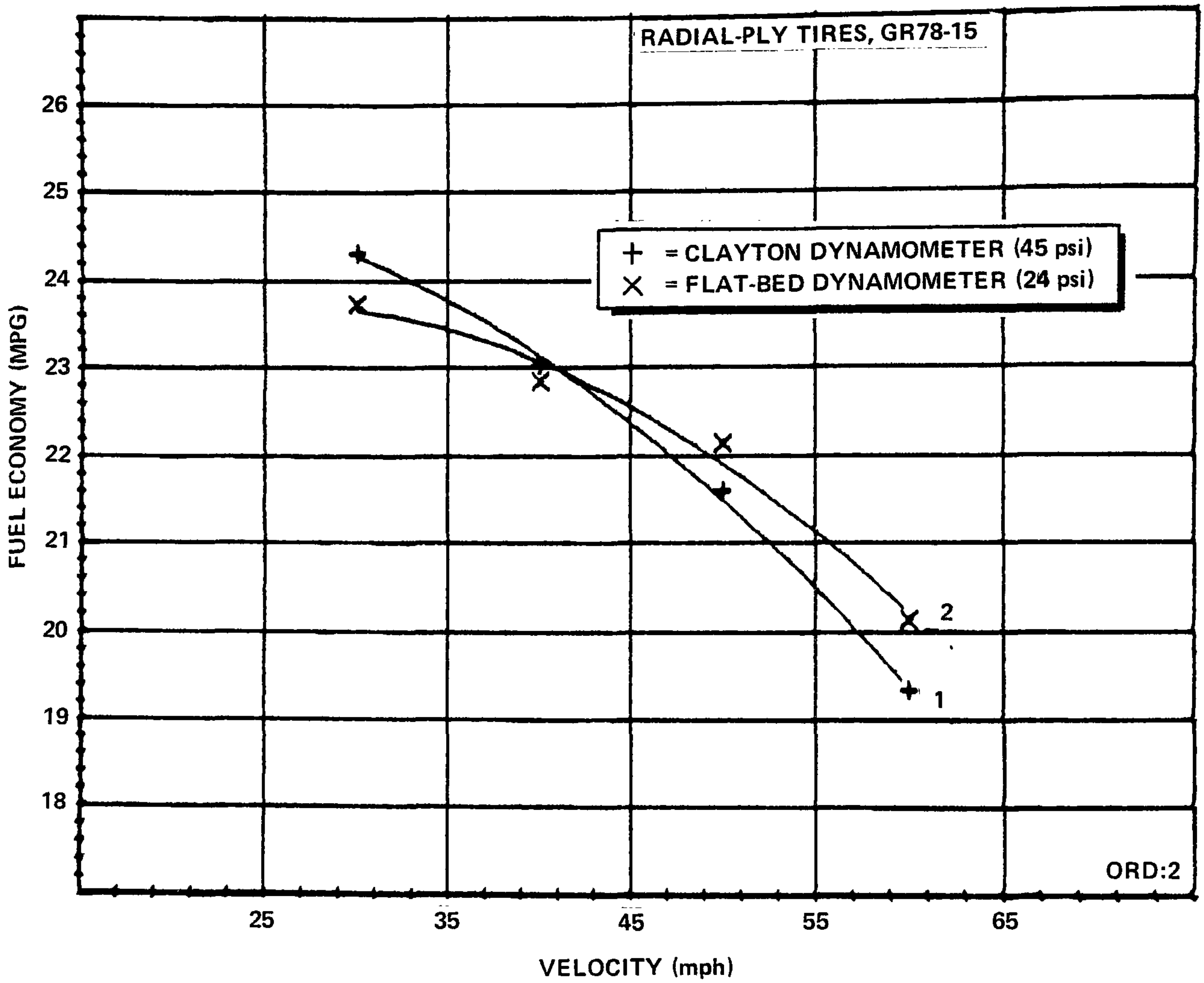

Figure 15 Fuel economy as a function of velocity, steady-state tests on radial-ply tires.

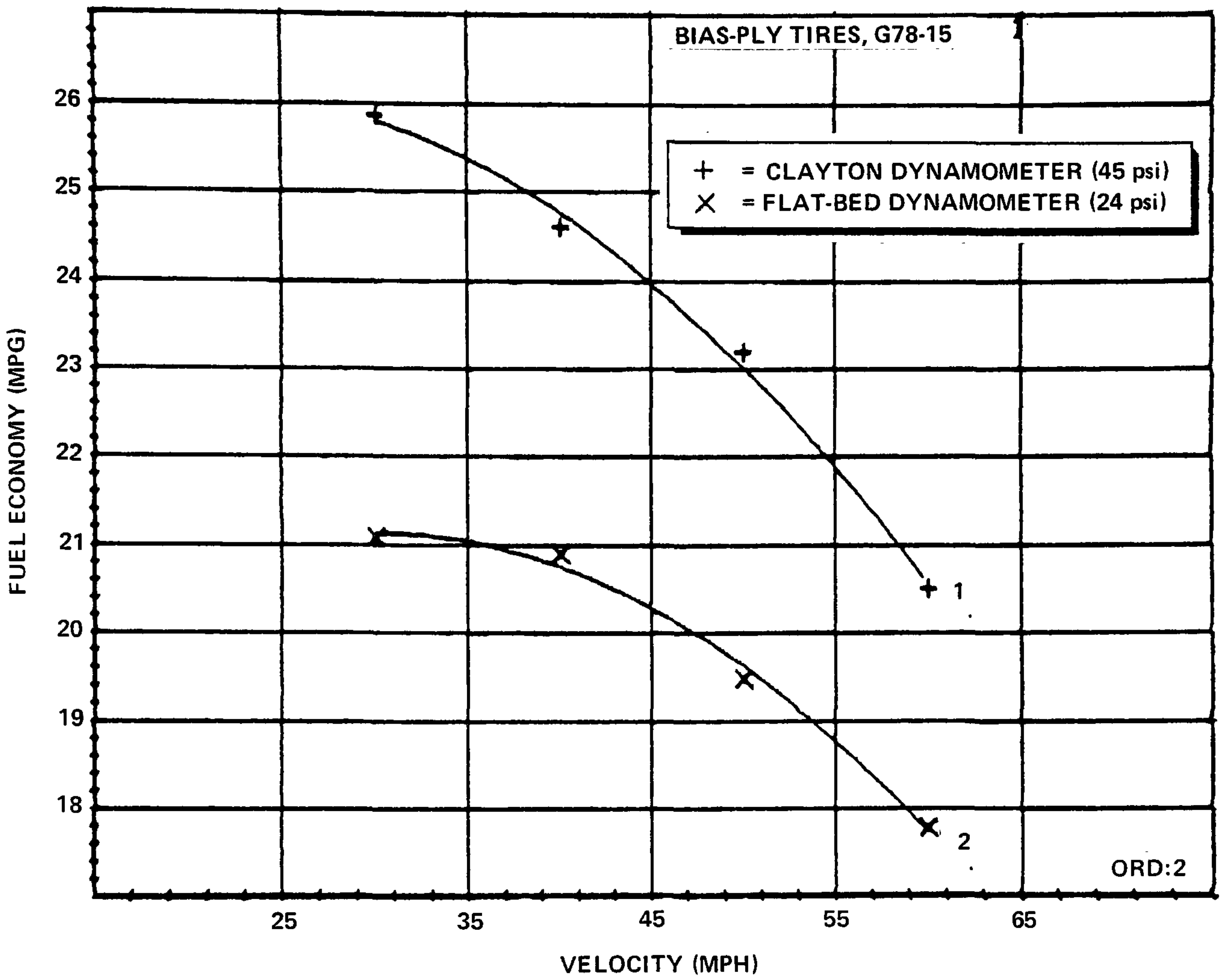

Figure 16 Fuel economy as a function of velocity, steady-state tests on bias-ply tires.

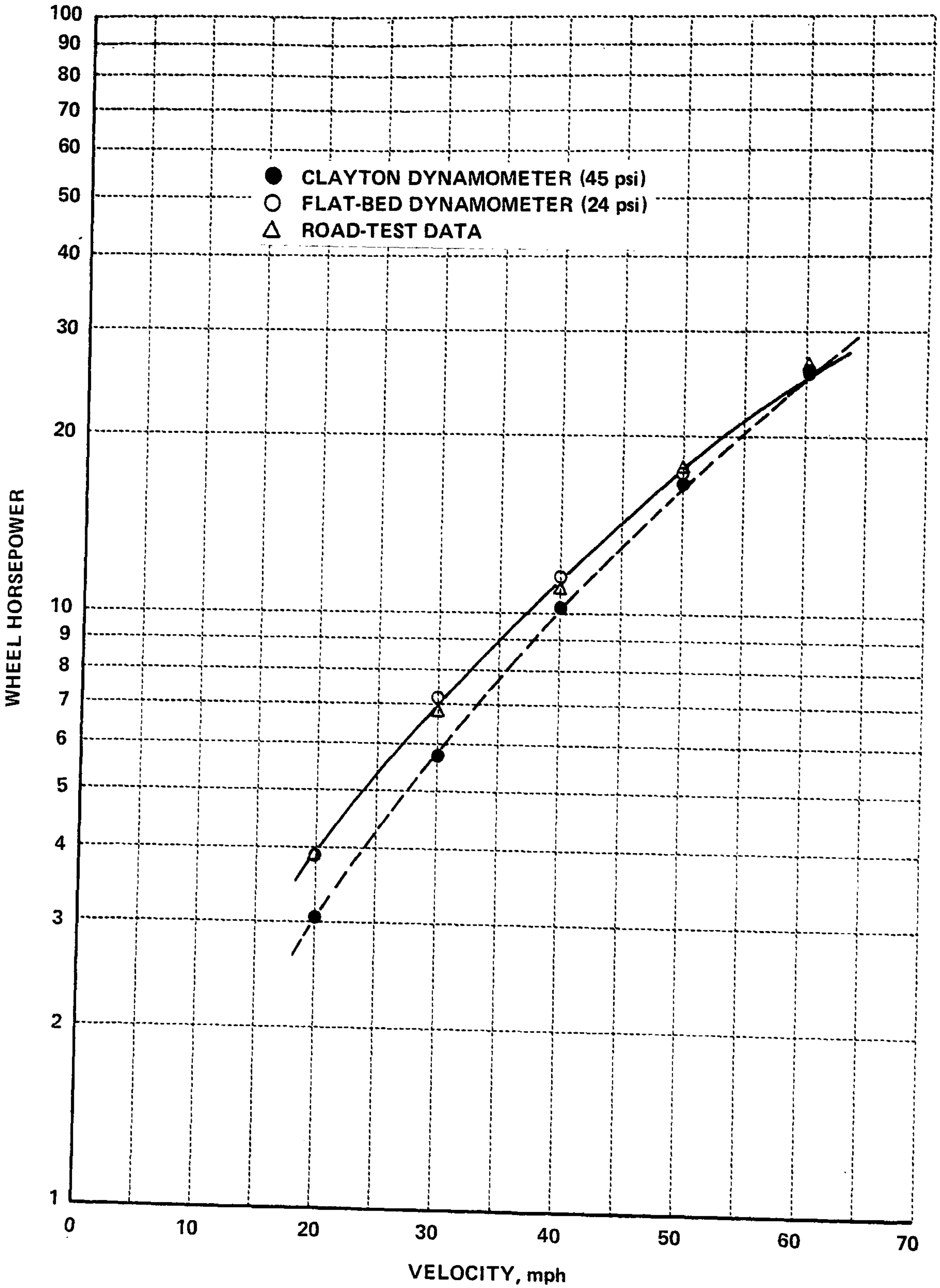

Figure 17 Steady-state tests - Oldsmobile 98 wheel horsepower versus velocity for radial-ply tires (GR78-15); indicated HP = PR.

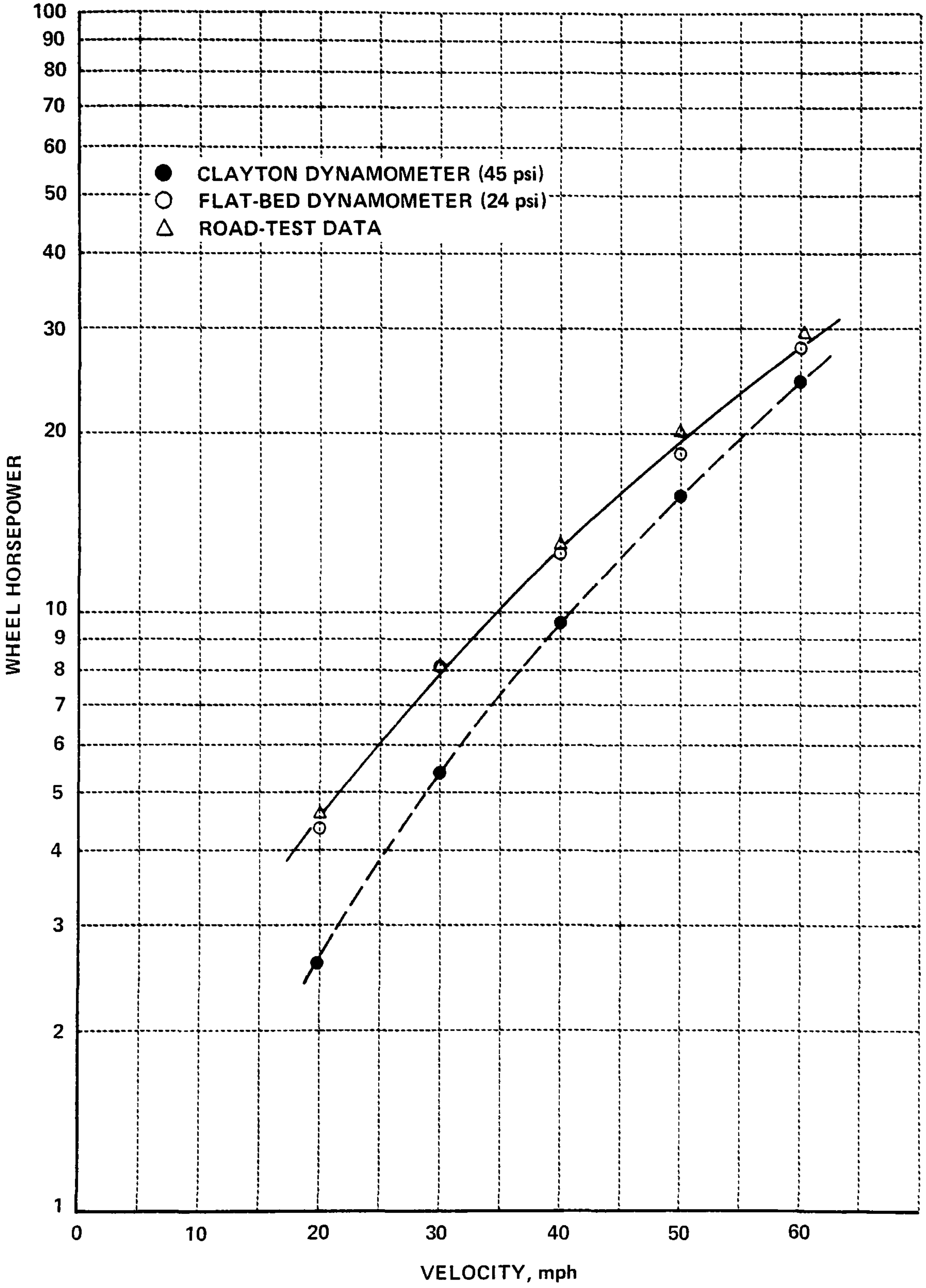

Figure 18 Steady-state tests - Oldsmobile 98 Wheel horsepower versus velocity for bias-ply tires (G78-15); indicated HP = PR.

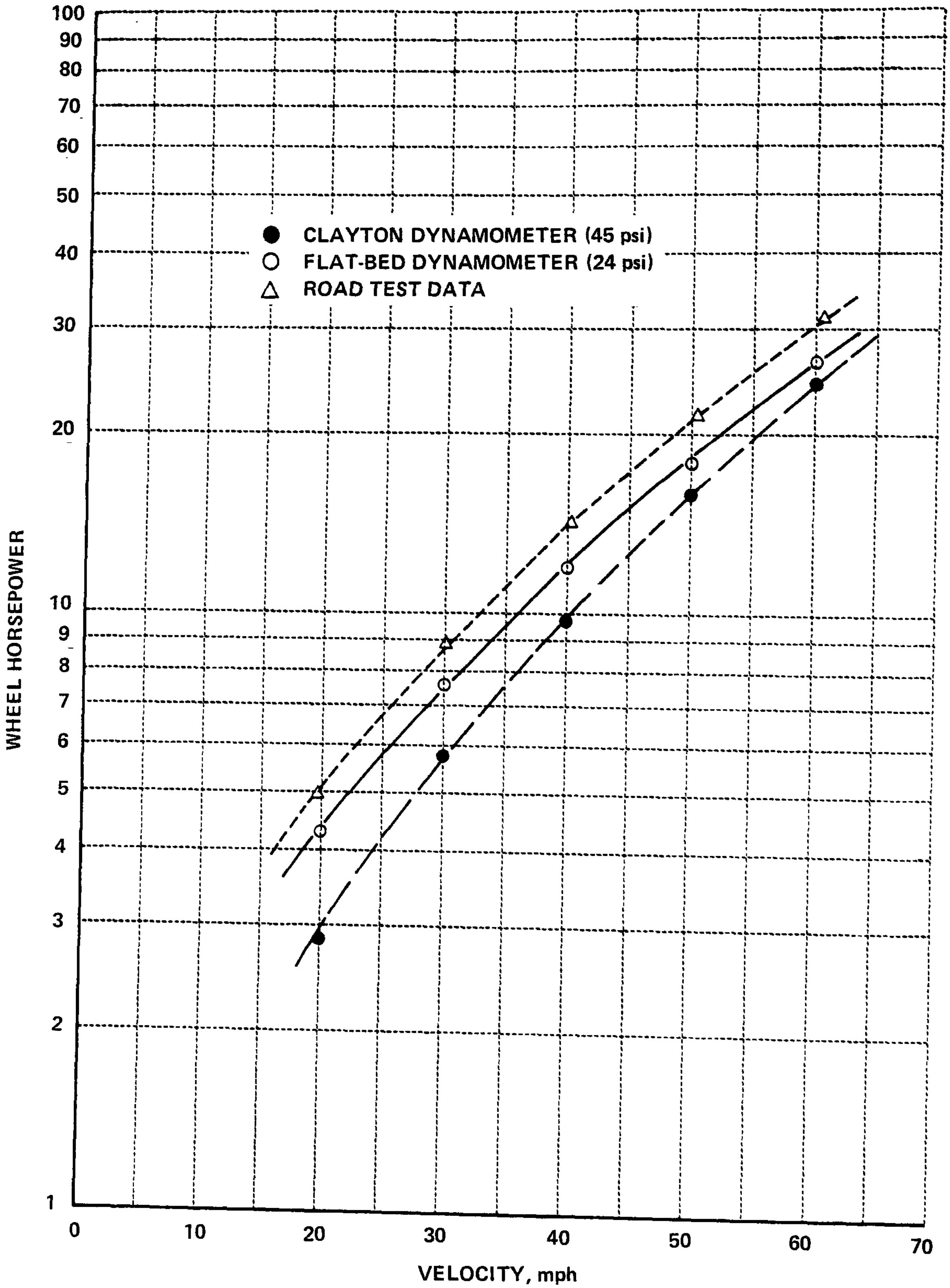

Figure 19 Steady-state tests - Oldsmobile 98 wheel horsepower vs velocity for bias-belted tires (G78-15); indicated HP = PR.

tire construction also ranks in the intermediate position in terms of fuel economy. It thus appears that bias and bias-belted tires operating on the flat-bed dynamometer exhibit different relative rolling losses than they do when operating on a test track or on the TIRF machine.

For dynamometer tests in which the true absorbed horsepower and the wheel horsepower at each velocity are known, the tire power consumption represents the differences in the corresponding two data points. Since it was not possible to directly determine the true absorbed power for the flat-bed dynamometer, tire power consumption could only be calculated for the roll-type dynamometer. The data appear in Table 8 and are shown in graphical form in Figure 20 where linear regression lines have been fitted to the test results. Radial-ply tires are seen to show substantially higher rolling losses on the roll dynamometer relative to both the bias-belted and bias-ply tires.

As described in Appendix C, the dynamometer indicated hp was set properly prior to each of the test sequences (FTP, HFET and SS) and then checked at the completion of each test sequence following one minute of operation at 50 mph. In all cases, for both dynamometers the differences were so small (<0.3 hp) that these data are not tabulated in this report.

4.6.3.4 Statistical Analysis

Standard statistical tests were performed to identify differences in means between specific data-block pairs at the 90, 95, and 99 percent levels of confidence. The analyses were made to the extent that the available data permitted, recognizing that not all tests were completed and that only single runs were made for some test conditions. The "t" test of significance between two sample means for unpaired variates (6) was employed.

For convenience of reference, Table 9 contains a concise identification of each data Block Number in terms of the following set of descriptors: dynamometer used, type of test performed, number of tests involved, tire construction used, tire inflation pressure (cold) and dynamometer indicated horsepower setting used. A tabular summary of the results of the analysis for the FTP and HFET tests is presented in Table 10 where the code used to denote levels of significance, if any, is explained in the footnote.

An examination of the results shows that there is a consistency between the FTP and HFET tests and that the following general observations apply:

- The most significant differences in data means occur between tests performed on (1) bias-ply tires on the flat-bed and the roll dynamometers and (2) radial-ply and bias-ply tires on the flat-bed dynamometer.

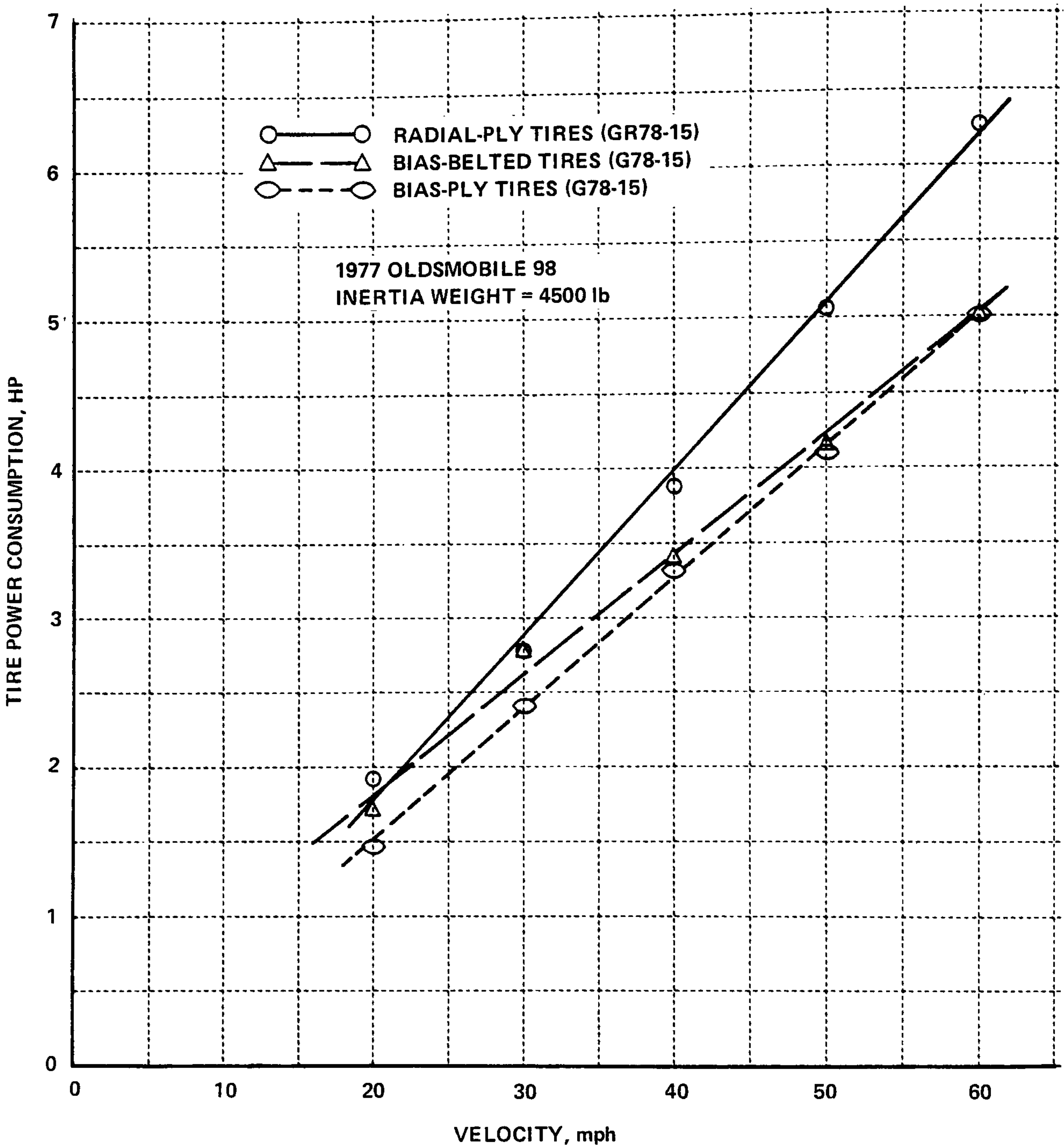

Figure 20 Tire horsepower consumption versus velocity; Clayton dynamometer; tire pressure = 45 psi, dyno indicated HP = PR.

Table 9

BLOCK NUMBER DESIGNATIONS FOR
STATISTICAL TESTS

BLOCK NO.	DYNA-MOMETER	TYPE OF TEST	NO. OF TESTS	TYPE TIRE	INFLATION PRESSURE	INDICATED HP
1	FB	FTP	3	Radial	MRP	PR
2	FB	FTP	3	Bias	MRP	PR
3	FB	HFET	3	Radial	MRP	PR
4	FB	HFET	3	Bias	MRP	PR
5	FB	SS	2	Radial	MRP	PR
6	FB	SS	2	Bias-B	MRP	PR
7	FB	SS	2*	Bias	MRP	PR
8	FB	SS	1	Radial	45psi	PR
9	FB	SS	1	Bias-B	45psi	PR
10	FB	SS	1**	Bias	45psi	PR
11	FB	FTP	3	Bias	MRP	PRA
12	FB	HFET	3	Bias	MRP	PRA
13	FB	SS	2	Bias	MRP	PRA
14	CLAY.	FTP	3	Radial	45psi	PR
15	CLAY.	FTP	3	Bias	45psi	PR
16	CLAY.	HFET	3	Radial	45psi	PR
17	CLAY.	HFET	3	Bias	45psi	PR
18	CLAY.	SS	2	Radial	45psi	PR
19	CLAY.	SS	2	Bias-B	45psi	PR
20	CLAY.	SS	2	Bias	45psi	PR

NOTE: All SS Tests @ 20, 30, 40, 50 and 60 MPH

MRP = Manufacturer's recommended inflation pressure.

* only one test completed

** test not completed

Table 10

SUMMARY OF THE RESULTS OF TESTS OF SIGNIFICANCE APPLIED TO THE DIFFERENCES BETWEEN MEANS OF DATA FOR THE FTP AND HFET RUNS

BLOCK PAIR	TYPE TEST	TESTS PER BLOCK	TEST PARAMETER: HC GM/MI	CO GM/MI	NO_x GM/MI	CO_2 GM/MI	FUEL ECONOMY MPG	AVG+TORQ LB-FT	AVG-TORQ LB-FT
1-2	FTP	3	**	***	-	***	***	**	-
1-11	FTP	3	-	-	**	***	***	***	*
1-14	FTP	3	-	***	***	*	*	**	-
2-11	FTP	3	**	***	-	-	-	-	-
2-15	FTP	3	**	***	***	***	***	***	**
14-15	FTP	3	-	***	-	-	-	*	-
3-4	HFET	3	ANALYSIS NOT REQUIRED				***	***	-
3-12	HFET	3					***	***	-
3-16	HFET	3					*	-	-
4-12	HFET	3					-	-	*
4-17	HFET	3					***	***	-
6-17	HFET	3					*	-	-

CODE: - = not significant (<90%)
* = significant at the 90% level
** = significant at the 95% level
*** = significant at the 99% level

- The least significant differences in data means occur between tests performed on (1) radial-ply and bias-ply tires on the roll dynamometer and (2) bias-ply tires on the flat-bed dynamometer with the indicated hp changed from PR to PRA.

The results of tests of significance on the difference between means of the emissions data (HC, CO and NO_x) are characterized by inconsistencies exacerbated by insufficient data replication. For example, the test conditions applicable to data-block pairs 1-2 and 1-11 were identical except for a small change in indicated hp between data blocks 2 and 11. This change should have had only a minor impact on the measured data, yet results in Table 10 show significance levels at 95% and 99% changing to levels of no significance between data-block pairs 1-2 and 1-11. Clearly the results of statistical analyses of the emissions data must be treated with caution.

It is apparent also that the CO_2, fuel economy and positive torque results are closely correlated. Differences in the negative-torque means, in most cases, were not found to be significant.

The results of tests of significance applied to data means obtained from the series of steady-state tests concerned with fuel economy and tire consumption are shown in Table 11. As regards fuel economy, the following conclusions can be drawn:

- The most significant differences in data means occur between tests performed on (1) bias-belted tires on the flat-bed and on the roll dynamometers, (2) radial-ply and bias-ply tires on the flat-bed dynamometer and (3) radial-ply and bias-belted tires on the flat-bed dynamometer.

All other designated data pairings fail to show any consistent indications of significances in means. From the velocity standpoint, the least number of cases of significance was found for the 20-mph velocity and the largest number at the 30-mph velocity.

Tire power consumption data as determined on a dynamometer were available only from the roll-dynamometer tests. These data failed to show, except for two isolated instances out of 15, any significant differences between the three tire constructions.

Table 11

SUMMARY OF THE RESULTS OF TESTS OF SIGNIFICANCE APPLIED TO THE DIFFERENCES BETWEEN MEANS OF DATA FOR THE STEADY-STATE RUNS

BLOCK PAIR	TESTS PER BLOCK	TEST PARAMETER	VELOCITY, MPH				
			20	30	40	50	60
5-6	2	Fuel Economy, MPG	*	***	**	**	*
5-13	2		**	***	**	**	**
5-18	2		-	**	-	-	-
6-19	2		-	***	***	***	**
18-19	2		-	-	*	-	-
18-20	2		-	**	-	-	-
19-20	2		-	**	-	-	-
18-19	2	Tire Power Consumption, HP	-	-	-	*	-
18-20	2		-	-	-	**	-
19-20	2		-	-	-	-	-

CODE:
- - = Not significant (<90%)
- * = Significant at the 90% level
- ** = Significant at the 95% level
- *** = Significant at the 99% level

NOTE: Test conditions corresponding to each block number are identified in Table

4.6.4 Comments on the Results

In drawing inferences and conclusions from the numerical data that have been presented, it is important to recognize that a number of different factors were involved in the test program that affected the resultant data. Some of these have been directly or indirectly alluded to in other sections of the report but they are gathered here for ease of reference.

At the outset of this program, one of the objectives was to minimize the differences between the roll and flat-bed dynamometers so that the test data would reflect only the effects of tires operating on rolls or on a flat belt. Unfortunately, this desirable condition could only be approached but not realized. The friction horsepower of the flat-bed unit unavoidably was considerably larger than that of the roll dynamometer. As a result, in setting the indicated horsepower the horsepower absorbed by the PAU on each unit was also considerably different. A further complicating factor was the use of an automatic road load power control unit on the roll dynamometers and a manual PAU on the flat-bed unit. Because of known hysteresis effects in the latter, the transient response would be expected to be different. Data from the FTP tests would be primarily affected by this factor.

Another operational characteristic that affected all the data was the difference in the true-horsepower/velocity relationship between the two dynamometers. The flat-bed unit had a higher power absorption level at all speeds below 50 mph than the roll dynamometer when the settings were equal at 50 mph.

At a much lower level of effect, it is assumed that the use of several different roll-dynamometer installations contributed some variability in the test results.

A difference in tailpipe back pressure was found to exist between the flat-bed test site and the roll dynamometer sites. This difference amounted to only 0.4 inch of water, well within the one-inch tolerance permitted by the Federal Register regulations. This fact may account for some of the increased NO_x levels obtained for the flat-bed tests relative to the roll-dynamometer tests. This effect is considered of secondary inportance.

The flat-bed dynamometer was operated in a laboratory space that was not subject to the same high level of temperature and humidity control that is exercised in the space occupied by the regular dynamometer test sites. What effect, if any, this condition might have had on the data cannot be evaluated.

Finally, it must be recognized that the statistical analyses were limited by the lack of adequate replication in view of the well-known variability of such data as exhaust emissions, for example. Undoubtedly there are instances where significance was found and none was warranted and, conversely, no significance was found where significance did, in fact, exist.

REFERENCES

1. *Cassidy, R. J. (Editor), A Feasibility and Preliminary Design Study of an Advanced Tire Force and Moment Test Facility, Cornell Aeronautical Laboratory, Report No. YD-2639-K-IR, November 1969, pp. 269.

2. Schuring, D. J., Energy Loss of Pneumatic Tires Under Freely Rolling, Braking and Driving Conditions, Tire Science and Technology, Vol. 4, No. 1, February 1976. pp. 3-15.

3. Gusakov, I., Measuring Rolling Resistance of Tires in the Laboratory, Presented at the International Rubber Conference, Kiev (Russia), October 10-14, 1978, 20 pp.

4. Leiferman, M. W., Performance and Cost Analysis of Chassis Dynamometers, EPA Technical Report LDTP 76-1, February 1976.

5. Juneja, W. K., D. D. Horchler, and H. M. Haskew, A Treatise on Exhaust Emission Variability, SAE International Automotive Engineering Congress and Exposition, February 28 - March 4, 1977, Paper No. 770136, 24 pp.

6. Handbook of Chemistry and Physics, Thirty-Sixth Edition (1954-1955), Chemical Rubber Publishing Co., Cleveland, Ohio, pp. 215-217.

7. Bird, K. D. and J. F. Martin, The Calspan Tire Research Facility: Design, Development and Initial Test Results, SAE Automotive Engineering Meeting, May 14-18, 1973, Paper No. 730582.

* This reference describes an analogous development, on a larger scale using an air bearing.

APPENDIX A

A PHYSICAL DESCRIPTION OF THE FLAT-BED DYNAMOMETER

INTRODUCTION

The heart of the flat-bed dynamometer consists of a pair of simulated roadway units (SRU) which take the place of the dual rolls that are located between the power absorption unit (PAU) and the inertia wheels in a conventional chassis dynamometer. Built under license from Calspan, the two SRU's were purchased from Akron-Standard with certain mechanical details tailored to fit the specific needs of this particular flat-bed dynamometer. Design and fabrication of the dynamometer were undertaken based on the following initial considerations:

- The PAU and inertia-flywheel components from a Calspan-owned Clayton CTE-50 dynamometer were to be used.
- Checkout tests had to be performed at Calspan where a dyno pit did not exist.
- The dynamometer had to fit a standard dyno pit at the GM Proving Ground at Milford.
- 2250-lb. and 4500-lb. inertia class vehicles were to be accommodated (specifically, a Chevrolet Chevette and an Oldsmobile 98).

The effect that these constraints exerted on the design of the dynamometer will be discussed.

First, the flywheel unit available at Calspan was one in which the wheels were engaged by belts and pulleys. Since this arrangement is subject to slippage problems, a direct-coupled flywheel unit was obtained on a loan basis from the GM Vehicle Emissions Laboratory at Milford (M-VEL). This unit used five inertia wheels and had a full scale range of 5500-lbs. equivalent weight*. The PAU did not have the automatic road load control feature desired, but was used for reasons discussed elsewhere (Section 4.5).

* When incorporated in a Clayton chassis dynamometer.

To perform dynamometer check tests in the absence of a pit in which to anchor the individual component parts, it was necessary to fabricate a supporting structure upon which the dynamometer could be assembled, aligned and rigidly attached. In designing this structure, the critical envelope dimensions had to be compatible with the pit dimensions supplied by GM (3 ft. deep x 8 ft. wide x 15 ft. long). Finally, the two specified vehicles established the exact equivalent weights that the dynamometer had to provide as well as the rear-wheel track widths that had to be accommodated.

Simulated Roadway Units

The SRU consists of two 19.25-inch diameter steel drums, 15 inches in width, which support an endless belt. This belt is fabricated from 301 stainless steel and is 0.024 inches in thickness, 15.75 inches in width and 144.55 inches in length. It is covered with a replaceable textured material to simulate road surfaces. Support for the tire vertical load on the belt is provided by a linear hydrostatic bearing located at the midpoint of the unsupported span of the belt. Water is used as the bearing working fluid. Both drums operate in bearings located in two, 3/4-inch thick, parallel vertical steel frames. One drum "floats" longitudinally on mechanical flexures to adjust belt preload through a spring arrangement. A preload of 10,000 psi is used so that there is no belt/drum slippage during vehicle accel/decel operation. Belt preload is checked using strain-gaged adjusting bolts.

Belt tracking in the lateral direction is augmented by the crowned contact surfaces of the drum (0.0034 inches taper per inch length). The drum surfaces are circumferentially grooved (21 grooves) to preclude accumulation of water in the belt/drum interface. Containment of the hydrostatic bearing fluid is achieved by a seal/scraper assembly preloaded against the underside of the belt. The assembly is enclosed by an elastomeric boot so variations in the vertical position of the seal can be accommodated. Figure A-1 shows a photograph of one SRU installed in the dynamometer assembly. The various features described above are identified by labels.

Dynamometer Layout

A plan view of the dynamometer is shown in schematic form in Figure A-2. All rotating shafts can be visualized as lying in the plane of the paper except for the shaft of the inertia unit which is in a plane above, but parallel to, the plane of the paper. Placement of the inertia unit was dictated by the dimensions of the standard dyno pit. All of the dynamometer hardware was mounted on a welded steel-beam supporting base and resulted in an overall envelope having the following dimensions: 51.5 inches in height, 99.5 inches in width and 183.5 inches in length.

The right-side SRU* and the PAU are attached to a common base plate to permit adjusting the dynamometer track width (distance between centers of the water bearings) to that of the Oldsmobile (60.7 inches) and that of the Chevette (51.2 inches). SRU and PAU shafts are direct coupled. Figure A-2 shows the configuration used for the Oldsmobile in which the two SRU shafts are joined by two rubber-type flex couplings with an intervening floating shaft (see Figure A-1). To accommodate the narrower track of the Chevette, the floating shaft together with one-half of each flex-coupling is removed and the PAU/SRU assembly is shifted laterally 9.5 inches permitting the two remaining halves of the couplings to be mated and form a single unit.

The left SRU is coupled to the inertia unit by a gearbelt/pulley combination. A 60-tooth gearbelt pulley is mounted on the SRU shaft while a 32-tooth gearbelt pulley is mounted on a shaft operating in a pair of pillow-block bearings and is coupled to the inertia unit. Two, three-inch wide gearbelts operate on these pulleys. A close-up view of the gearbelt drive is shown in Figure A-3. The smaller diameter pulley is flanged for the purpose of belt retention.

Inertia Requirements

The equivalent weight provided by the dynamometer inertia at the surface of the rolls for commercial chassis dynamometers is a calculated quantity based on roll diameter and the inertia of the rotating components. Since the rotating components are usually regularly-shaped bodies of revolution, the moments of inertias can be easily calculated if the dimensions and the density of the materials of construction are known. This same procedure was used in configuring the flat-bed dynamometer to provide exact settings of 2250-lbs. and 4500-lbs. equivalent weight at the tire patch.

The moments of inertia for the PAU and the inertia unit were obtained from the manufacturer** Moments of inertia were calculated for all rotating SRU components including drums, belts, shafts pulleys, couplings, etc. Data for the gearbelt pulleys and the flex-couplings were obtained from the manufacturers. Using all of the inertia flywheels, it was determined that to obtain an equivalent weight of 4500-lbs. at the SRU belt surface, a step-up ratio of about 1.93 was needed between the SRU's and the inertia unit. Standard gearbelt pulleys were purchased that achieved a slightly smaller ratio of 1.875. Small, demountable flywheels were fabricated to be attached to the inertia unit shaft (see Figure A-2) to achieve exactly 4500-lbs. with the inertia unit selector switch set to 5500-lbs. and 2250-lbs. with the selector switch set to 2500-lbs. Despite the significant inertias of the SRU drums, the step-up ratio to the inertia unit is necessitated because the SRU drums are 19.25 inches in diameter while the Clayton dynamometer rolls are 8.65 inches in diameter.

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* From the point of view of the driver of the vehicle.

** Telecon: Max Moore, Clayton Manufacturing Company, El Monte, California, May 2, 1977

Water System Description

The hydrostatic bearings were designed to operate at tire contact pressures up to 100 psi with a water supply pressure of 225 psi and a flow of 110 gpm to each bearing. To meet these requirements, a centrifugal pump with a capacity of 225 psi and 220 gpm is used. It is driven by a 75 horsepower motor operating at 3600 rpm on 440 volts A. C. Each hydrostatic-bearing, high-pressure manifold is supplied by dual lines to reduce pressure losses. The low-pressure plenum chamber is drained by gravity forces. Large-diameter plastic piping routes the discharge water to a 65-gallon sump. This sump is equipped with high-and low-limit electrical switches which control a 7.5 hp sump pump that has a flow capacity of 300 gpm.

Water from the sump is returned to a 500-gallon reservoir. The reservoir is a free-standing, polyethylene cylinder that is open at the top. This reservoir supplies the high-pressure pump and acts as the dump for the return flow. Figure A-1 shows some of the water lines in the region of a hydrostatic bearing.

Two particulate filters were installed in the high-pressure water system to trap contaminants which could obstruct flow through the individual bearings which are used in a geometrical array to form the composite water bearing. Reduced flow could result in the steel belt riding on the bearing faces rather than on the water film. Except for the reservoir, all components of the water system were mounted on the dynamometer support structure.

At a given pressure, the flow through the hydrostatic bearing varies inversely with the viscosity of the fluid. The viscosity of water at $130^{o}F$ is only one half of that at $68^{o}F$. If water temperature is allowed to increase, the flow will increase and the required pumping power will increase. Increased flow will also require active scavenging of the bearing plenum chamber by a pump. To avoid these difficulties water temperature must be controlled so as not to exceed $\approx 105^{o}F$. Because of the large amount of energy put into the water in the form of heat by the high-pressure pump, this temperature would be exceeded in about 20 minutes of continuous dynamometer operation.

A heat exchanger could be used to control water temperature and achieve a closed water system (except for makeup water required to replenish leakage losses). As a temporary, economical alternative, temperature control was maintained throughout the test program by the simultaneous draining of warm return water from the sump and the adding of an equal volume of chilled ($\approx 50^{o}F$) water at rates of several gallons per minute.

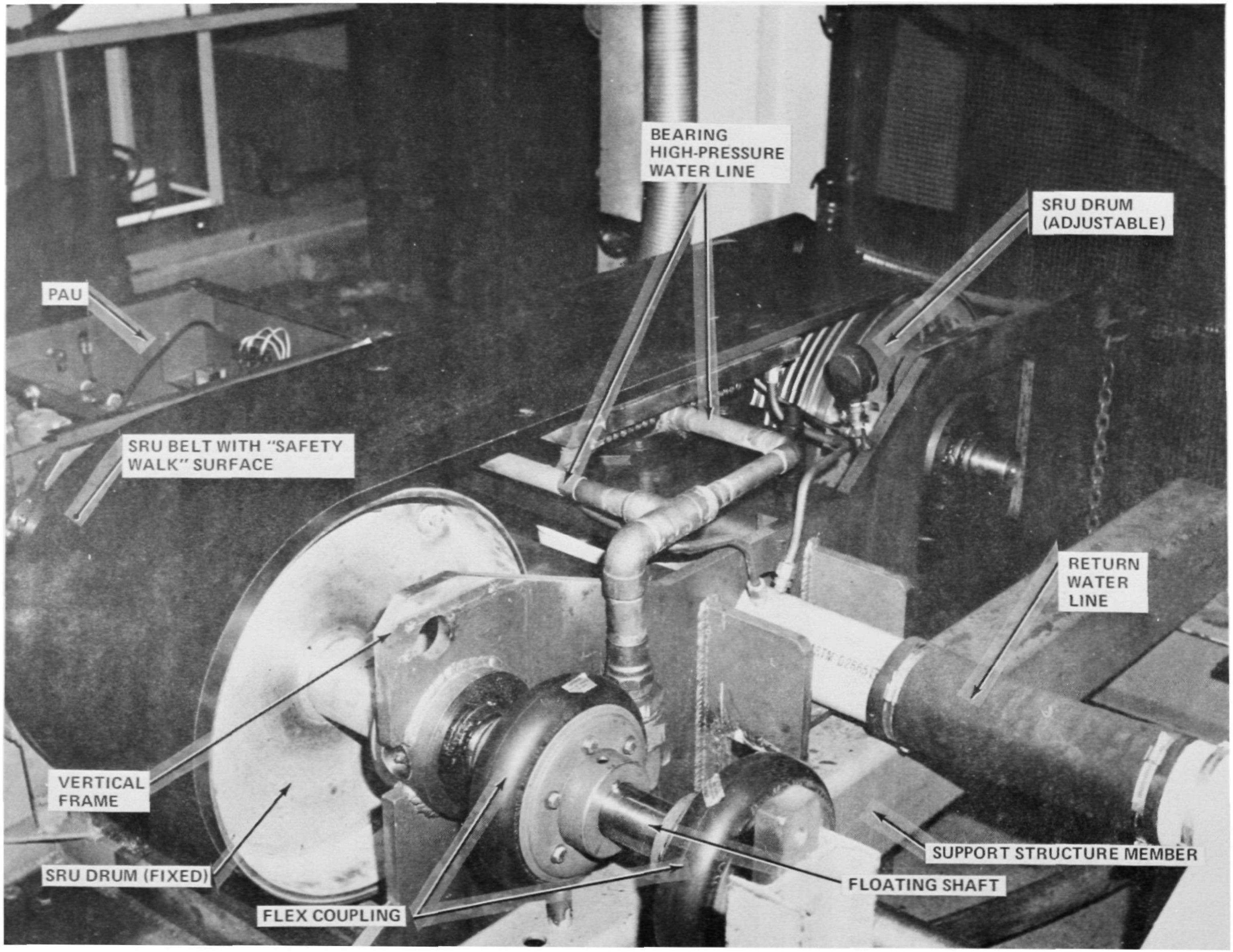
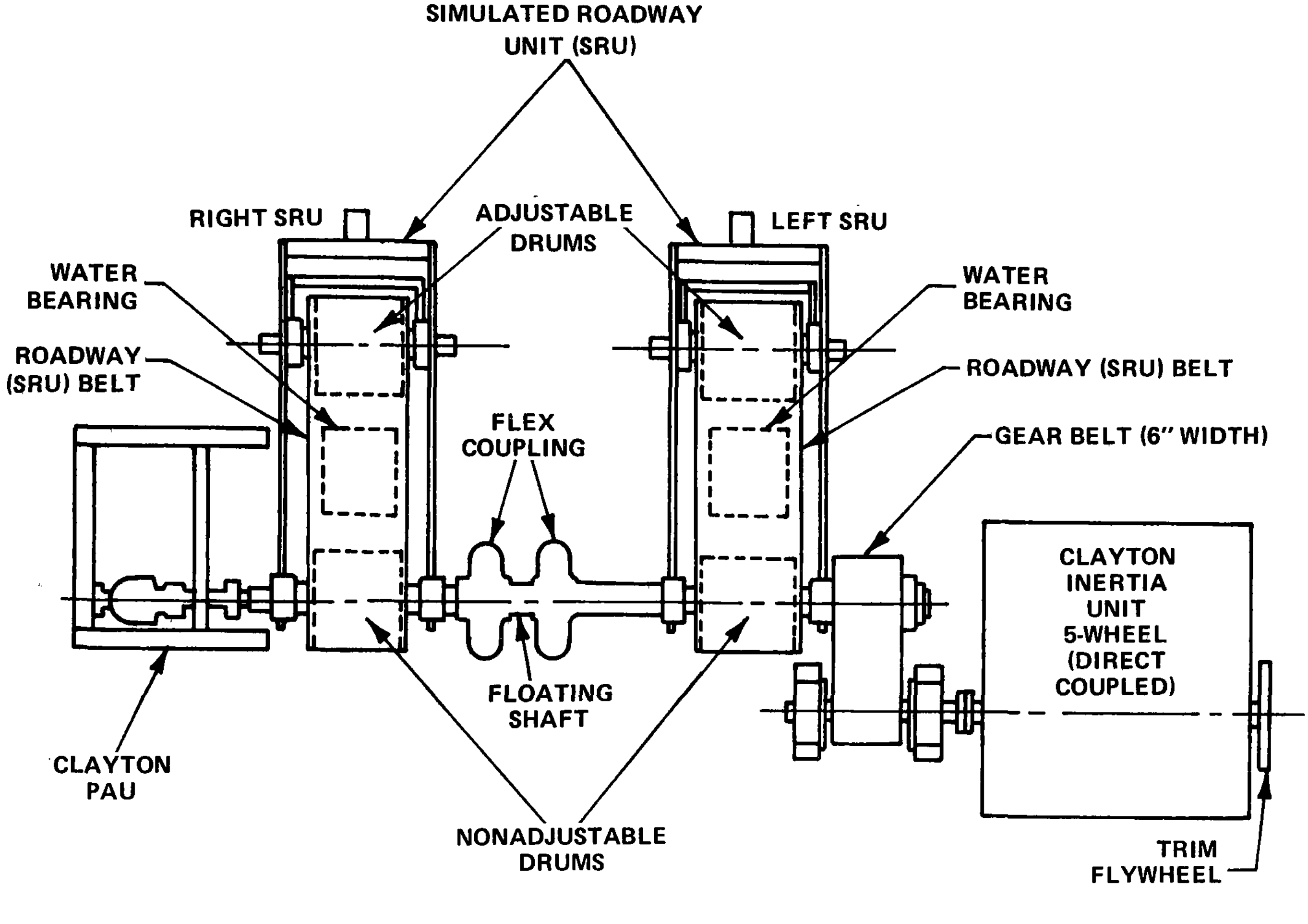


Figure A-1 View of the right half of the flat-bed dynamometer.



(NO SCALE)

Figure A-2 Flat-bed dynamometer plan-view arrangement.

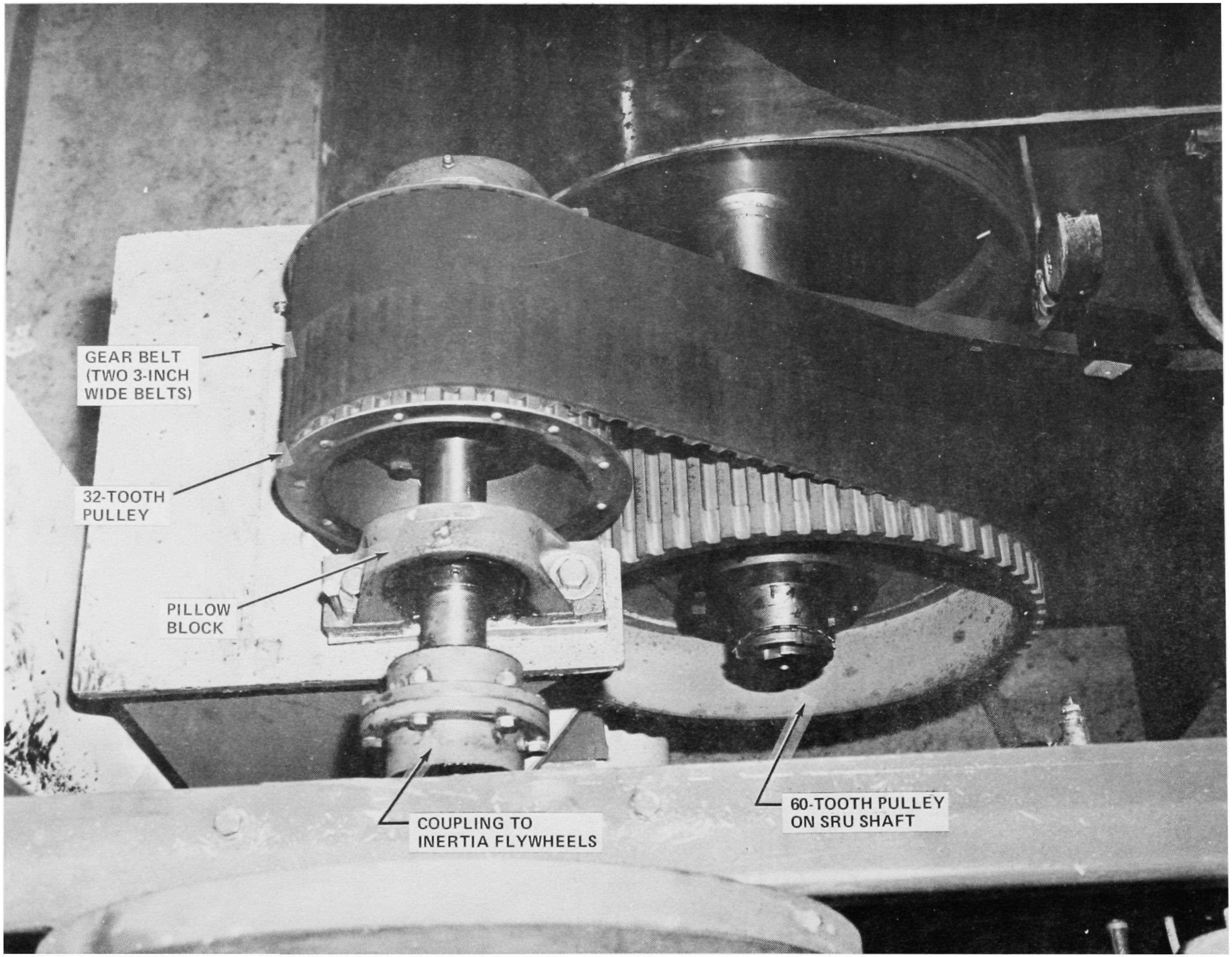


Figure A-2   Close-up view of gearbelt drive arrangement.

APPENDIX B

THE TEST SCHEDULE FOR THE DYNAMOMETERS

The schedule followed for the test vehicles on the flat-bed and the Clayton (double-roll) chassis dynamometers was explicitly defined in the Scope of Work section of the contract. This schedule is outlined in Table B-1 and provides for measurements of rear-wheel torque and exhaust emissions for the following test cycles: (1) the non-evaporataive Federal, Test Procedure (FTP), (2) the Highway Fuel Economy Test (HFET) and (3) steady-state tests (SS).

Steady-state tests were made at the following velocities and in the sequence shown: 60, 50, 40, 30 and 20 mph. Each velocity was maintained constant for a period of ten minutes. Exhaust emissions measured included HC, CO, NO_x and CO_2. The wheel torques were measured directly as integrated values extending over the duration of the test. For the FTP and HFET cycles, separate values of the positive and negative integrated torques were recorded.

A perusal of Table B-1 shows that three replicate tests of each of the aforementioned test cycles were made using radial-ply and bias-ply tires on the test vehicle on each dynamometer. Only the steady-state tests were performed on the bias-belted tires. The manufacturer's recommended cold inflation pressure of 24 psi was used for all tire constructions tested on the flat-bed dynamometer. For each tire construction one steady-state test was performed on the flat-bed dynamometer using a cold inflation pressure of 45 psi. All testing on the Clayton unit was conducted with tire cold inflation pressures of 45 psi.

Road-load power setting on each dynamometer was established in the following manner. The test vehicle was fitted with the radial-ply tires and operated on the dynamometer for 20 minutes at 50 mph to warm up the unit. With the vehicle at 50 mph, the power absorption unit was adjusted until the rear wheel torque was the same as the mean torque value measured during road tests on that vehicle equipped with the same radial tires. The corresponding reading of dynamometer indicated horsepower is identified as PR in the Table and was used for tests on all three types of tires.

A repeat set of test runs (substantially so) was made only on the bias-ply and only on the flat-bed dynamometer with the sole exception that the road-load power setting was changed (increased). Using rolling-resistance force data measured for each of the vehicle's two front bias-ply and radial-ply tires, the difference in the total power loss between the two pairs of tires was calculated. This increment of power loss was added to the previously measured PR reading and the value, as shown in Table B-1, was identified as PRA.

For reasons given in the body of the report, the above schedule of runs (except for two flat-bed tests) was completed only for the 4500-lb. inertia class vehicle. To minimize the possibility of introducing an inadvertent bias into the test data, a randomized test sequence was followed in performing the tests scheduled for the flat-bed and the Clayton dynamometers.

TABLE B-1. DYNAMOMETER TEST SCHEDULE

FB = FLAT BED, C = CLAYTON

Purpose	No. of Runs	Dyno Type	Tire Type	Cold Pressure	Test Cycle	Dyno Ind. hp	Measurements	
							Wheel Torque	Exhaust Emissions
Ind. hp		FB/C	Radial	(1)	50 mph	x	(2)	
Warm-Up (3)		↓	-	-	50 mph	Set PR		
Data	1	↓	Radial	(1)	FTP	PR	x	x
↓	1	↓	↓	↓	HFET	↓	x	x
↓	5	↓	↓	↓	SS	↓	x	x
Warm-Up (3)		↓	-	-	50 mph	Set PR		
Data	1	↓	Radial	(1)	FTP	PR	x	x
↓	1	↓	↓	↓	HFET	↓	x	x
↓	5	↓	↓	↓	SS	↓	x	x
Warm-Up (3)		↓	-	-	50 mph	Set PR		
Data	1	↓	Radial	(1)	FTP	PR	x	x
↓	1	↓	↓	↓	HFET	↓	x	x
↓	5	↓	↓	45 psi	SS	↓	x	x
Warm-Up (4)		↓	Bias Belt	-	50 mph	Set PR		
Data	5	↓	↓	(1)	SS	PR	x	x
↓	5	↓	↓	↓	SS	↓	x	x
↓	5	↓	↓	45 psi	SS	↓	x	x
Warm-Up (3)		↓			50 mph	Set PR		
Data	1	↓	Bias	(1)	FTP	PR	x	x
↓	1	↓	↓	↓	HFET	↓	x	x
↓	5	↓	↓	↓	SS	↓	x	x
Warm-Up (3)		↓			50 mph	Set PR		
Data	1	↓	Bias	(1)	FTP	PR	x	x
↓	1	↓	↓	↓	HFET	↓	x	x
↓	5	↓	↓	↓	SS	↓	x	x
Warm-Up (3)		↓			50 mph	Set PR		
Data	1	↓		(1)	FTP	PR	x	x
↓	1	↓	Bias	↓	HFET	↓	x	x
↓	5	↓	↓	45 psi	SS	↓	x	x
Warm-Up (3)		FB			50 mph	Set PRA (5)		
Data	1	↓	Bias	24 psi	FTP	PRA	x	x
↓	1	↓	↓	↓	HFET	↓	x	x
↓	5	↓	↓	↓	SS	↓	x	x
Warm-Up (3)		↓			50 mph	Set PRA (5)		
Data	1	↓	Bias	24 psi	FTP	PRA	x	x
↓	1	↓	↓	↓	HFET	↓	x	x
↓	5	↓	↓	↓	SS	↓	x	x
Warm-Up (3)		↓			50 mph	Set PRA (5)		
Data	1	↓	Bias	24 psi	FTP	PRA	x	x
↓	1	↓	↓	↓	HFET	↓	x	x

(1) Tire manufacturer's recommended pressure, MRP, of 24 psi used on the flat-bed dyno, 45 psi used on Clayton Dyno.

(2) Using test vehicle equipped with radial tires, the dyno indicated hp was adjusted so that the rear wheel torque was the same as that measured on the road tests at 50 mph. This value of indicated hp equals PR.

(3) Dyno was warmed up for 20 min @ 50 mph using non-test vehicle. At end of warm-up, indicated hp was set to proper value.

(4) Same as above except that test vehicle was used.

(5) PRA = PR + (difference in rolling tire power loss between the bias and radial tires on the front of the test vehicle).

APPENDIX C

PROCEDURES FOR PERFORMING THE DYNAMOMETER TESTS

A detailed account is presented in this appendix of the test procedures that were used in performing the dynamometer tests which are identified in Table B-1 of Appendix B. The procedural details are shown in an itemized format and, except for minor editorial revisions required to achieve consistency with the rest of the report, are reproduced verbatim as supplied by General Motors.

The step-by-step instructions and procedures are written in the future tense since they were prepared prior to the initiation of the test effort itself. All dynamometer testing took place in accord with the explicit details outlined below.

A tabulation of selected specifications for the engine, driveline and emission control system for the two test vehicles is shown at the end of this Appendix.

1.0 Preliminary Vehicle Checks

1.1 Prior to testing, torque rims and the radial tires will be installed on the drive wheels of the vehicle.

1.2 The test vehicle will be serviced to assure that it is mechanically sound. Adjustments and repairs will be made, as necessary to assure that the vehicle is operating at the required tune-up specification.

1.3 A "slave" canister will be installed on the vehicle. A "slave" canister eliminates variability in emissions tests due to evaporative fuel losses.

1.4 The vehicle will be ballasted so that with a full tank of fuel and driver the wheel weights are the same as those measured in the road tests.

NOTE: Two Total Torque Testers (TTTs) will be used for this project. One unit will record positive torque and horsepower, negative torque and horsepower, and total distance. The second unit will record elapsed time and wheel revolutions.

2.0 Preliminary Instrumentation Calibration

2.1 The TTT used with the torque wheels will be calibrated.

2.2 The Driver's Air recorder on the flat-bed dynamometer will be calibrated at 50.0 mph.

2.3 The power absorption unit (PAU) and horsepower meter on the flat-bed dynamometer will be calibrated using the dead weight technique per the Clayton calibration procedure.

2.4 The critical flow venturi (CFV) sampler, used to collect exhaust in the flat-bed site,will be verified. Critical flow orifice (CFO) propane injection tests will be run to insure that the flow calibration is correct and that there are no leaks in the sample system.

2.5 The simulated roadway unit's (SRUs) belt tension on the flat-bed dynamometer will be set to the proper value by a Calspan representative.

3.0 Determine PR

The flat-bed and Clayton PAUs must be adjusted so that the vehicle's drive wheel torque, at 50 mph, is the same on both dynamometers. PR, as measured in the road tests, is the average drive wheel torque, at 50 mph, for each vehicle when equipped with radial tires at manufacturer's recommended pressure (MRP), and operating on a flat road surface. The PAU settings to achieve PR will be determined by the following procedure.

3.1 Set the drive wheel radial tire pressure to the proper value (45 psi Clayton, MRP flat-bed). Set the required inertia weight.

3.2 Warm up the dynamometer using the test vehicle for 30 minutes at 50 mph.

3.3 Let the vehicle coast to a stop in neutral. Adjust the TTT zero bias and gain to the proper values.

3.4 Drive the vehicle at 50 mph.

3.5 Adjust the absorber load to obtain a rear wheel torque equivalent to PR. Record the meter's indicated HP (and also the corresponding actual HP on the Clayton dynamometer).

3.6 Let the vehicle coast to a stop in neutral. Check and record the TTT zero bias and gain readings.

3.7 Repeat steps 3.1 through 3.6 several times (on each dynamometer) to insure that PR is correct.

3.8 Repeat steps 3.1 through 3.7 on at least two Clayton dynamometers. Determine the average PR setting for these dynamometers.

4.0 Frictional Power Absorption Characteristics

4.1 Flatbed Dynamometer

4.1.1 Set the drive wheel radial tire pressures to MRP. Set the required inertia weight.

4.1.2 Disconnect the PAU from the dynamometer rolls.

4.1.3 Warm up the dynamometer for 30 minutes at 50 mph using the test vehicle.

4.1.4 Let the vehicle coast to a stop in neutral. Adjust the TTT zero bias and gain to the proper values.

4.1.5 Drive 2 miles at 20 mph; then 2 miles of data collection at 20 mph.

4.1.6 Drive 2 miles at 30 mph; then 2 miles of data collection at 30 mph.

4.1.7 Drive 2 miles at 40 mph; then 2 miles of data collection at 40 mph.

4.1.8 Drive 2 miles at 50 mph; then 2 miles of data collection at 50 mph.

4.1.9 Drive 2 miles at 60 mph; then 2 miles of data collection at 60 mph.

4.1.10 Let the vehicle coast to a stop in neutral. Check and adjust, if necessary, the TTT zero bias and gain to the proper values.

4.1.11 Repeat steps 4.1.5 through 4.1.9. Start at 60 mph, however, and proceed to 20 mph.

4.1.12 Calculate the average wheel horsepower and plot as a function of speed.

NOTE:

$$\text{wheel horsepower}_V = \frac{HP_{int}}{t_{int}} \times \frac{R_T}{d_{int}} \times 2\pi \times R_{int}$$

where:

HP_{int} = integrated HP (HP-sec) as measured by the TTT

t_{int} = integrated time (sec)

d_{int} = integrated distance travelled (ft)

R_{int} = integrated revolutions, vehicle wheel

R_T = rolling radius used in TTT electronics = 1.1484 (ft)

4.1.13 Calculate the average horsepower consumption for the two rear tires, at each speed, from the TIRF rolling resistance data.

NOTE:

$$\text{average tire HP}_V \text{ (2 tires)} = \frac{(F_{LR} + F_{RR}) \times V}{375}$$

where: F_{LR} = the average rolling resistance force for the left rear radial type test tire (lb)

F_{RR} = the average rolling resistance force for the right rear radial type test tire (lb)

V = average velocity (mph)

4.1.14 Calculate dynamometer friction horsepower at each speed (wheel HP - rear tire HP). Plot friction horsepower as a function of speed.

NOTE: This technique assumes the tire rolling resistance on the flat-bed dynamometer is the same as that on the TIRF tire test facility as both are flat-bed machines.

4.2 Clayton Dynamometer

4.2.1 Disconnect the PAU from the dynamometer rolls. Set the required inertia weight.

4.2.2 Warm up the dynamometer for 20 to 30 minutes at 50 mph.

4.2.3 Drive the dynamometer to 65 mph and raise the vehicle off the rolls. Allow the front and rear rolls to coast down to at least 15 mph.

4.2.4 Calculate the friction horsepower from the coast down times at 60, 50, 40, 30, and 20 mph.

NOTE: friction HP_V = (front roll friction)$_V$ + (rear roll friction)$_V$

$$= 6.073 \times 10^{-5} \left(V_1^2 - V_2^2\right) \left[\frac{(IWT - 155)}{t_f} + \frac{155}{t_r}\right]$$

where: friction HP_V = horsepower at velocity of $(V_1 + V_2)/2$

V_1 = initial velocity (mph)

V_2 = final velocity (mph)

IWT = dynamometer inertia weight setting (lb)

155 = dynamometer rear roll inertia (lb)

t_f = front roll coast down time (sec)

t_r = rear roll coast down time (sec)

4.2.5 Repeat steps 4.2.3 and 4.2.4 at least once. Determine the average friction horsepower at each speed.

4.2.6 Repeat steps 4.2.1 through 4.2.5 on at least two Clayton dynamometers. Calculate the average friction horsepower at each speed for three dynamometers.

5.0 True Dynamometer Absorbed Horsepower (Clayton only)

The true absorbed horsepower vs speed curve on each Clayton dynamometer can be determined directly from coast down times with the PAU indicated horsepower adjusted to achieve PR. An alternate method is to calculate the average true load by the method shown below.

$$\text{Avg. true absorbed } HP_V = \text{avg. windage } HP_V + \text{friction } HP_V$$
$$= KV^3 + \text{friction } HP_V$$

where: V = roll velocity (mph)

friction HP_V = the dynamometer friction HP for the appropriate inertia setting (4.2)

$$K = \frac{(\text{avg. actual HP @ PR}) - (\text{avg. front roll friction HP @ 50 mph})}{(50.0)^3\ (\text{mph})^3}$$

6.0 FTP, HFET, and Steady Speed Tests

6.1 Test Sequence

NOTE: The test design calls for tests on both dynamometers with three tire types. In general, a test day will begin with a cold start FTP test followed by a HFET and steady speed tests. Tests between the two dynamometer types will be randomized.

6.1.1 Perform the required tests for the radial tires, on both dynamometers, in a random order.

6.1.2 Perform the tests for the bias-belted tires, on both dynamometers, in a random order.

6.1.3 Perform the tests for the bias-ply tires, on both dynamometers, in a random order.

NOTE: Steps 6.2 to 6.9 describe in detail how each test will be performed.

6.2 Vehicle Preparation

6.2.1 Prior to each day's testing, the test vehicle will be filled with room temperature Indolene clear fuel.

6.2.2 If the vehicle is scheduled for a cold start FTP test, it must have a dynamometer prep within the previous 12 to 36 hours. A dynamometer prep (for this project) will be considered a 23 minute LA-4 test (Bag 1 and 2) and/or an HFET or series of steady speed tests.

6.3 Dynamometer Preparation

6.3.1 Select the required dynamometer inertia.

6.3.2 The dynamometer will be warmed-up for 20 to 30 minutes at 50 mph (for the FTP tests, a non-test vehicle is used).

6.3.3 Adjust the dynamometer indicated HP to achieve PR or PRA, as required.

NOTE: The flat-bed dynamometer must be set to the proper indicated HP within 1 hour prior to the start of either a FTP, HFET, or steady speed test. The Clayton dyno will be operated in the automatic road-load mode and therefore will be warmed-up within 2 hours of the start of the test.

6.4 CVS/CFV Preparation

6.4.1 CVS (Constant Volume Sampler)

6.4.1.1 Check that the CVS pump, heater and temperature controller are on and that the pump inlet temperature is statilized at $100^{o}F \pm 5^{o}F$.

6.4.1.2 Operate the automatic sample bag purge and evacuate sequence.

6.4.1.3 Replace the flip-top filters.

6.4.1.4 Turn on the sample pumps. Set the flow to the proper values.

6.4.2 CFV (Critical Flow Venturi Sampler)

6.4.2.1 Manually fill and evacuate the bags with dilution air. Repeat at least 2 times.

6.4.2.2 Replace the flip-top filter.

6.4.2.3 Enter the corrected barometric pressure into the CFV using the thumbwheel switches.

6.4.2.4 Turn on the ambient and sample pumps.

NOTE: The CFV electronic control module will be left on 24 hours a day to prevent drift.

6.5 Pre-Test Vehicle Preparation

6.5.1 Move the test vehicle onto the dynamometer (do not start the engine if an FTP test is to be performed).

6.5.2 Turn on the cooling fan.

6.5.3 Set the wheel chocks. Install the vehicle safety restraints.

6.5.4 Open the vehicle hood.

6.5.5 Check to see that the air conditioning is off.

6.5.6 Check the Driver's Aid recorder to be sure the power is on, the pens are operational, and the chart speed is 6"/minute.

NOTE: On the flatbed dynamometer site, preprinted driver's traces are used.

6.5.7 Check that the TTTs are on and operating properly.

NOTE: The TTTs will be left on 24 hours a day to minimize drift.

6.5.8 Connect the tail pipe to the sampler hose immediately prior to starting the test (cold start FTP).

6.5.9 Make sure the tire pressure is at the proper value.

6.6 FTP Test Dynamometer Procedure

6.6.1 Record the barometric pressure and the wet and dry bulb temperatures.

6.6.2 Set the TTT zero bias gain to the proper values.

6.6.3 Simultaneously start the engine, the TTTs, and the CVS or CFV sampler.

6.6.4 When the engine starts, turn on the Driver's Aid recorder, and drive the test schedule.

NOTE: False starts and engine stalls will be handled per M-VEL procedures.

6.6.5 At the end of phase I record the TTT data and the CVS/CFV corrected flow.

6.6.6 At the and of phase II (2 seconds after the end of the last deceleration) turn off the engine and stop the TTTs. Five seconds after the engine stops, stop the CVS/CFV sampler. Start the 9-11 minute soak period.

6.6.7 Immediately after the end of phase II, turn off the cooling fan, disconnect the hose from the tail pipe, and close the hood.

6.6.8 Record the TTT and CVS/CFV sampler data.

6.6.9 Record the TTT zero bias and gain readings, and reset the displays.

6.6.10 Immediately before the start of phase III reconnect the tail pipe hose, turn on the fan, and open the vehicle hood.

6.6.11 Simultaneously start the engine, the TTTs and the CVS/CFV sampler.

6.6.12 When the engine starts, turn on the Driver's Aid recorder, and drive the test schedule.

NOTE: False starts and engine stalls will be handled per M-VEL* procedures.

6.6.13 At the end of phase III, turn off the engine, the TTTs and the CVS/CFV sampler.

6.6.14 Record the TTT and CFS/CFV sampler data.

6.6.15 Start engine, drive the vehicle at 50 mph and record the dynamometer indicated horsepower.

6.6.16 Let the vehicle coast to a stop in neutral. Check and record the TTT zero bias and gain readings.

6.7 HFET Dynamometer Procedure

6.7.1 Record the barometric pressure and the wet and dry bulb temperature.

6.7.2 Immediately prior to the HFET pre-conditioning cycle, drive the test vehicle at 50 mph for a minimum of 1 minute.

6.7.3 Adjust the indicated horsepower to achieve PR or PRA, as required. Record the indicated horsepower.

6.7.4 Let the vehicle coast to a stop in neutral. Adjust the TTT zero bias and gain, if required, to the proper values. Record these values.

* Milford-Vehicle Emissions Laboratory

6.7.5 Drive the HFET pre-conditioning cycle.

6.7.6 Simultaneously start the HFET data cycle, the TTTs, and the CVS/CFV sampler.

6.7.7 At the end of the HFET data cycle, immediately turn off the engine and stop both the CVS/CFV sampler and the TTTs.

6.7.8 Record the TTT and CVS/CFV sampler data.

6.7.9 Start engine, drive the vehicle at 50 mph and record the indicated horsepower.

6.7.10 Let the vehicle coast to a stop in neutral. Check and record the TTT zero bias and gain reading.

6.8 <u>Steady Speed Test Dynamometer Procedure</u>

6.8.1 Record the barometric pressure and the wet and dry bulb temperatures.

6.8.2 Drive the vehicle at 50 mph for a minimum of one minute. Adjust the indicated horsepower to achieve PR or PRA, as required. Record the indicated horsepower.

6.8.3 Let the vehicle coast to a stop in neutral. Check and adjust, if necessary, the TTT zero bias and gain to the proper values. Record these values.

6.8.4 Drive the vehicle at the required steady speed.

6.8.5 After the vehicle speed is stable, simultaneously start the TTTs and the CVS/CFV sampler.

6.8.6 At the end of 600 seconds, simultaneously stop the TTTs and the CVS/CFV sampler.

6.8.7 Record the TTT and CVS/CFV sampler data.

6.8.8 Drive the vehicle at 50 mph and record the indicated horsepower.

NOTE: Steps 6.8.2 through 6.8.8 will be repeated for each "back-to-back" steady speed test. The steady speed tests will be conducted at 60, 50, 40, 30 and 20 mph in named order.

6.9 <u>FTP, HFET and Steady Speed Test Exhaust Emissions Analysis</u>

NOTE: All bag analyses will be made on emissions analysis consoles that meet M-VEL calibration requirements for certification tests.

6.9.1 Zero and span the proper analyzer ranges for bag sample analysis.

6.9.2 Turn on the bench sample pumps. Analyze the ambient bag HC, CO, NO_x and CO_2. Allow the analyzers to stabilize before taking a computer reading.

6.9.3 Analyze the sample bag HC, CO, NO_x and CO_2. After the analyzers have stabilized, take a computer reading.

6.9.4 Conduct a zero and span check after completion of the bag analyses. If this check shows a change of 1% of full scale or greater, repeat steps 6.9.1 through 6.9.4.

7.0 Data Quality Assurance Checks

7.1 Clayton Dynamometer

7.1.1 All tests will be made on sites that meet M-VEL's calibration requirements.

7.2 Flatbed Dynamometer

7.2.1 The PAU indicated horsepower meter will be checked periodically using the Clayton calibration procedure.

7.2.2 The Driver's Aid speed trace will be checked and calibrated periodically.

7.2.3 CFO propane injections will be used to check CFV calibration accuracy and sample system integrity.

7.3 Total Torque Tester

7.3.1 The TTT will be re-calibrated each time the tires and torque wheels are changed.

7.4 Repetitive Tests

7.4.1 The number of tests needed for this project has been defined in Table B-1 of Appendix B. Quality control charts will be kept on the torque and emissions data. Tests that are invalidated for equipment and/or procedure problems will be repeated.

7.4.2 As stated previously, tests between the Clayton and flatbed dynamometers will be randomized. Randomized tests minimize systematic errors in repetitive testing.

SELECTED VEHICLE DATA

	Oldsmobile 98	Chevrolet Chevette
Year/Body Style	1977/2 door	1977/2 door
Engine	403 CID (V-8)	1.6 litre (4 cyl.)
Carburetor	4 bbl. Model M4MC	1 bbl. Model 1ME
Transmission	CBC-350	THM-200
Axle Ratio	2.41	3.07
Emission Controls	• integral backpressure EGR • oxidizing catalytic converter (260 in^3) • standard GM evaporttive control	• ported vacuum EGR • oxidizing catalytic converter (160 in^3) • 4 cyl. pulse air injection • standard GM evaporative control

APPENDIX D

A DESCRIPTION OF THE SPECIAL INSTRUMENTATION USED FOR THE VEHICLE TESTS*

The purpose of this appendix is to describe, in somewhat more detail than was possible in the text of the report, some of the special instruments employed in the road tests and dynamometer tests performed on the vehicles.

The drive axle on each test vehicle was equipped with a pair of torque wheels developed at the Milford Proving Ground. Both vehicles on this program used the normal sensitivity torque wheels (Mod. 10W) wiich provide a range of ± 2000 ft-lb with an accuracy of 1%. Strain gages are employed as the basic sensors. Both sets of torque wheels were made specially for the program in order to preserve the normal rear-wheel track of the vehicle. This requirement was a function of the design of the flat-bed dynamometer which matched the rear-wheel tracks of the Oldsmobile and Chevette vehicles within a small tolerable margin. Each torque wheel was fitted with a closed slip-ring assembly (Mod. 2) which is resistant to dust and moderate amounts of moisture and thus is useful for outdoor testing in dry conditions. The slip-ring assembly carries power to the strain-gage bridges and permits picking-off the output electrical signals.

Integral with the mechanical package containing the slip rings is an optical encoder that provides a measurement of wheel revolutions. This transducer provides a high degree of resolution in this measurement since it utilizes a digital output consisting of 160 electrical pulses per each revolution.

Figure D-1 shows the torque wheel and its associated instrumentation at the right-rear wheel position of the Oldsmobile vehicle which is resting on the flat-bed dynamometer.

Distance-travelled data, whether in road testing or dynamometer testing, were measured using a one-foot circumference wheel consisting of a metal rim and a solid-rubber periphery (tire). This wheel was mounted in a portable, detachable frame and the wheel shaft was coupled to an optical encoder of the same type as used with the torque wheels. Since the circumference of the wheel was known precisely, a measurement of total number of wheel revolutions was directly relatable to the total distance travelled. In road tests, the vehicle towed a bicycle-type fifth wheel and the one-foot circumference wheel

* The information contained in this Appendix is based on data and descriptive material supplied by General Motors.

operated against it. In dynamometer tests, this small wheel operated directly against the rear cradle roll of the Clayton unit or the SRU belt in the case of the flat-bed unit. Figure D-2 is a photograph that shows the one-foot circumference wheel as installed on the left-side SRU of the flat-bed dynamometer.

Power input and signal conditioning for the torque wheels and the optical encoders were supplied by the Total Torque Tester (TTT). The Total Torque Tester is a portable electronic instrument specifically designed by the GM Proving Ground Noise and Vibration Laboratory for use with torque wheels and optical encoders. This device, operating in conjunction with the torque wheels and a fifth wheel, functions as a system capable of accumulating vehicle performance data as transmitted or received at the rear wheel interface. The instrument display is digital in units of work (horsepower seconds), torque x time (foot pound seconds) and distance (feet). As the torque at the rear wheel is bidirectional, the tester separates the data with respect to the zero baseline and provides two separate displays; positive foot pound seconds and negative foot pound seconds. Since horsepower is the product of rotational speed and torque, separate displays are also provided of positive and negative horsepower seconds. In addition, the unit has the capability to make instantaneous measurements of positive and negative foot pounds and feet per second. This option can be exercised by the operator.

Two Total Torque Testers were used for this program. The one was a standard unit and was employed to collect data on wheel torque and distance travelled. The second, a modified unit, collected data on torque-wheel revolutions (using the optical encoder) and elapsed time. These data were used to calculate wheel horsepower based on wheel torque, wheel speed and effective tire rolling radius.

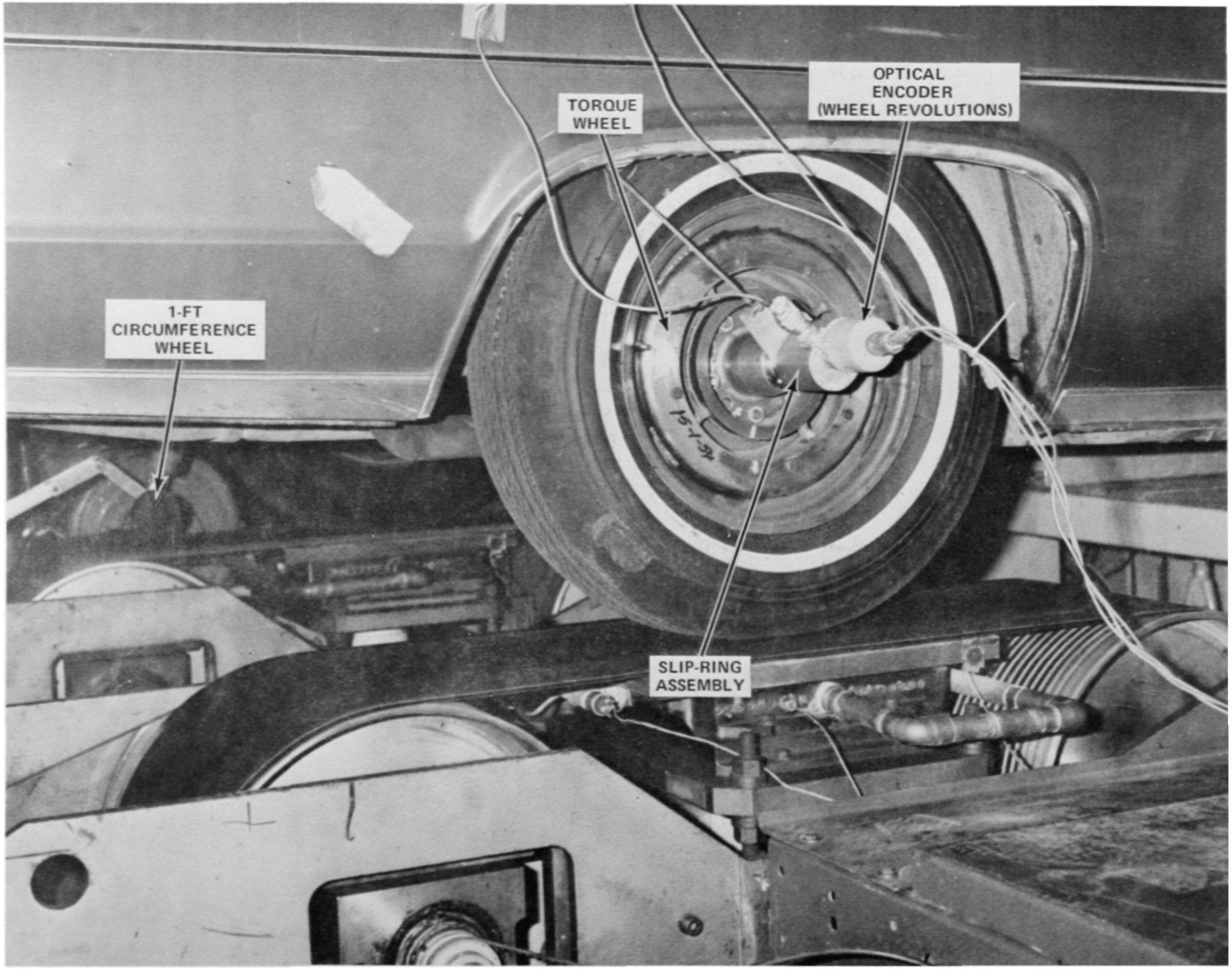


Figure D-1 Torque wheel and instrumentation; 1977 Oldsmobile.

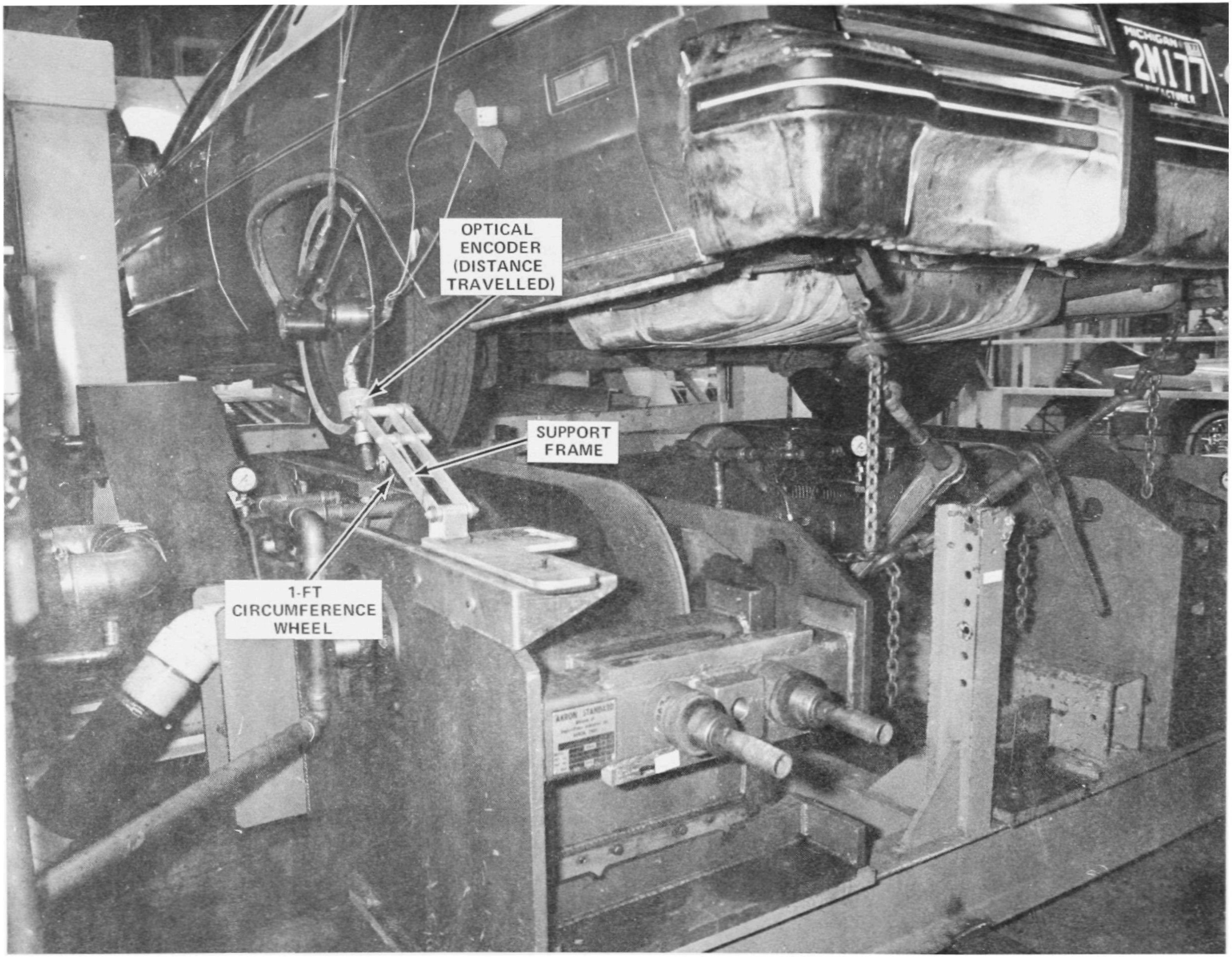


Figure D-2 **Distance measuring instrumentation; one-foot circumference wheel mounted on the flat-bed dynamometer**

APPENDIX E

THE CALSPAN TIRE RESEARCH FACILITY (TIRF)

A photograph of the TIRF facility is shown as Figure E-1; a dimensional view of the facility is shown in Figure E-2. The primary features of the machine are:*

Tire Positioning System

The tire, wheel, force sensing balance and hydraulic motor to drive or brake the tire are mounted in the movable upper head. The head provides steer, camber and vertical motions to the tire. These motions (as well as vertical loading) are servocontrolled and programmable for maximizing test efficiency. The ranges of the position variables, the rates at which they may be adjusted and other information are shown in Table E-1.

Roadway

The 28-inch wide roadway is made up of a stainless steel belt covered with material that simulates the frictional properties of actual road surfaces. The belt is maintained flat to within 1 to 2 mils under the tire patch by the restraint provided by an air bearing pad which is beneath the belt in the tire patch region. The roadway is driven by one of the two 67-inch diameter drums over which it runs. The road speed is servocontrolled; it may be programmed to be constant or varied.

The surfaces usually used are "Safety Walk"**. These surfaces have excellent microtexture giving a wet skid number*** of about 60 in the untreated condition. The surfaces are honed to reduce the wet skid number to lower values (typically surfaces of skid number 50 and 30 are used).

A unique feature of TIRF is the ability to carry out tests under wet road conditions. A two-dimensional water nozzle spans the roadway. This nozzle has an adjustable throat which can be set to the desired water depth.

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* A more complete description of this facility will be found in Reference 7.

** Manufactured by the 3M Company

*** At 40 mph and 0.020-inch water depth using the ASTME-501 Standard Pavement Traction Tire

The flow through the nozzle is then varied by controlling the water pressure. At each test condition the water film is laid on tangential to the belt at belt velocity. The film thickness may be varied from as low as 0.005 inches up to 0.4 inches.

Tire-Wheel Drive

A drive system which is independent of the roadway drive is attached to the tire-wheel shaft. This separate drive allows full variation of tire slip both in the braking and driving modes. The tire slip ratio, referenced to road speed, is under servocontrol.

Balance System*

A six-component strain gage balance surrounds the wheel drive shaft. Three orthogonal forces and three corresponding moments are measured through this system. A fourth moment, torque, is sensed by a torque link in the wheel drive shaft. The load ranges of the basic passenger car and truck tire balances are shown in Table E-2. Transfer of forces and moments from the balance axis-system to the conventional SAE location at the tire-roadway interface is in the data reduction computer program.

System Operation

Data Acquisition Program (DAP) Control

The data acquisition program (DAP) is a software system which controls machine operation and logs data during tests. DAP controls test operations by means of discrete setpoints which are generated in the computer by the program. These setpoints are sent to the machine servos which respond and establish tire test conditions. After the setpoints are sent to the servos, a delay time is provided which starts after the machine variables have reached a steady state value within predetermined tolerances. This allows the system to stabilize before data are taken. After data are taken, the next set of test conditions is established and testing continues.

One or two variables can be changed during DAP testing. The other test parameters are kept fixed throughout the test. Up to twenty data points can be used for each variable in a run.

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* More detailed information on the balance systems and their calibration may be found in Reference 7.

A data reduction program is used to operate on the raw data collected during testing. These new data are reduced to forces and moments in the proper axis system and all variables are scaled to produce quantities with engineering units. Raw and reduced data are temporarily stored in a disc file. Both reduced and raw data can be transferred to magentic tape and maintained as a permanent record.

Reduced data points can be listed, plotted and curves can be fitted to the points. All of the standard Calspan plots can be generated from DAP test data.

Data lists and plots are displayed on the screen of a CRT console. Hard copies of this information can be made off this display.

Continuous Sampling Program (CSP) Control

The continuous sampling program (CSP) is a software system which controls machine operation and continuously logs data during tests. Test variables can be constant or changed at rapid rates. One or all variables can be changed during a test. Data can be sampled at rates up to 100 samples per second. Pauses are used so that data can be logged during desired intervals of the test.

CSP testing can be conducted quickly which in turn reduces tire wear during severe tests. The high rate of data sampling also permits limited dynamic measurements to be made.

Two-parameter plots of data can be made. Carpet and family plots of test data cannot be made with this program at the present time. CSP data will also reflect time effects if tire characteristics are a function of the rate of change of testing variables.

Data reduction is accomplished in a manner similar to that employed in DAP testing.

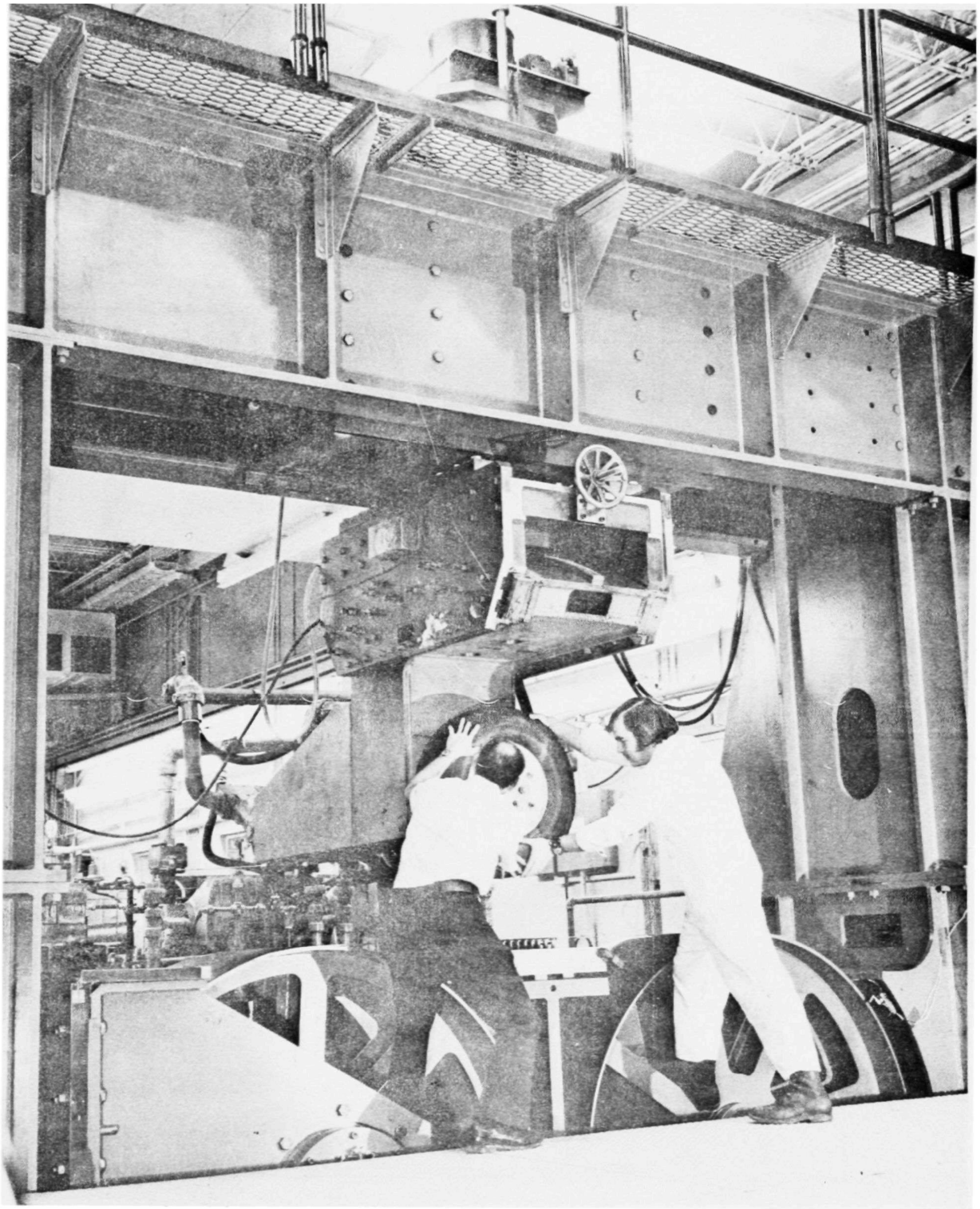

Figure E-1 CALSPAN TIRE RESEARCH FACILITY (TIRF)

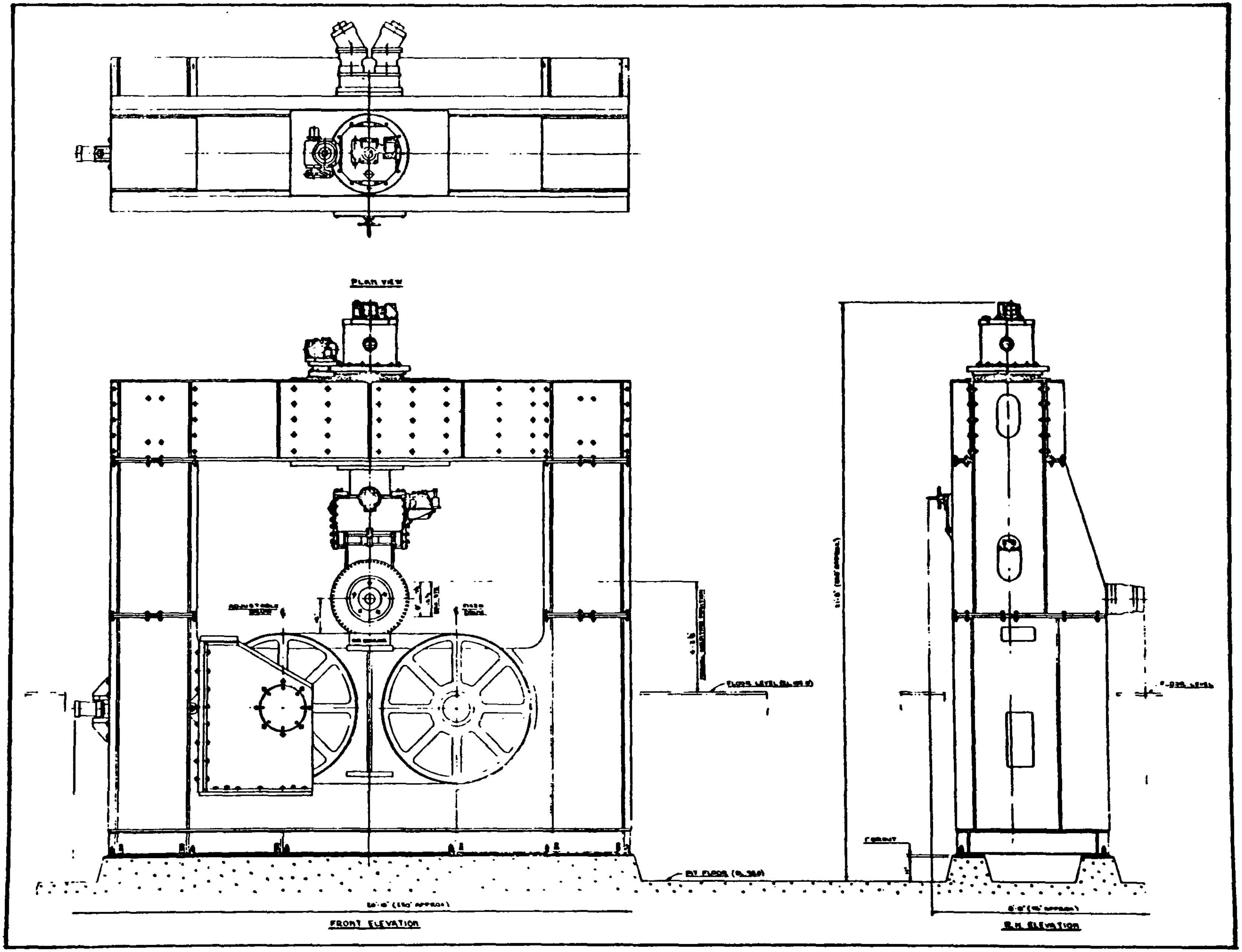

Figure E-2 TIRE RESEARCH MACHINE

TABLE E-1

TIRF CAPABILITIES

CHARACTERISTIC	RANGE
TIRE SLIP ANGLE (α)	$\pm 30^{o}$**
TIRE INCLINATION ANGLE (γ)	$\pm 30^{o}$***
TIRE SLIP ANGLE RATE (α)	10^{o}/sec
TIRE INCLINATION ANGLE RATE (γ)	7^{o}/sec
TIRE LOAD RATE (TYPICAL)	2000 lb/sec
TIRE VERTICAL POSITIONING RATE	2"/sec
ROAD SPEED (V)	0-200 mph
TIRE OUTSIDE DIAMETER	Up to 46"
TIRE TREAD WIDTH	24" MAX.
BELT WIDTH	28"

TABLE E-2

BALANCE SYSTEM CAPABILITY

COMPONENT	PASSENGER CAR TIRE BALANCE	TRUCK TIRE BALANCE
TIRE LOAD	4,000 lb	12,000 lb
TIRE TRACTIVE FORCE	±4,000 lb	±9,000 lb
TIRE SIDE FORCE	±4,000 lb	±8,000 lb
TIRE SELF ALIGNING TORQUE	±500 lb ft	±1,000 lb ft
TIRE OVERTURNING MOMENT	±1,000 lb ft	±2,000 lb ft
TIRE ROLLING RESISTANCE MOMENT	±200 lb ft	±400 lb ft

** Can be increased to 90^{o} with special setup.
*** Can be increased to 60^{o} with special setup.