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COLLEGE OF ENGINEERING
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Final Report

THE FLEXIBLE ENGINE

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ABSTRACT

The report covers an analysis of an engine and transmission system in which the latter is capable of adjusting the ratio between vehicle and engine speed in such a manner that the fuel flow is always at the minimum possible quantity for the ground horsepower requirements of the vehicle at that time.

No new engine concepts are involved except that a wider usable speed range of the engine is required, the extension of range being necessary at the low-speed end of the scale but not at the top-speed end.

The results of this analysis indicate that a 50% reduction in fuel flow is possible (alternatively, a corresponding increase in range of operation), if the required conditions can be fulfilled over the typical 48-hour Battlefield Day examined. This Battlefield Day involved operation at all vehicle speeds from 0-70 mph over all types of terrain. The above gain in economy applied equally to both spark-ignition and compression-ignition engines systems.

The main penalty to be paid for this improved economy is reduced acceleration. However, a suitable gear set could be made available that would give the present acceleration and still achieve a 40-45% improvement in fuel economy for the conditions examined.

I. OBJECT

The object of this investigation is to examine the widely varying conditions under which the internal combustion engine in a vehicle has to function, with a view to achieving maximum economy at all times under all conditions of vehicle performance.

II. INTRODUCTION

The best overall combination of engine and transmission required to achieve this objective will be termed "flexible" since, to secure the desired results, it will be found that engine operation must occur over a much wider combination of speed and load range than that normally employed when coupled to existing types of transmission. To achieve the desired maximum in performance and economy, the transmission itself must also be capable of a wider range of operating conditions than is normally demanded. It must be admitted that neither the engine or transmission exists today that will completely achieve the desired results under all conditions of vehicle operation.

This investigation is an examination of the conditions that would have to be met if such an economical system is to be obtained. When these necessary conditions are known, it will then be possible to see what can be done, if anything, to combine them into a practical working mechanism.

III. DEFINITIONS

In order to have a common basis for study of the operation, the following definitions set forth what is to be understood as a flexible system.

A. ENGINE

The engine, be it of the spark-ignition or compression-ignition type, is assumed to be sufficiently flexible as regards speed of rotation, power output, etc., that it can at all times perform satisfactorily at its point of maximum fuel economy for the road conditions being imposed.

B. TRANSMISSION

The attached transmission will be of such a type that it will, if necessary, be infinitely variable; that is, capable of accommodating any combination of vehicle and engine speed as necessary to achieve maximum fuel economy at all times.

It is true that neither of these conditions represents practical available mechanisms at the present time. The results to be obtained will indicate, however, whether such a combination is of any value, if it could be achieved. Some idea of what is to be gained will then be available on which to base a judgment as to the value of achieving even part of the objective.

In what follows it will therefore be assumed that any combination of engine power and speed is a possibility at any vehicle condition, permitting a comparison to be made with operation under present engine and transmission combinations.

IV. GENERAL

The Army Tank-Automotive Center has great interest in both spark-ignition and compression ignition engines. The former is, in general, employed in engines of the lower horsepower ranges, while the latter is in the heavy vehicles involving 200 hp and up.

The M-151, 1/4 ton 4x4 Utility Truck (the modern jeep) represents one of the smaller vehicles employed in large numbers. It is of recent design and thus represents one vehicle type consuming relatively large quantities of gasoline in total. This unit is to be employed as a typical example of the spark-ignition engine for this investigation. Fairly complete data on both vehicle and engine performance, in its presently designed condition, are available on which to base the comparison.

The compression-ignition engine selected for the study was a General Motors 6-71 E Diesel engine of 200 hp net (approximately 2000 rpm) fitted to a hypothetical medium truck of 5-ton gross vehicle weight. This vehicle was employed since reasonably reliable data could be predicted for its road resistance etc., plus the fact that some engine performance data at various speeds and loads were also available.

These two examples do not give anywhere near a complete coverage of the whole subject, but it is believed the results will indicate if there is any necessity to continue the analysis beyond this first analysis point.

V. M-151 MODEL 1/4 TON 4x4 UTILITY TRUCK

As mentioned earlier, this unit represents a typical small vehicle fitted with a spark-ignition gasoline engine. All the data employed for this so-called standard or conventional system were obtained from material supplied by the Army Tank-Automotive Center on the standard "Transport Vehicle Engineering Data Sheets" plus engine performance test data recorded by the manufacturer on endurance runs.

The engine performance curves are represented in Fig. 1, the full-load data; Fig. 2, full-load data after 52-1/2 hours of endurance running; and Fig. 3, the part-load performance of the engine. The rolling resistance of the vehicle on pavement at 2350 lb weight is recorded in Fig. 4; an effective rolling radius of 14.2 in. was employed.

Utilizing the above data, Fig. 5 was first produced showing the vehicle resistance for off-the-road conditions for soils giving 1.5, 2.0, and 3.0 times pavement rolling resistance.

The engine data at various percentage loads were then plotted on a base of rpm as in Fig. 6, from which a reasonable prediction of performance at speeds below 1000 rpm could be obtained. This was followed by Fig. 7 showing the percentage of BHP from Fig. 3 at each speed and the fuel flow in lb/hr. These curves were extrapolated to zero BHP to obtain the idle fuel flow. With the aid of the frictional horsepower from Fig. 1, these results were converted to, and then plotted on, an IHP basis as a check of the extrapolations. A satisfactory agreement was shown.

To obtain a further correction on the fuel flows, these corrected data were replotted as in Fig. 8, showing fuel flow in lb/hr on a base of rpm for the various percentage loads. In this diagram the idle values from Fig. 7 were included to again mean out the extrapolation. This diagram then permitted the addition to Fig. 7 of the 500 rpm fuel flow line shown there.

It is now possible to plot Fig. 9, showing fuel flow versus BHP at various speeds. By the use of these diagrams the combined vehicle performance can be obtained for all engine operating conditions.

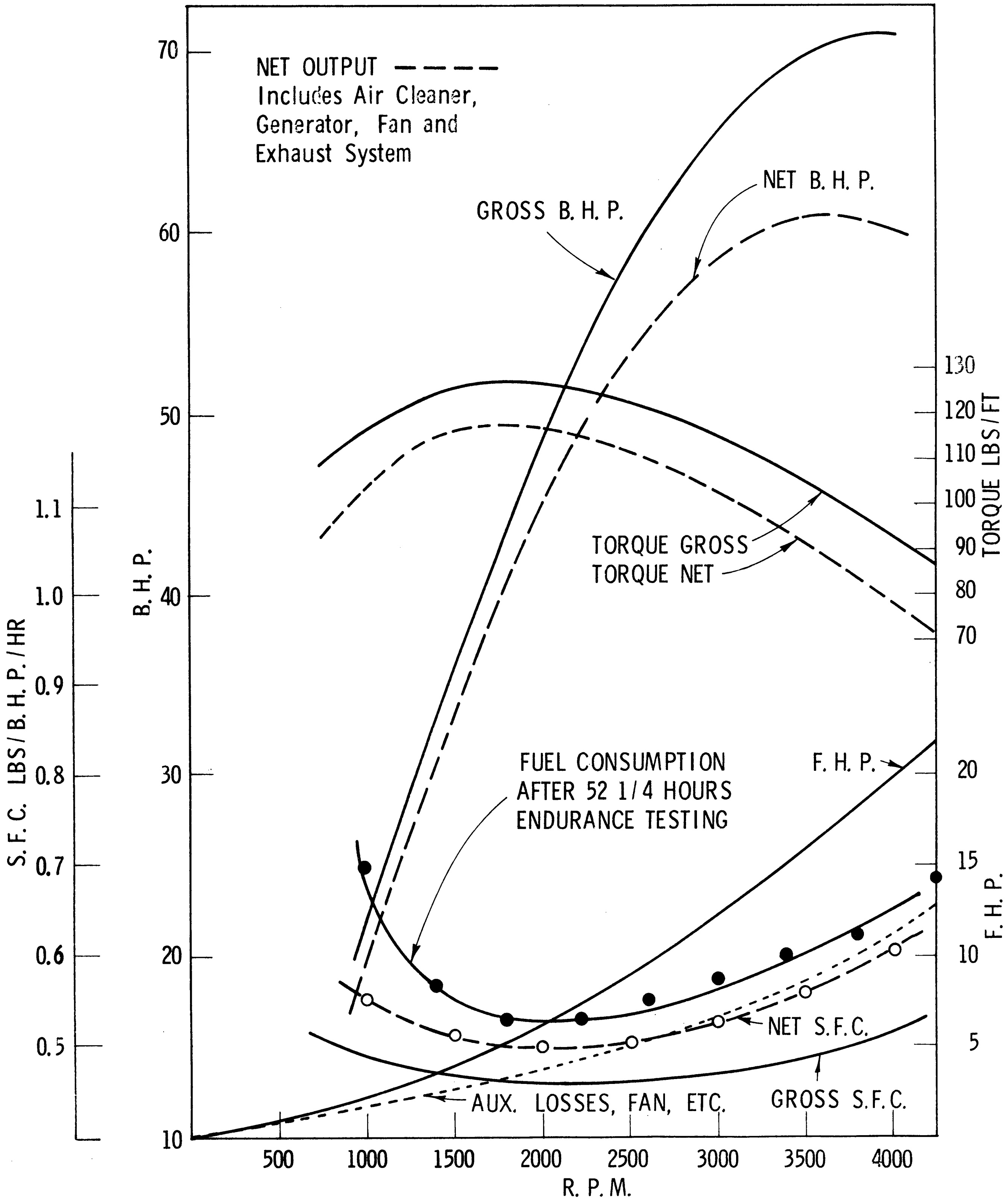

Fig. 1. M-151 engine performance test results at full load.

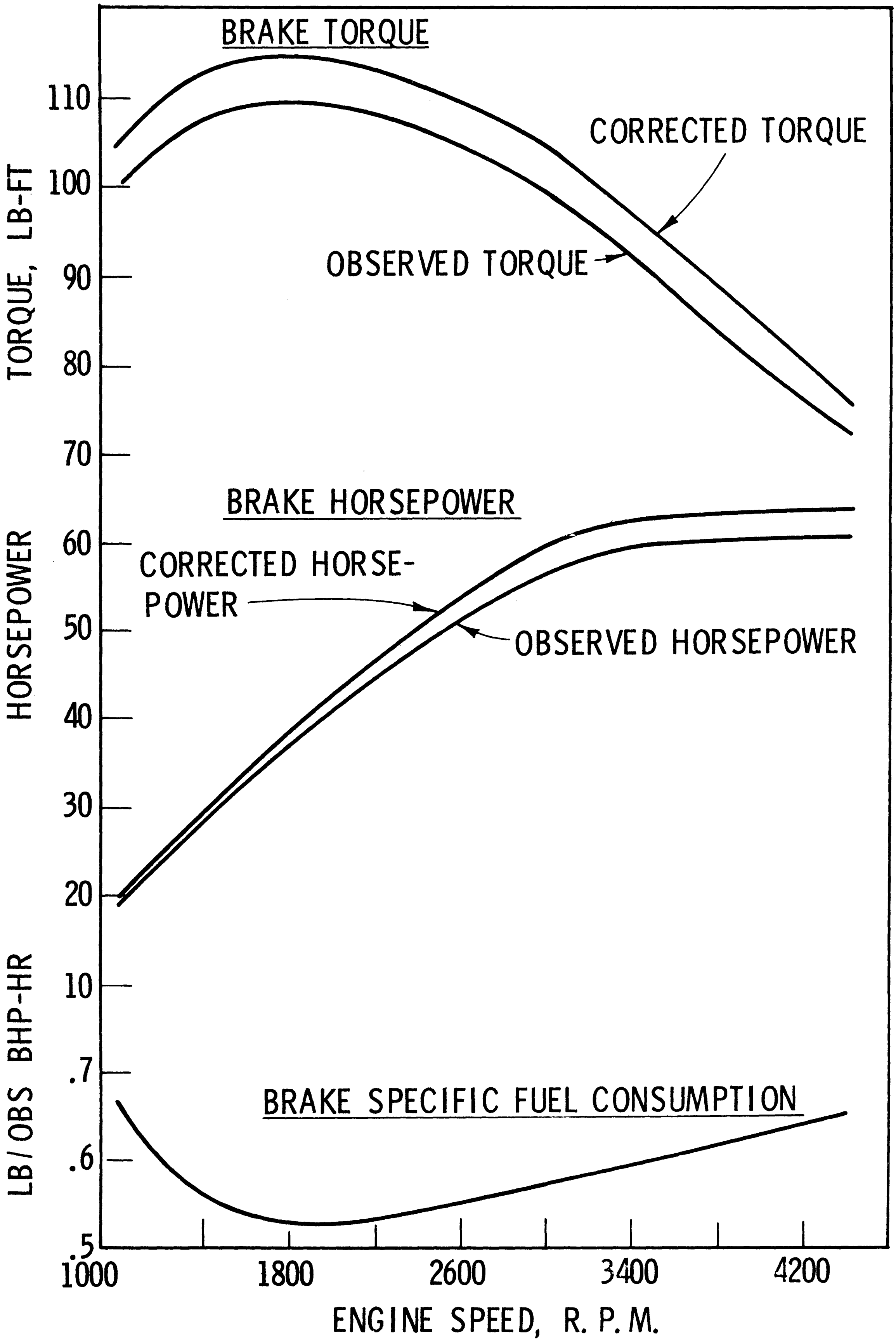

Fig. 2. M-151 engine performance after 52-1/2 hours of endurance testing.

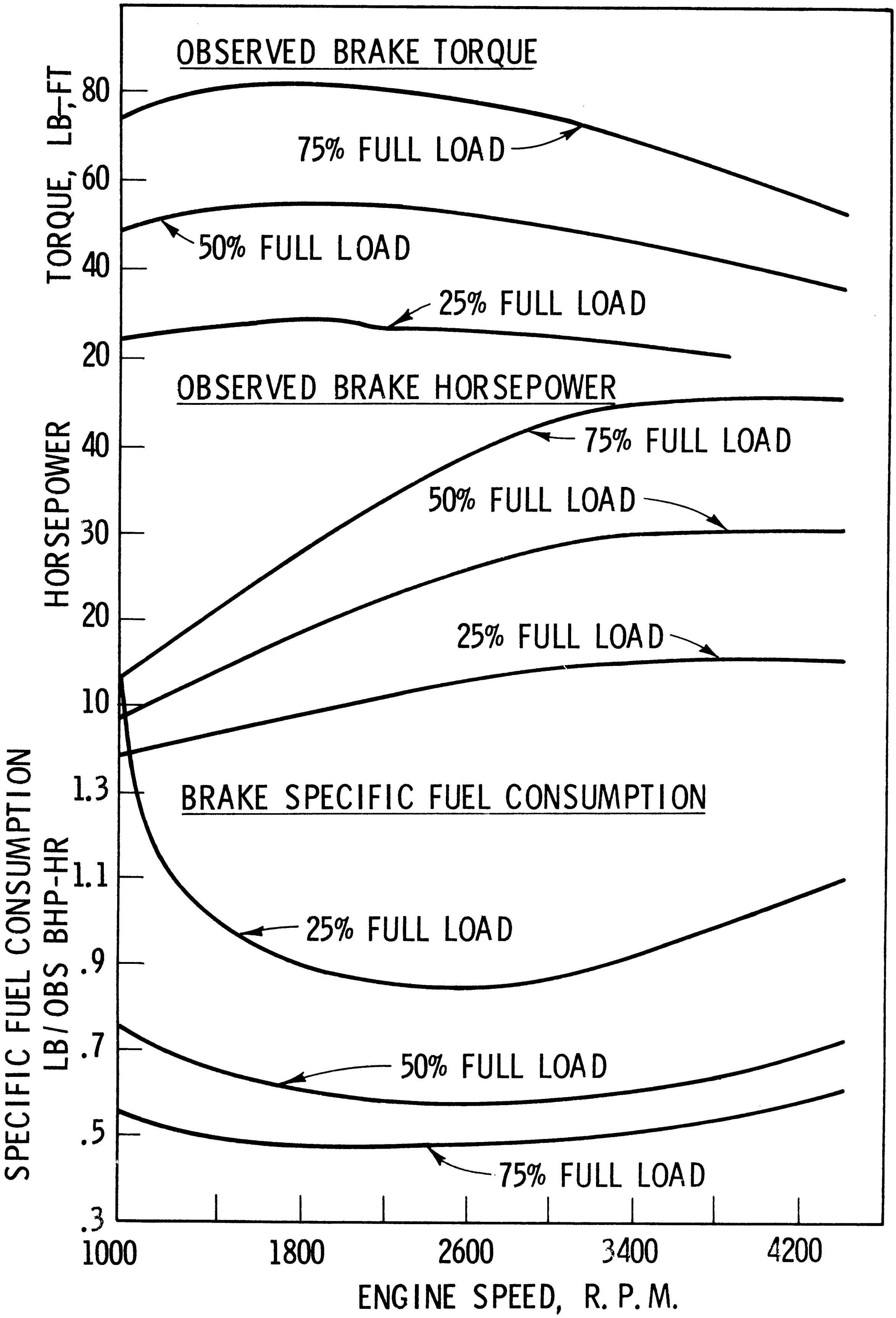

Fig. 3. M-151 engine performance test results at part load.

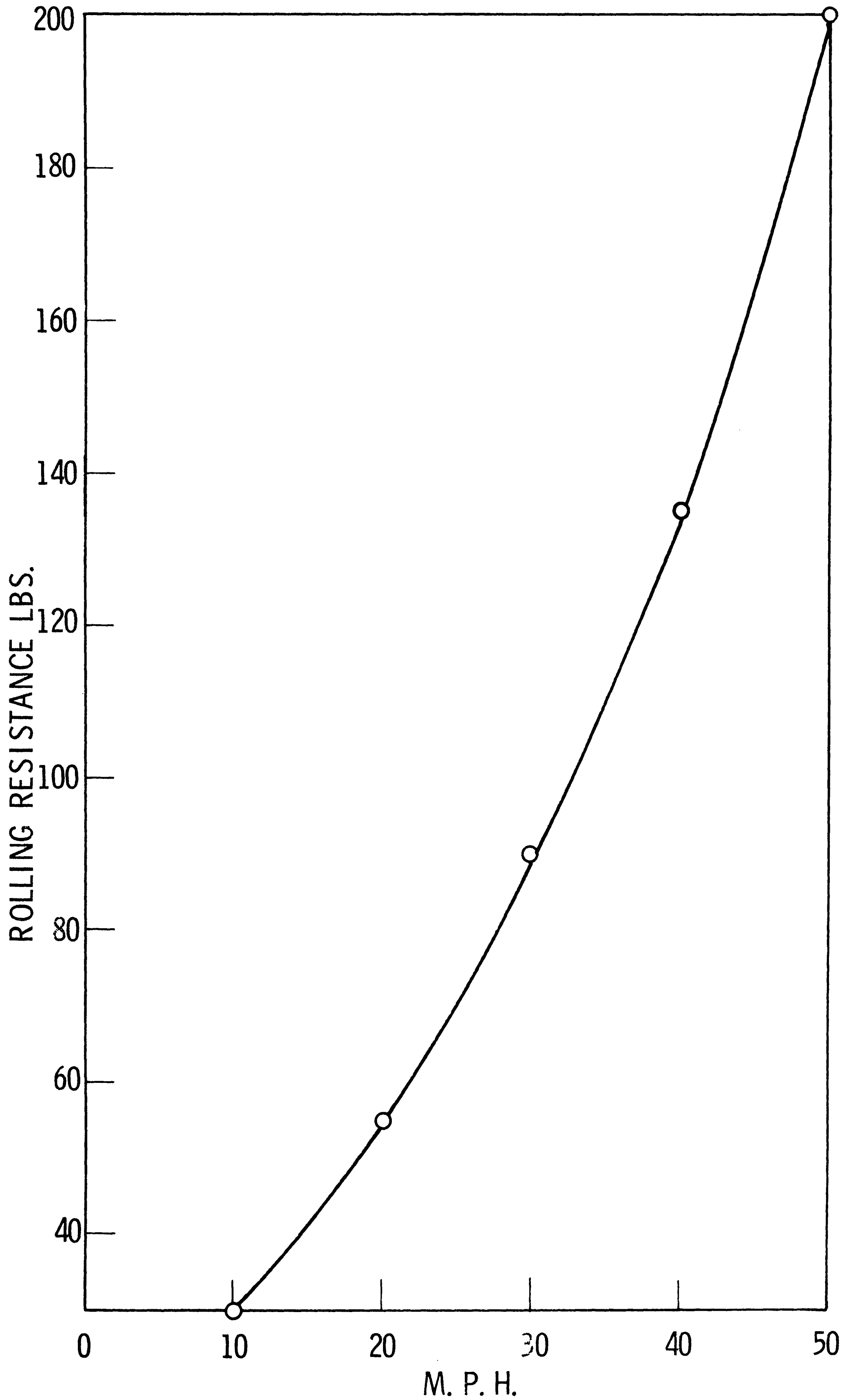

Fig. 4. M-151 vehicle rolling resistance on pavement.

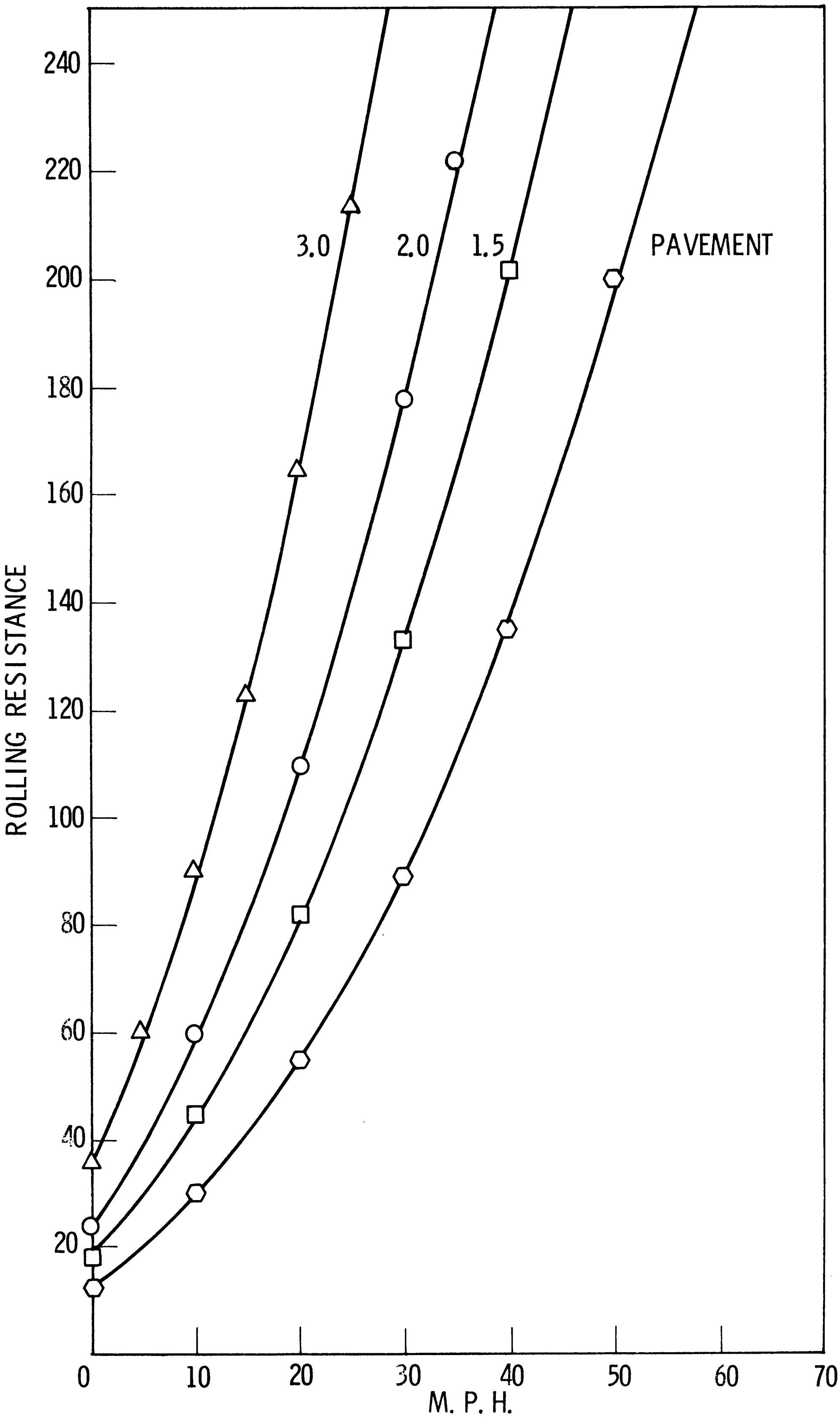

Fig. 5. Rolling resistance for various types of soils.

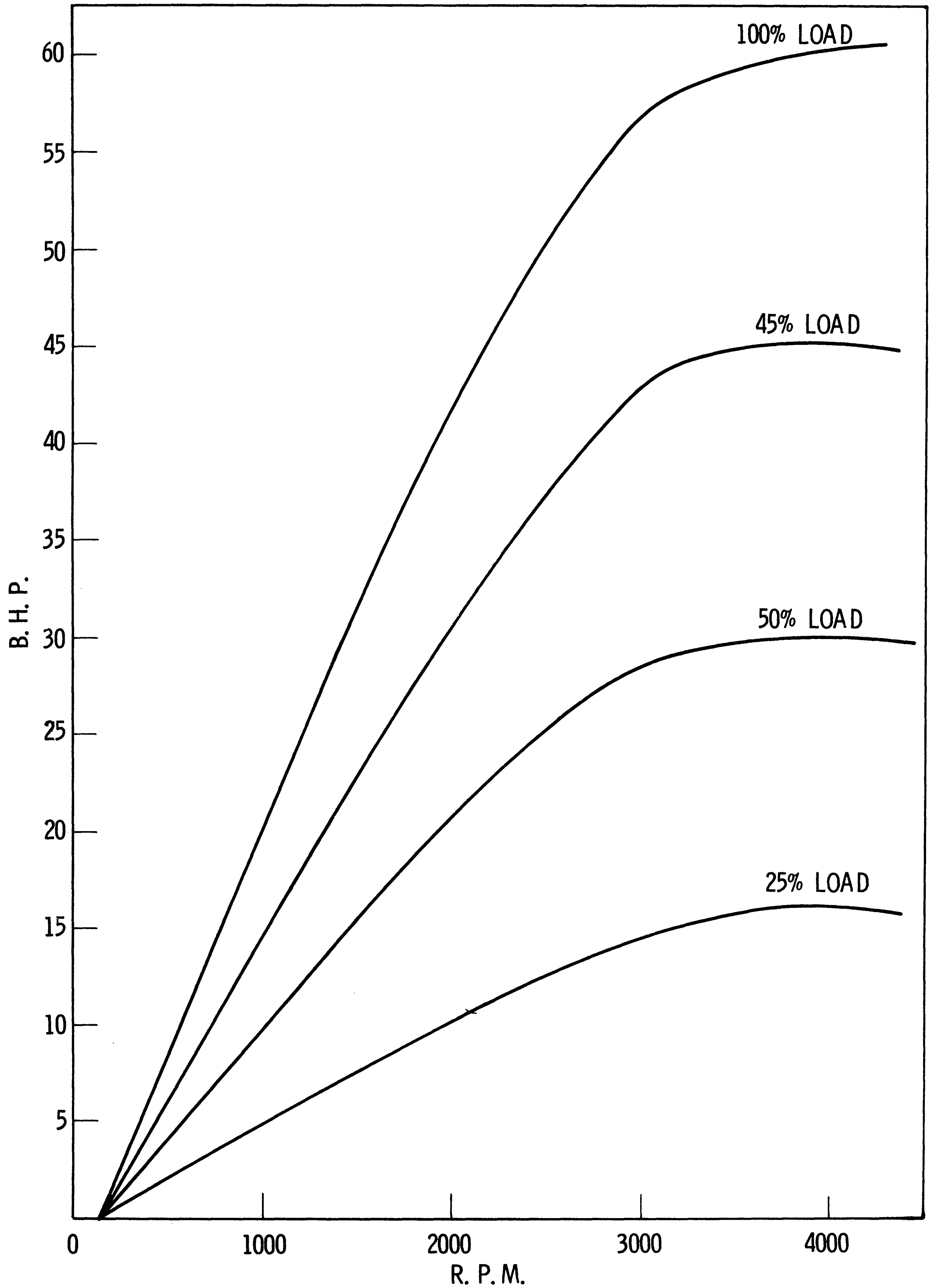

Fig. 6. Brake horsepower vs. revolutions per minute relationship for engine.

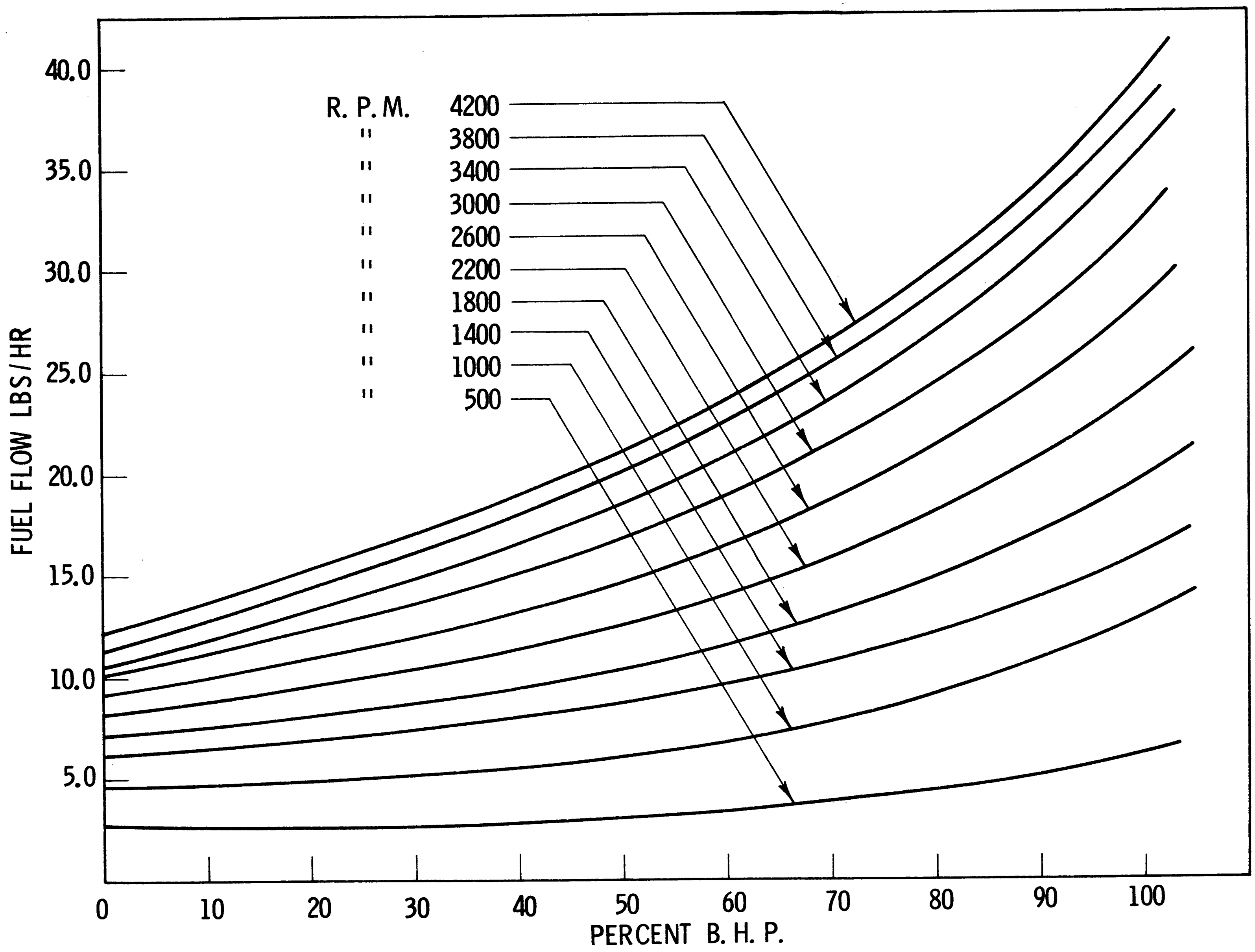

Fig. 7. Percent load vs. fuel flow relation.

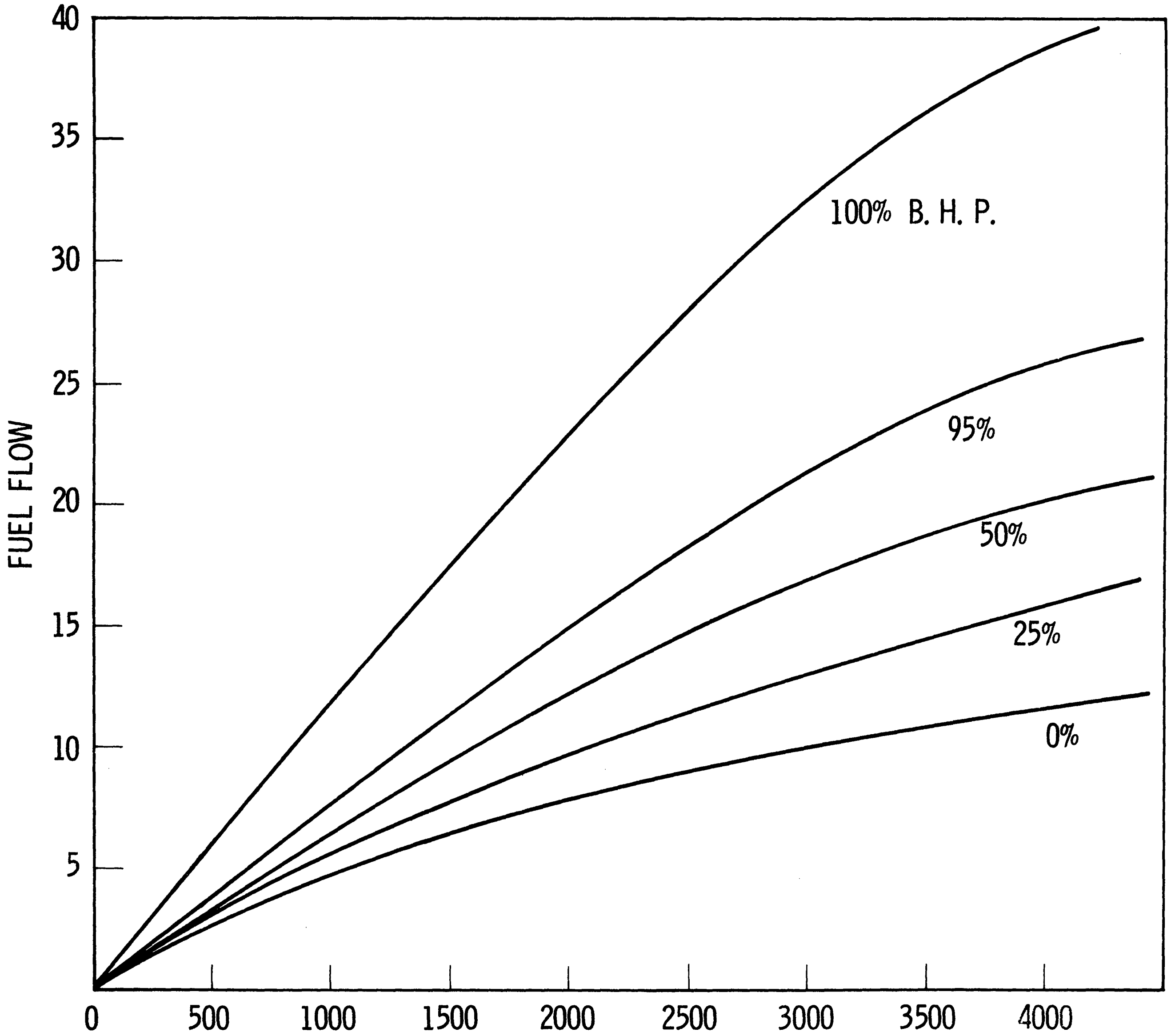

Fig. 8. Fuel flow vs. revolutions per minute at various percent loads.

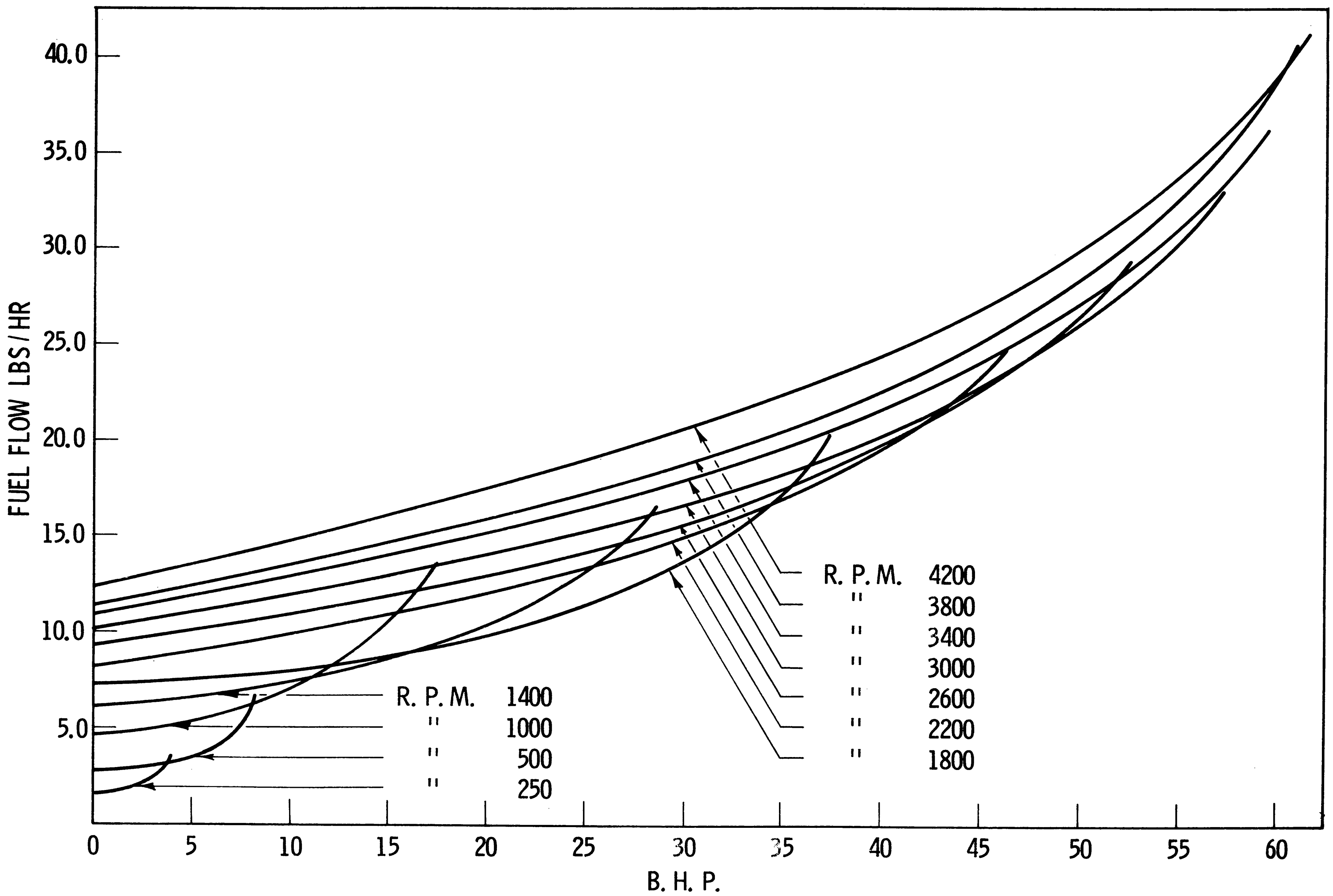

Fig. 9. Fuel flow vs. brake horsepower at different revolutions per minute.

VI. STANDARD VEHICLE SYSTEM PERFORMANCE

It is proposed to determine first the operating conditions, fuel consumption, etc., of the M-151 as at present constituted. This has a four-cylinder liquid-cooled OHV engine of 3.875 in. diam by 3.0 in. stroke developing 61 BHP net approx. at 3600 rpm, fitting to a Selective-Synchro-Mesh transmission with four forward speeds and one reverse with ratios as follows: 1st—5.712:1; 2nd—3.179:1; 3rd—1.674:1; 4th—1.0:1.0; Rev.—7.497:1.

The rear axle had a gear ratio of 4.86:1, giving overall drive ratios, indicated by the symbol DR_O, as follows: 1st—27.72:1; 2nd—15.44:1; 3rd—8.12:1; 4th--4.86:1; Rev.—36.4:1.

With the aid of the appropriate diagrams, the data of Tables I-III can be calculated.

The above ground-resistance data provide the material for the calculation of the horsepower to be applied at the wheels, as is shown in Table II. If a ground slip of 5% is assumed, then Table III gives the horsepower to be supplied to the wheels by the transmission.

The horsepowers of Table III remain constant for each of the vehicle speeds and ground resistances irrespective of transmission and engine characteristics, but this power can be supplied to the wheels in a variety of ways, depending upon the gear ratio employed.

TABLE I

VEHICLE RESISTANCE IN POUNDS FOR VARIOUS SURFACES

mph	Pavement Resistance, lb			
	x 1.0	x 1.5	x 2.0	x 3.0
0	12.0	18.0	24.0	36.0
10	30.0	45.0	60.0	90.0
20	55.0	82.5	110.0	165.0
30	89.0	133.5	178.0	267.0
40	135.0	202.5	270.0	405.0
50	200.0	300.0	400.0	600.0
60	265.0	397.5	530.0	795.0
70	340.0	510.0	680.0	1020.0

TABLE II

GROUND HORSEPOWER REQUIREMENTS

mph	Ground Horsepower at Pavement Resistances			
	1.0	1.5	2.0	3.0
0	0	0	0	0
10	0.8	1.2	1.6	2.4
20	2.93	4.39	5.76	8.79
30	7.11	10.66	14.22	21.35
40	14.4	21.6	28.8	43.2
50	26.7	40.1	53.4	80.1
60	42.4	63.6	84.8	127.2
70	63.4	95.2	126.8	190.0

TABLE III

GROUND HORSEPOWER REQUIRED WITH FIVE PERCENT SLIP

mph	Horsepower to be Supplied to Wheels, 5% Slip			
	1.0	1.5	2.0	3.0
0	0	0	0	0
10	0.84	1.26	1.68	2.51
20	3.08	4.61	6.05	9.24
30	7.47	11.2	14.95	22.4
40	15.13	22.7	30.5	45.4
50	28.02	42.1	56.1	84.2
60	44.5	66.8	89.0	133.6
70	66.6	100.0	133.2	199.5

Due to the varying number of tooth contacts in the different gear trains, the efficiency of transmission, from the engine to the wheels, will vary. In order to arrive at the required engine horsepower, these efficiencies must be known or assumed. The values given below for transmission and rear axle respectively were employed in these calculations.

<u>Transmission Efficiency</u>

1st gear	2nd gear	3rd gear	4th gear	Rear axle
92%	94%	96%	98%	95%

Overall Transmission Efficiency

Gear	1st	2nd	3rd	4th
η_o%	87.3	89.3	91.2	93.1

By employing the above values, the data of Table III can be transposed into engine horsepower in the different gear ratios. These data are shown in Table IV.

The corresponding rpm of the engine, with an effective rolling radius of 14.2 in. together with a 5% slip, is given by Eq. (1).

$$\text{rpm of engine} = \frac{\text{mph} \times 12 \times DR_o \times 5280}{\pi D \times 60 \times 0.95}$$

$$= 12.46 \times DR_o \times \text{mph} \qquad (1)$$

where

DR_o = overall drive ratio from engine to rear wheels.

It is thus possible to obtain the engine speed for each road speed when using the different gear ratios as shown by Table V.

The horspower, engine speed, fuel flow/hr, vehicle speed in mph, and road resistance can now be plotted on one diagram as in Fig. 10, where in the left hand portion of the plot is shown a construction for engine rpm with 5% slip against vehicle speed in mph for any overall drive ratios from 2 to 35:1. Those ratios of particular interest, i.e., 1st, 2nd, 3rd, and 4th gears, are shown by the heavy lines drawn on the chart.

To obtain a line for any other gear ratio, join the origin to the point corresponding to that ratio plotted on the left-hand vertical axis and along the 60.0 BHP line at the top of the chart. In this same plot are given the engine horsepower curves for the relative resistances of 1.0 to 3.0 times pavement resistance when the vehicle is in 1st gear, which has the assumed overall efficiency of 87.3%. Thus the relationship between road speed, engine speed, and engine horsepower is available for all gear ratios at an efficiency of 87.3%.

In order to obtain the fuel flow at the different overall efficiencies corresponding to the other gears, the righ-hand portion of the graph contains four diagonal lines of relative efficiencies of 87.3, 89.3, 91.2, and 93.1%, representing the four gears. In the right-hand quadrant, fuel flow is

TABLE IV

BRAKE HORSEPOWER REQUIRED IN THE DIFFERENT GEARS

mph	Engine Horsepower at Pavement Resistances				mph	Engine Horsepower at Pavement Resistances			
	1.0	1.5	2.0	3.0		1.0	1.5	2.0	3.0
		First Gear					Third Gear		
0	0	0	0	0	0	0	0	0	0
10	0.96	1.44	1.93	2.87	10	0.92	1.38	1.84	2.75
20	3.53	5.28	6.93	10.58	20	3.38	5.05	6.64	10.14
30	8.56	12.84	17.12	25.7	30	8.19	12.28	16.4	24.6
40	17.3	26.0	34.9	52.0	40	16.58	24.9	33.4	49.8
50	32.1	48.2	64.2	96.4	50	30.7	46.2	61.5	92.4
60	51.0	76.5	102.0	153.0	60	48.8	73.2	97.6	146.5
70	76.2	114.5	152.5	228.5	70	73.0	109.6	141.0	219.0
		Second Gear					Fourth Gear		
0	0	0	0	0	0	0	0	0	0
10	0.94	1.41	1.88	2.81	10	0.90	1.35	1.81	2.70
20	3.45	5.16	6.77	10.35	20	3.31	4.95	6.5	9.9
30	8.36	12.53	16.75	25.1	30	8.02	12.02	16.1	24.1
40	16.94	25.4	34.1	50.8	40	16.25	24.4	32.7	48.7
50	31.4	47.1	62.8	94.3	50	30.1	45.2	60.2	90.4
60	49.8	74.8	99.6	149.5	60	47.8	71.9	95.6	143.5
70	74.5	112.0	149.0	223.2	70	71.5	107.5	143.0	214.0

TABLE V

ROAD AND ENGINE SPEEDS IN THE DIFFERENT GEARS

mph	Engine Speeds in the Different Gears			
	1st	2nd	3rd	4th
0	0	0	0	0
5	1726	961	507	303
10	3455	1921	1014	605
15	5180	2880	1520	908
20	--	3840	2028	1211
30	--	5760	3040	1817
40	--	--	4060	2422
50	--	--	5070	3025
60	--	--	--	3630
70	--	--	--	4240

plotted along the horizontal axis against the BHP for various constant engine speeds from 250 to 4200 rpm.

The use of the chart can be illustrated by an example of two:

(1) At a vehicle speed of 45 mph in 4th gear on pavement what hp, engine speed, and fuel flow occur?

Follow the vertical line at 45 mph to its intersection with the pavement hp curve at "A" and read the hp in 1st gear on the vertical axis at "B," result 24 hp; proceed to the right to the intersection with 1st gear efficiency line of 87.3% at "C" then vertically downward to the 4th gear efficiency line of 93.1% at "D" and read power required on axis at "E," viz. 22.4 hp. Now proceed vertically from "A" to "G," the intersection with the 4th gear ratio line of 4.86:1, and read engine speed at 2730 rpm. Finally move horizontally from "D" to "F" at constant hp until the intersection with the fuel line at a speed of 2730 rpm is made and read the fuel flow from the horizontal scale at 14.2 lb/hr. Results: rpm = 2730; BHP = 22.4; fuel flow = 14.2 lb/hr.

(2) For the same vehicle speed and using 3rd gear, obtain the performance on ground having three times the resistance of pavement.

Start as before and obtain the intersection "H" with the load curve of 3 times pavement and find the horsepower of 48.5 in 1st gear, correct as before for efficiency of 3rd gear as shown by dotted lines and read 46.2 as the required horsepower.

The intersection "J" with the 3rd gear ratio line of 8.12:1 in the left-hand plot gives the engine speed of 4560 rpm. Projecting the horsepower of 46.2 to the fuel line for a speed of 4560 rpm gives an estimated fuel flow of 28.8 lb/hr. Results: rpm = 4560; hp = 46.2; fuel flow = 28.8 lb/hr.

It will be observed that in this last example the diagram says that the results are outside the present rating of the engine since the speed is high and this final point "K" is not inside the fuel flow map. Thus the performance given here is an estimated one.

Proceeding in the above manner, the engine performance lines for 1st, 2nd, 3rd, and 4th gears have been determined for operation on hard pavement and are drawn in on the fuel flow map of Fig. 10.

Repeating this process for all four gear ratios at the four road resistances employed produced the data of Table VI and Fig. 11.

TABLE VI

STANDARD SYSTEM PERFORMANCE AT FOUR ROAD RESISTANCES

mph	First Gear			Second Gear			Third Gear			Fourth Gear		
	BHP	RPM	Fuel Flow, lb/hr	BHP	RPM	Fuel Flow, lb/hr	BHP	RPM	Fuel Flow, lb/hr	BHP	RPM	Fuel Flow, lb/hr
						(a) Pavement						
5	0.3	1710	6.9	0.25	950	4.6	0.2	500	2.6	0.2	300	1.7
10	0.8	3420	10.7	0.75	1910	7.4	0.6	1000	4.9	0.6	600	3.2
15	1.9	5170	14.6	1.8	2860	10.2	1.7	1510	6.5	1.6	900	4.5
20				3.5	3830	11.9	3.4	2020	8.3	3.2	1210	5.8
25				5.9	4790	15.2	5.7	2520	10.0	5.5	1510	7.1
30							8.5	3030	11.8	8.3	1820	8.7
35							12.0	3540	13.3	11.6	2110	10.0
40							16.6	4050	15.7	16.2	2420	12.0
45							23.0	4560	19.4	22.9	2730	14.2
50										30.0	3030	17.1
55										38.8	3330	21.6
60										48.0	3630	27.4
						(b) Secondary Roads—1.5 x Pavement						
5	0.6	1710	7.0	0.35	950	4.7	0.5	500	2.7	0.4	300	1.7
10	1.4	3420	10.9	1.5	1900	7.6	1.4	1000	5.0	1.3	600	3.3
15	3.1	5170	14.9	2.9	2860	10.3	2.8	1500	6.8	2.7	900	4.8
20				5.0	3830	12.4	4.9	2020	8.7	4.7	1210	6.2
25				8.0	4790	15.7	7.8	2530	10.4	7.5	1510	7.4
30							11.8	3030	12.4	11.6	1820	9.3
35							17.2	3540	14.4	17.2	2120	11.2
40							24.7	4050	17.7	24.0	2420	13.7
45							33.0	4560	23.2	32.2	2730	17.0
50										43.0	3030	22.2
55										56.4	3330	31.4
60										--	3630	--

TABLE VI (Concluded)

mph	First Gear			Second Gear			Third Gear			Fourth Gear		
	BHP	RPM	Fuel Flow, lb/hr	BHP	RPM	Fuel Flow, lb/hr	BHP	RPM	Fuel Flow, lb/hr	BHP	RPM	Fuel Flow, lb/hr
(c) Cross Country—2.0 x Pavement												
5	0.8	1710	7.1	0.70	950	4.8	0.7	500	2.75	0.6	300	1.8
10	2.0	3420	11.0	1.9	1900	7.7	1.9	1000	5.1	1.8	600	3.4
15	4.0	5170	15.0	3.8	2860	10.5	3.7	1500	6.9	3.5	900	5.0
20				6.8	3830	12.8	6.6	2020	8.9	6.4	1210	6.5
25				11.0	4790	16.5	10.8	2530	10.9	10.5	1510	7.9
30							16.2	3030	14.4	15.9	1820	10.3
35							23.0	3540	16.7	22.5	2120	12.5
40							33.3	4050	20.5	32.4	2420	16.4
45							46.2	4560	28.8	45.0	2730	22.5
50							--	--	--	59.6	3030	--
55							--	--	--	--	3330	--
60							--	--	--	--	3630	--
(d) Cross Country—3.0 x Pavement												
5	1.1	1710	7.2	1.2	950	4.9	1.0	500	2.8	1.0	300	1.9
10	2.9	3420	11.2	2.9	1910	7.8	2.6	1000	5.2	2.7	600	3.5
15	5.6	5170	15.9	5.6	2860	10.8	5.5	1510	7.1	5.2	900	5.2
20				9.0	3830	13.2	9.8	2020	9.4	9.6	1210	7.0
25				17.0	4790	18.3	16.5	2520	12.4	16.1	1510	9.5
30							26.0	3030	16.0	25.3	1820	13.0
35							35.5	3540	19.8	35.5	2120	17.2
40							49.0	4050	28.4	49.0	2420	--

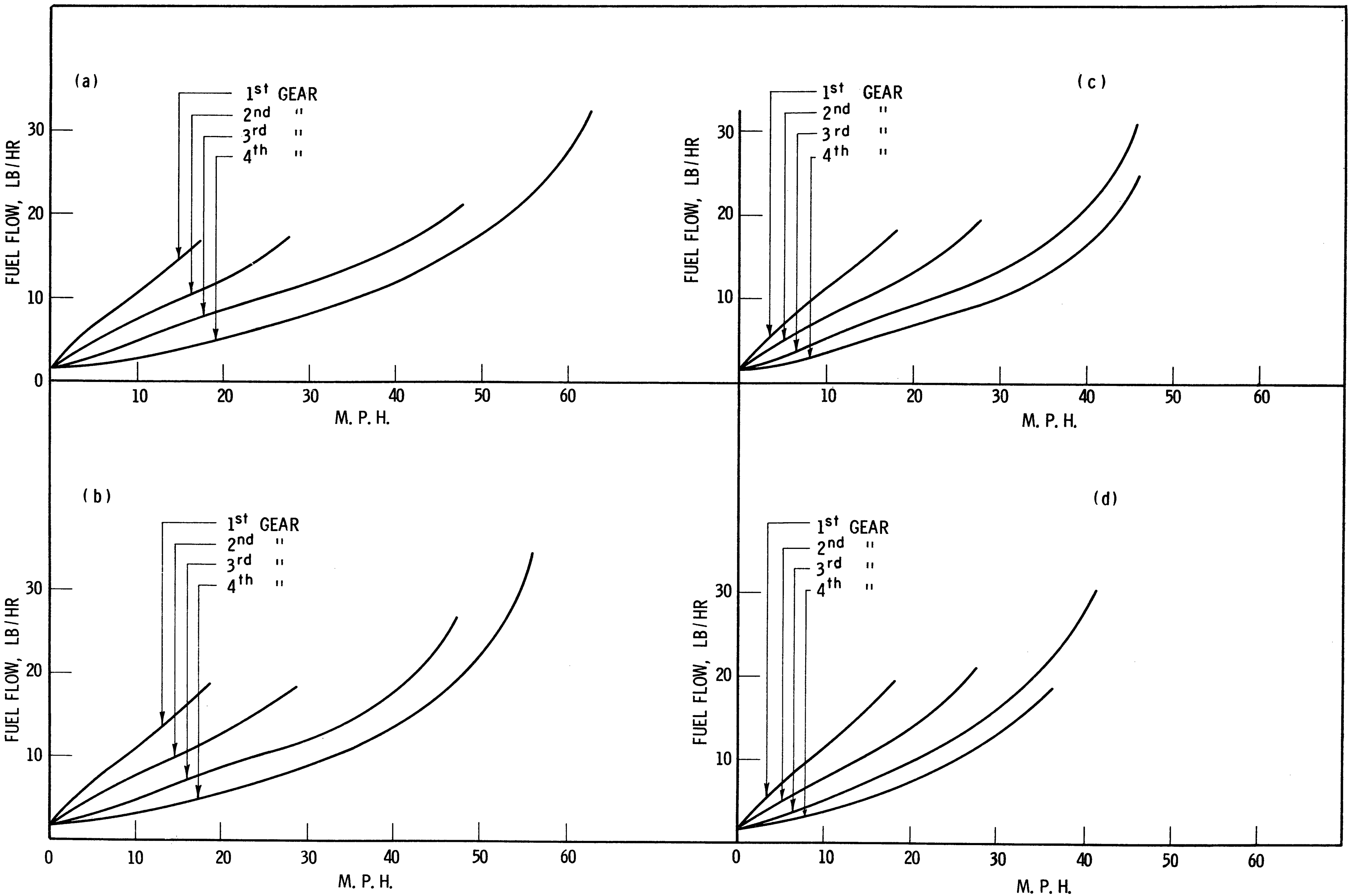

Fig. 11. Fuel flow vs. miles per hour at four road resistances.

VII. FLEXIBLE VEHICLE SYSTEM

The present problem of obtaining the absolute minimum fuel flow for any given condition can be solved simultaneously on this same diagram. The fuel map records all possible engine operating conditions; thus the required horsepower conditions of Example (1), viz. 22.4 BHP to give 45 mph on pavement, can be obtained theoretically at any point along the 22.4 hp line where it crosses any speed line of the fuel map, provided that the transmission can permit the appropriate engine speed that corresponds to the fuel flow selected. It follows that the minimum fuel flow is at that speed where the horsepower line crosses the first fuel line at the slowest speed.

The dotted line of Fig. 10 showing the envelope in the left side of the fuel map represents the minimum fuel flow over the total BHP range of the existing engine. It follows that the minimum possible fuel flow in Example (1) would be at point "L" where the engine operated at 22.4 BHP at 1400 rpm, the flow being 11.4 lb/hr in place of the 14.2 lb when in conventional 4th gear.

Proceeding in this manner, the minimum fuel flow given in Table VII can be determined irrespective of the practicability of engine operation under such conditions. The results so obtained do represent the absolute minimum fuel consumption for the particular engine and vehicle combination being considered.

The plot of minimum fuel flow, rpm, and horsepower is given in Fig. 12.

The data presented in Fig. 12 show the BHP of the engine irrespective of the gear ratio employed; it is a plot of BHP versus fuel flow and speed of the engine at minimum consumption for each power. It is only when tied in with the left-hand portion of Fig. 10 that the engine horsepower is that for 1st gear.

Figure 12 thus shows BHP, fuel flow, and revolutions of the engine under minimum economy conditions for each BHP. The points of the fuel-flow curve are seen to be relatively smooth. Near zero horsepower it was assumed that no matter what horsepower was required, the revolutions would not go below 250, hence the flat portion of the dotted rpm curve. It is also seen that at other speeds more than one horsepower can be obtained at minimum fuel flow for one given engine speed. This is due to the speed curve and enveloping minimum fuel-flow curve lying on top of one another for a range of powers at such points. The finally accepted rpm curve in Fig. 12 was the full-line outer envelope of the dotted curve of the plotted observation; this is on the conservative side since more speed and power capabilities exist along such a curve than the stepped dotted one.

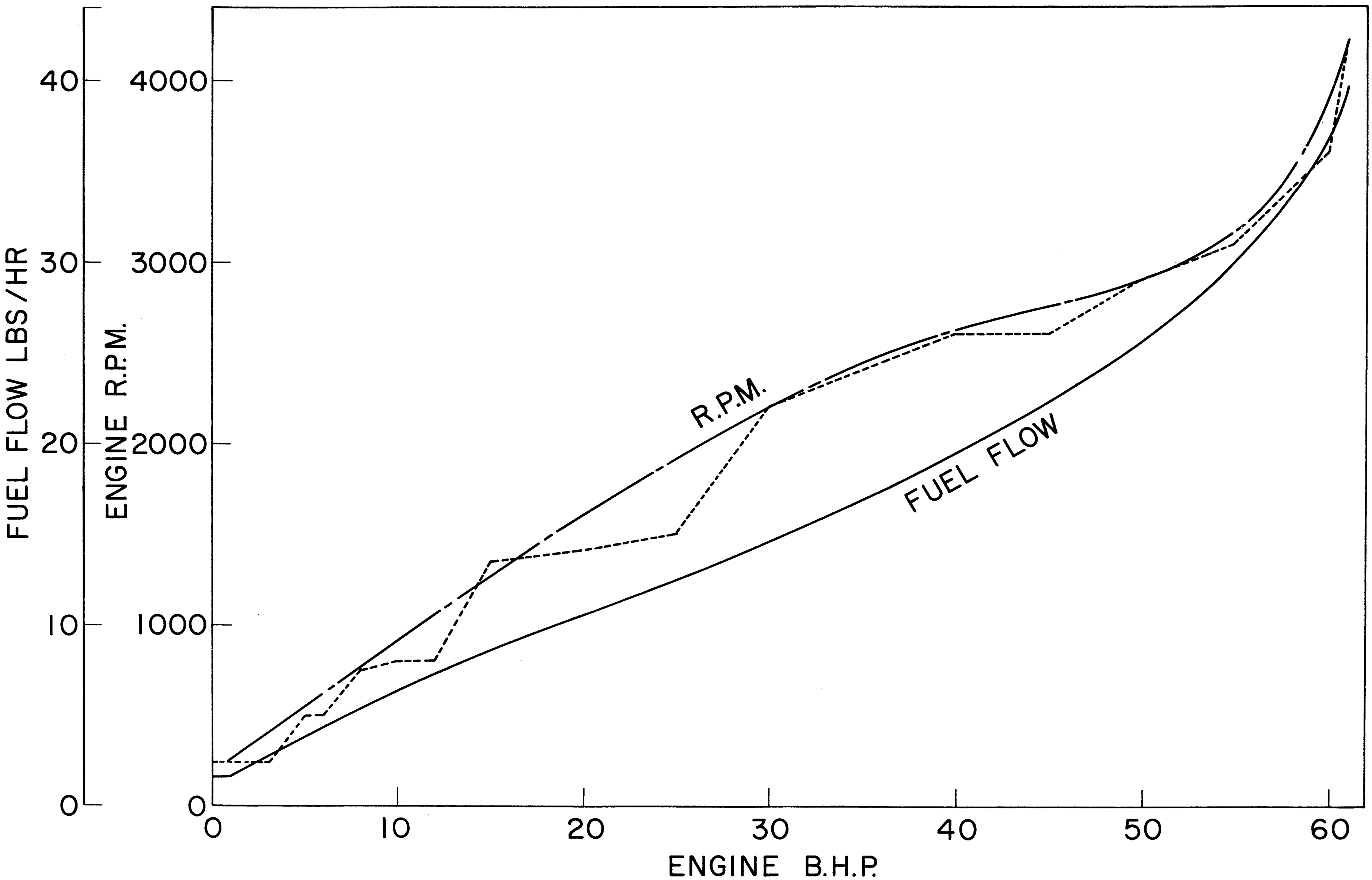

Fig. 12. Flexible engine performance.

TABLE VII

FLEXIBLE ENGINE PERFORMANCE

rpm	BHP	Fuel Flow, lb/hr
250	1.0	1.6
250	2.0	1.8
250	3.0	2.4
350	4.0	3.2
500	5.0	3.6
500	6.0	4.2
750	8.0	5.5
800	10.0	6.4
1350	15.0	8.5
1400	20.0	10.5
1500	25.0	12.5
2200	30.0	14.7
2200	35.0	16.9
2600	40.0	19.3
2600	45.0	22.2
2900	50.0	25.7
3100	55.0	30.3
3600	60.0	36.5

The curves of Fig. 12 assume that the transmission is of such an infinitely variable variety that the engine speed demanded for minimum fuel for any road speed and horsepower combination can be met at all times. This condition is necessary if the proposed scheme is to be employed. For example, 40 mph on pavement requires 17.4 hp at 87.3% transmission efficiency from the engine to provide the required traction; the transmission must then adjust itself to give an engine speed of 1440 rpm with a fuel flow of 10 lb/hr—the minimum fuel for 17.4 hp from the engine at any operating speed. This means an overall drive ratio of 2.89:1 is required with a 5% wheel slip. At the 25 mph and 6 BHP combination, a fuel flow of 4.3 lb/hr can be obtained if an engine speed of 630 rpm can be achieved resulting in an overall drive ratio of 2.05.

Assuming for the time being that such difficult conditions can be met, it is now possible to examine what gains in economy can be made. Would the development of such a transmission be justified?

VIII. COMPARISON OF STANDARD AND FLEXIBLE SYSTEMS

In order to obtain a standard of comparison between the two systems, some typical operating schedule must be employed. In evaluating this problem the following schedule of operation was employed in all cases.

A. OPERATING SCHEDULE

The 48-hour Battlefield Day is to consist of the following:

Fraction	Road Surface Operation	Vehicle Resistance
1/3	Hard Surface	Pavement Resistance Curve Provided by ATAC
1/3	Secondary Road	1.5 x Pavement Resistance Curve Provided by ATAC
1/3	Cross Country	2.0 x Pavement Resistance Curve Provided by ATAC

Speed Schedule

mph	Operating Time	
	Percent	Hour
Idle	10	4.8
0-10	21	10.08
10-20	37	17.76
20-30	21	10.08
30-40	10	4.80
50-60	1	0.48
	Total Hours	48.00

In addition to the time schedule, the question of the gear ratio to be employed is involved when establishing the performance of the standard engine and transmission. It will be assumed that the engine will be operated on the gears given in the table below at all times.

mph	Road	Gear
0-10	Pavement	2nd
0-10	Secondary	2nd
0-10	Cross Country	1st
10-20	Pavement	3rd
10-20	Secondary	3rd
10-20	Cross Country	2nd
20-60	Pavement	4th
20-60	Secondary	4th
20-30	Cross Country	3rd
30-60	Cross Country	4th

This schedule employs first gear as a starting aid only: this would be true, probably, except for steep hills.

B. STANDARD SYSTEM FUEL REQUIREMENTS

During the above-defined 48-hour Battlefield Day, the standard engine and transmission will require fuel flows as given in Table VIII (based upon the road surface) and the time schedule set out above. In this connection, the 50-60 mph group for cross country operation seems to be impossible to achieve, first because of the power requirements reaching or exceeding the limits of the engine, second because over rough ground such speeds would produce excessive bouncing, requiring all personnel and equipment to be adequately belted down. (And even then the motion could be tolerated only for short periods.) There is possibly some cross country terrain over which high speed could be achieved, but it is believed to be a rather exceptional circumstance. However, for comparative purposes, the highest possible speeds are included in the tables.

If the percentages of times on various types of roads are changed to 25% pavement, 35% secondary roads, and 40% cross country, then the fuel requirement becomes:

$$\left.\begin{array}{l}\text{Total fuel for 48-hour BFD}\\ \text{with above distribution}\\ \text{of roads}\end{array}\right\} = 372.9 \text{ lb}$$

From the data of Table VIII any desired combination of road speeds, etc., can be employed and the total fuel requirements determined for the standard vehicle.

TABLE VIII

STANDARD SYSTEM REQUIREMENTS FOR BATTLEFIELD DAY

Surface	mph	Hours	Gear	rpm	Fuel Flow	
					lb/hr	Total, lb
Hard Pavement	Idle	1.6	--	500	2.6	4.16
	0-10	3.36	2nd	500-1910	4.2	17.5
	10-20	5.92	3rd	1000-2020	6.6	39.1
	20-30	3.36	4th	1210-1820	7.3	24.5
	30-40	1.6	4th	1820-2420	10.3	16.5
	50-60	0.16	4th	3030-3630	21.3	3.4
	Total Hours = 16				Total Fuel Flow =	106.16
Secondary Roads	Idle	1.6	--	500	2.6	4.16
	0-10	3.36	2nd	500-1910	4.5	15.1
	10-20	5.92	3rd	1000-2020	6.8	40.2
	20-30	3.36	4th	1210-1820	7.6	25.5
	30-40	1.6	4th	1820-2420	11.4	18.3
	50-56	0.16	4th	3030-3400	3400	4.0
	Total Hours = 16				Total Fuel Flow =	107.26
Cross Country Roads	Idle	1.6	--	500	2.6	4.16
	0-10	3.36	1st	500-3420	6.8	23.9
	10-20	5.92	2nd	1910-3830	10.5	62.2
	20-30	3.36	3rd	2020-3030	11.2	37.6
	30-40	1.60	4th	1820-2420	12.8	20.5
	40-45	0.16	4th	2420-2730	19.7	3.2
	Total Hours = 16				Total Fuel Flow =	151.56

Total fuel for 48-hr BFD including pavement, secondary roads, and cross country with standand engine and transmission = 363.98 lb

C. FLEXIBLE SYSTEM

Figure 10 is also employed to determine the absolute minimum fuel flow for any combination of traction resistances. It should be remembered that there is now only one engine speed possible--that giving minimum fuel flow—for any given horsepower output as shown by Table VII and Fig. 12. It follows that Fig. 12 can be employed with greater ease than Fig. 10.

The engine horsepower will depend upon the efficiency of the imaginary variable-ratio transmission. Since nothing is yet known about how the variability is to be obtained, assumptions must be made. Variability instinctively indicates more complexity, and complexity generally indicates greater losses. It follows that some loss in efficiency of transmission is to be expected.

It will be assumed that this special duty gearbox will have an efficiency equal to that of the standard one when in 1st gear, viz. 87.3%. It follows that the engine horsepower requirements are those given by the left-hand portion of Fig. 10. Using this efficiency the horsepower values of Fig. 10 for any ground surface enables the engine speed, gear ratio, and fuel flow required for minimum fuel flow to be obtained, since,

$$\begin{matrix}\text{Overall gear ratio} \\ \text{(with 5\% slip)}\end{matrix} = \frac{\text{rpm (engine)}}{12.46 \times \text{mph}} \qquad (2)$$

Proceeding in this manner, Table IX is constructed. From the data of Table IX Fig. 13 has been plotted and a comparison can now be made with the results shown for the standard engine and transmission of Table VI. The results obtained from Table IX for the same schedule employed for the standard system are given in Table X.

D. COMPARISON OF FUEL REQUIREMENTS

Comparing the Battlefield Day with standard and flexible systems, the results show a fuel requirement of 364 lb for the former and 193 for the latter—almost a 2:1 reduction in favor of the flexible assembly. To obtain such a gain by other means (supercharging, compression ratio, fuel rating, etc.) is not to be thought of, due to the involvement of some difficult factors which enter such engine developments. To achieve the indicated results a new type of transmission may be required, a development of no mean undertaking, if the results aimed for were to be in complete adherence to the principles employed in the above calculations. It would be possible to sacrifice quite a percentage of the unlimited flexibility assumed, and still come up with a fuel reduction of considerable magnitude compared with that to be obtained by other means.

TABLE IX

FLEXIBLE SYSTEM PERFORMANCE AT FOUR ROAD RESISTANCES

MPH	BHP	RPM	Fuel Flow, lb/hr	Overall Drive Ratio Required	MPH	BHP	RPM	Fuel Flow, lb/hr	Overall Drive Ratio Required
				(a) Pavement					
Idle	-	250	1.6	--	20.0	3.6	450	3.1	1.805
2.0	0.1	250	1.6	10.4	25.0	6.1	640	6.1	2.05
4.0	0.2	250	1.6	5.2	30.0	9.0	840	9.0	2.25
6.0	0.4	250	1.6	3.5	35.0	12.5	1090	12.5	2.50
8.0	0.6	250	1.6	2.5	40.0	17.4	1430	17.4	2.87
10.0	0.8	250	1.6	2.01	45.0	24.0	1850	24.0	3.29
12.0	1.2	260	1.7	1.74	50.0	32.1	2300	32.1	3.69
14.0	1.7	300	2.0	1.72	55.0	41.5	2670	41.5	3.90
16.0	2.2	350	2.3	1.755	60.0	51.5	2960	51.5	3.96
18.0	2.9	400	2.7	1.782					
	(b) Secondary Roads—1.5 x Pavement					(c) Cross Country—2.0 x Pavement			
Idle	-	250	1.6	--	Idle	-	250	1.6	--
2.5	0.3	250	1.6	8.02	2.5	0.55	250	1.6	8.02
5.0	0.62	250	1.6	4.01	5.0	0.80	250	1.6	4.01
7.5	1.1	270	1.7	2.89	7.5	1.40	280	1.8	2.99
10.0	1.6	300	2.0	2.41	10.0	2.1	340	2.2	2.73
12.5	2.3	350	2.3	2.245	12.5	2.9	400	2.7	2.565
15.0	3.1	410	2.8	2.19	15.0	4.0	470	3.2	2.512
17.5	4.1	480	3.3	2.20	17.5	5.3	580	4.0	2.66
20.0	5.3	570	4.0	2.29	20.0	7.0	700	4.8	2.81
25.0	8.3	790	5.5	2.53	25.0	11.3	1000	6.9	3.2
30.0	12.5	1090	7.5	2.91	30.0	17.0	1400	9.4	3.74
35.0	18.4	1500	9.9	3.43	35.0	24.1	1860	12.1	4.26
40.0	25.8	1960	12.8	3.93	40.0	34.6	2410	16.7	4.83
45.0	34.5	2410	16.6	4.29	45.0	48.3	2840	24.4	5.06
50.0	45.9	2770	22.8	4.44					
55.0	60.1	3670	39.0	5.35					
60.0	-								

TABLE X

FLEXIBLE SYSTEM REQUIREMENTS FOR BATTLEFIELD DAY

Surface	mph	Hours	Gear Ratio	rpm	Fuel Flow lb/hr	Fuel Flow Total, lb
Hard Pavement	Idle	1.6	--	250	1.6	2.56
	0-10	3.36	2.0-10.0	250	1.6	5.37
	10-20	5.92	2.0- 1.7	250- 450	2.3	13.64
	20-30	3.36	1.8- 2.2	450- 840	4.4	14.8
	30-40	1.6	2.2- 2.9	840-1430	7.6	12.16
	50-60	0.16	3.7- 4.0	2300-2960	20.8	3.33
	Total Hours = 16				Total Fuel Flow =	51.9
Secondary Roads	Idle	1.6	--	250	1.6	2.56
	0-10	3.36	10.0-2.4	250- 300	1.7	5.72
	10-20	5.92	2.4-2.3	300- 570	2.9	17.2
	20-30	3.36	2.3-2.9	570-1090	5.7	19.2
	30-40	1.6	2.9-3.9	1090-1960	10.1	16.2
	50-55	0.16	4.4-5.4	2770-3670	30.6	4.9
	Total Hours = 16				Total Fuel Flow =	65.8
Cross Country Roads	Idle	1.6	--	250	1.6	2.56
	0-10	3.36	10.0-2.7	250- 340	1.8	5.72
	10-20	5.92	2.7-2.8	340- 700	3.4	20.2
	20-30	3.36	2.8-3.7	700-1400	7.0	23.5
	30-40	1.6	3.7-4.8	1400-2410	12.7	20.3
	40-45	0.16	4.8-5.0	2410-2830	20.6	3.3
	Total Hours = 16				Total Fuel Flow =	75.6

Total fuel for 48-hr BFD including pavement, secondary roads, and cross country with flexible engine and transmission = 193.3 lb

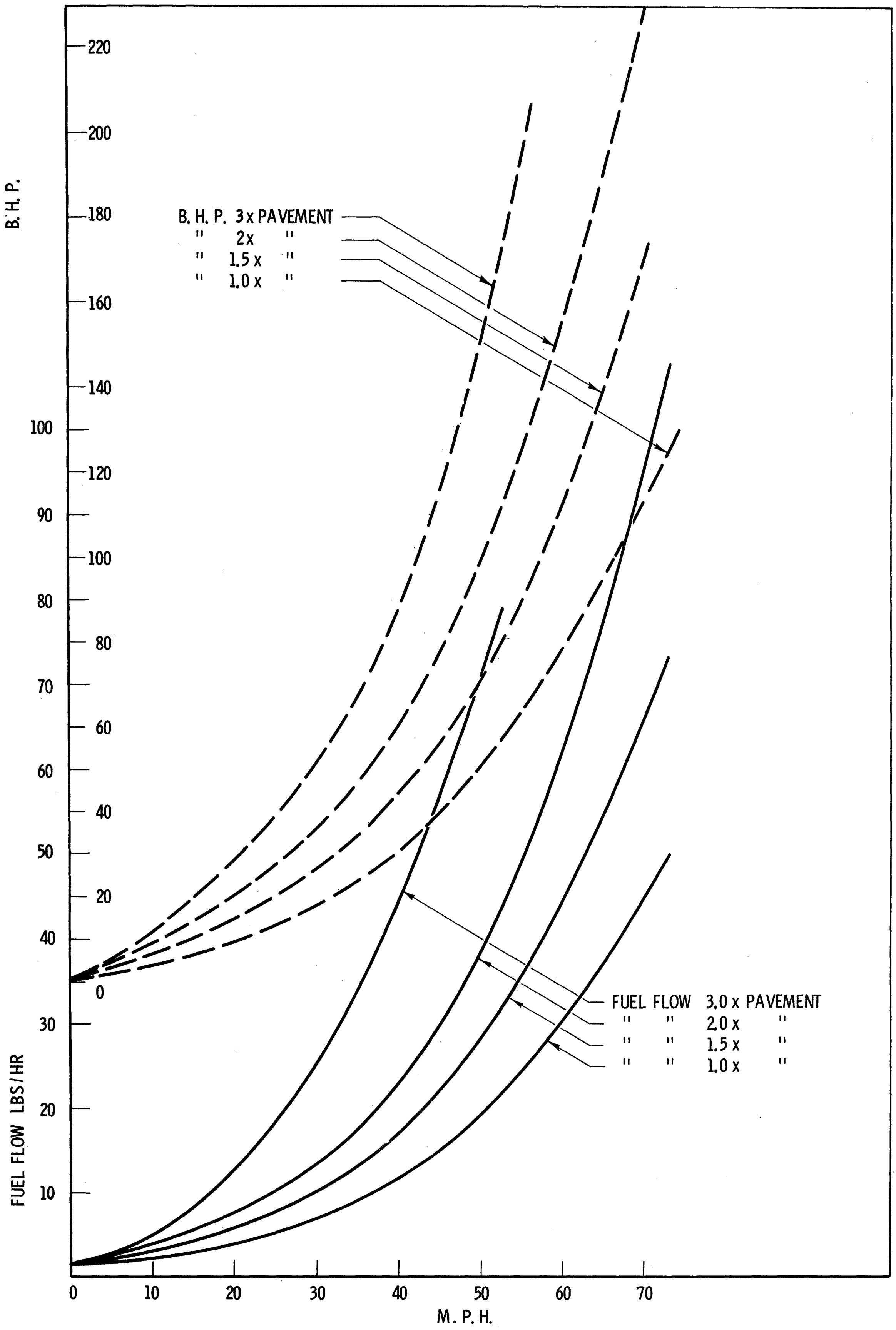

Fig. 13. Fuel flow flexible system.

In comparing these sets of results it must be kept in mind that the standard system has a higher transmission efficiency in all gear ratios, other than 1st, compared to that employed for the flexible assembly. The manner in which this affects the results can be seen when the engine load becomes great, such as 50-56 mph on secondary roads and 40-45 mph cross country. In these cases, it is seen that the fuel flow for the flexible engine exceeds that of the standard system. This is due to the BHP required for the flexible engine being some 4-5 hp greater than the standard, resulting from the reduced transmission efficiency. At these conditions the engine performance is entering the zone of fuel enrichment for maximum power, thus fuel consumption suffers a rapid increase for relatively small power increase. (This can be seen by the shape of the fuel curves from 45-60 BHP for both standard and flexible engines.)

It should also be pointed out that the 2:1 reduction of fuel is not achieved by some large gain at a particular local point. It is almost equally distributed over all speeds and types of terrain surfaces investigated in about the same proportion.

Looking at this performance comparison on a miles per gallon (mpg) basis at a constant speed of 35 mph the following data emerge:

<u>Standard Vehicle</u>

Fuel Tank Capacity = 102 lb

Assumed Usable Capacity = 90 lb

Cruising Speed = 35 mph

Fuel Flow at 35 mph = 10.3 lb/hr (on pavement)

Assume that one tenth of travel time is with engine idling at stop lights, or other causes then:

Fuel/hr of Travel = 0.9 x 10.3+0.1 x 1.6

= 9.43 lb/hr

Time to Consume 90 lb of Fuel = 90/9.43

= 9.54 hr

Time Actually Travelling at 35 mph = 0.9 x 9.54

= 8.58 hr

Distance Travelled = 35 x 8.58

= 300 miles

Fuel Mileage
(gasoline at 6.3 lb/gal) = 300 x 6.3/90.0

= 21.0 mpg

Fuel for 300 Miles = 14.30 gal

Vehicle With Flexible Power Train

The available tank capacity will be kept constant at 90 lb, as well as the cruising speed of 35 mph. Then:

Fuel Flow with Flexible Engine = 7.6 lb/hr
(on pavement)

Fuel per Hour of Travel = 0.9 x 7.6+0.1 x 1.6

= 6.84+0.16

= 7.00 lb/hr

Time to Consume 90 lb = 90/7 = 12.9 hr

Time Travelling at 35 mph = 0.9 x 12.9

= 11.61 hr

Distance Travelled = 35 x 11.61

= 407 miles

Fuel Mileage = 407 x 6.3/90

= 28.5 mpg

Fuel for 300 Miles = 10.5 gal

In the above results no allowance for the excess fuel used by the accelerating pump in the carburetor, for the energy required for acceleration, for that lost by braking, or for the fact that on normal roads there will be some up and down gradients; the calculations assumed a perfectly constant speed on a level road. The effects of the above factors, under good driving methods, could change the ideal mpg from 21.0 to about 18.0 mpg and under adverse conditions possibly as low as 17 mpg, with the standard system and 25-26 mpg for the flexible system.

This compares with the roughly 1:2 ratio when the whole BFD schedule is employed.

If the distribution of time over the various types of terrain is changed from that assumed to that shown below, then the comparative fuel figures for the two cases become as shown in Table XI.

Road Surface	Vehicle Resistance
25% Pavement	Hard Surface
35% Secondary	1.5 x Hard Surface
40% Cross Country	2.0 x Hard Surface

The results for this case indicate little change in the relative saving to be made; 170 lb of fuel for first case, and 174 lb for the second.

TABLE XI

FUEL REQUIREMENTS FOR 48-HOUR BATTLEFIELD DAY FOR STANDARD AND FLEXIBLE SYSTEMS FOR INCREASED CROSS COUNTRY TIME

Surface	Hours	Fuel Flow, lb	Total, lb
	Standard Engine and Transmission		
Pavement	12	78.8	
Secondary	16.8	112.6	
Cross Country	19.2	181.7	373.1
	Flexible Engine and Variable Transmission		
Pavement	12	38.9	
Secondary	16.8	69.1	
Cross Country	19.2	90.8	198.8

If a third case is examined (terrain in which the cross country resistance amounted to three times that of pavement), then the data of Table XII are obtained.

TABLE XII

FUEL REQUIREMENTS FOR BATTLEFIELD DAY FOR HEAVY SOIL RESISTANCE IN CROSS COUNTRY OPERATION

Surface	mph	Hours	Gear and Gear Ratio	rpm	Fuel Flow lb/hr	Fuel Flow Total, lb
			Standard Engine and Transmission			
	Idle	1.6	-	500	2.6	4.16
	0-10	3.36	1st	250-3430	6.8	22.8
Cross Country	10-20	5.92	2nd	1900-3830	10.8	63.8
3 x Pavement	20-30	3.36	3rd	2020-3030	12.5	42.0
	30-40	1.6	4th	1820-2420	18.5	29.6
	40-	0.16	4th	2420-	26.4	4.2
	Total Hours = 16			Total Fuel Flow = 166.56		
			Flexible Engine and Variable Transmission			
	Idle	1.6	-	250	1.6	2.56
	0-10	3.36	10.0 -2.7	250- 370	1.8	6.06
Cross Country	10-20	5.92	2.97-3.8	370- 950	4.4	26.1
3 x Pavement	20-30	3.36	3.8 -4.4	950-1650	9.8	32.9
	30-40	1.6	4.4 -6.02	1650-3000	19.6	31.3
	40-	0.16	7.4 -	3700-	36.5	5.84
	Total Hours = 16			Total Fuel Flow = 104.76		

The comparison between the two types of power systems (for the duty assumed in this case) thus becomes:

Standard System Fuel = 379 lb/48-hr BFD

Flexible System Fuel = 222 lb/48-hr BFD

This again emphasis that the ratio between the two systems varies but little over the operating ranges of values examined.

The above data can be converted to a basis of distance travelled for a given fuel supply. It will be assumed that the fuel supply for the standard vehicle will be available to both power train systems (373.1 lb of fuel for 48 hr) that the schedule of operations is that already outlined for the calculation of Table XI, viz., 25% pavement, 35% secondary roads, and 40% cross country; then we have Table XIII.

It follows that the distance travelled for the same fuel supply is almost doubled when using the flexible combination.

One other point of interest here is that the bulk of the fuel is burnt in the 15-25 mph range of vehicle velocities. It will be observed that the sum of the fuel used for the 10-20 and 20-30 mph condition exceeds that for all other speeds put together. This of course is partly a time factor, there are 9.28 hr of operation at these speeds compared with 6.72 of the rest speed of the schedule. The high-speed operation consumes a negligible fuel quantity for the schedule assumed.

TABLE XIII

RANGES OF OPERATION FOR STANDARD AND FLEXIBLE SYSTEMS

(Hours of operation = 48.0)

Surface	Average, mph	Time, hr	Distance, miles	Total	
				Miles	Fuel, lb
		Standard Vehicle System			
Hard Pavement	0	1.2	0		
	5	2.52	12.60		
	15	4.44	66.50		
	25	2.52	63.00		
	35	1.2	42.00		
	55	0.12	6.60	190.70	78.8
Secondary Roads	0	1.68	0		
	5	3.53	17.65		
	15	6.21	93.15		
	25	3.53	88.25		
	35	1.68	58.80		
	53	0.17	9.02	266.87	112.6
Cross Country Roads	0	1.92	0		
	5	4.03	20.15		
	15	7.108	106.22		
	25	4.03	100.75		
	35	1.92	67.20		
	42	0.192	8.16	302.88	181.7
Total distance for 373.1 lb of fuel (= 59.2 gal) in 48 hr				760.45	
		Flexible Vehicle System			
Hard Pavement	0	1.2	0		
	5	2.52	12.60		
	15	4.44	66.50		
	25	2.52	63.00		
	35	1.2	42.00		
	55	0.12	6.60	190.72	38.9
Secondary Roads	0	1.68	0		
	5	3.53	17.65		
	15	6.21	93.15		
	25	3.53	88.25		
	35	1.68	58.80		
	52.5	0.17	8.93	266.78	69.1
Cross Country Roads	0	1.92	0		
	5	4.03	20.15		
	15	7.108	106.62		
	25	4.03	100.75		
	35	1.92	67.20		
	42.5	0.192	8.16	302.88	90.8
Total distance for 373.1 lb of fuel (= 59.2 gal) in 48 hr				1430	

IX. TRANSMISSION

The object of this analysis was to examine economy as to fuel quantities, which has been carried out. However, in the process sufficient data regarding the overall drive reduction ratio have been accumulated to allow some observations regarding the transmission to be made.

Looking at the data of Tables IX and X it is seen that an overall drive ratio of the flexible system for the various types of terrain considered varies from a maximum of 8.02:1 to a low of 2.5:1 for cross country operation; from 8.02 to 2.20:1 for secondary roads; and from 10.4 to 1.72:1 for pavement. Of the above, the 10.4:1 is for pavement at a vehicle speed of only 2 mph while at 4 mph the DR_O required has already dropped to 5.2:1. The 8.02:1 for the other two cases also applies to about the same vehicle speed. If this low-speed end of the operation is allowed to be off the minimum fuel-flow curve, it is seen that a variable ratio of from 2.0 to about 5.0:1 would achieve the great majority of the gains already outlined, since the fuel for such low speed operation is small anyway.

The overall drive ratio includes the rear axle as well as the transmission ratio. The axle ratios usually employed for this type of vehicle are 3.5 up to 5.0 approx. It follows that to achieve a $DR_O = 2.0$, this could be made up of a 2:1 rear axle and a 1:1 transmission, while the other required ratios could be achieved by a variable unit capable of gradual variation through the range of 1:1 to 2.5:1.

The effect of a 2.0:1 rear axle would be that of increased torque with the need for increased load carrying gears etc., but due to the low speeds of rotation under these conditions the size increase could be minor.

Going one step further, a variable DR_O of 2.0 to 3.0, in place of 2.0 to 5.0, would enable all but the 2-3 mph and speeds in excess of 45.0 mph on pavement, 33 mph on secondary roads and 25 mph cross country to be achieved at minimum consumption. It is believed that the exclusion of the above speed ranges would be satisfactory in the great majority of cases under normal operating schedules. Performance at these excluded ranges could still be possible by some special provisions involving some small increase in fuel flow, with the result that the overall conditions would still result in a very satisfactory fuel saving.

There would still be the problem of a satisfactory start from rest on soft ground or a steep hill. This could be handled by the equivalent of a 1st gear giving high engine speed for the initial motion from rest. Examination of the required power curve for 1st gear in Fig. 10 reveals how little horsepower is demanded when in this gear ratio, but, of course, there is considerable torque applied to the wheels due to the reduction ration employed.

If the idea of a variable transmission is discarded for the moment and the gear ratios of Table IX examined, it is seen that the 2:1 axle plus a three speed transmission of, say, 2.5, 1.50, and 1:1 would provide overall drive ratios of 5, 3, and 2:1, which would bracket the group desired for economy operation in a fairly satisfactory manner. It will be observed that a 5:1 ratio exists compared with the 4.86:1 of the present 4th gear; thus highway travel would be little if any different, while cross country travel on relatively level terrain would be almost identical except for the improved fuel consumption.

The great difficulty would arise in the cases of high gradients on the roads or cross country. The suggested 1st gear ratio for starting would take care of the very steep grades but intermediate ones could only be negotiated at slow speeds in that gear to avoid overspeeding of the engine, or some other gear must be added.

An alternative could be the use of the present transmission with an overdrive added, the overdrive being about 2.2:1, then there would be gear ratios of: 2.21, 3.69, 4.86, 7.02, i.12, 12.6, 15.44, and 27.7.

Normal driving over pavement and fairly level country would be possible in the first 3 or 4 gears with considerable fuel savings, while the higher ratios would be used for hill climbing, etc. An overdrive added to a 3-speed in place of a 4-speed box would provide all that is available in the standard system.

The above represents one method of attacking the problem of economy. A second and better solution would be the combination of a variable step in the transmission as discussed earlier. What this unit would be like it is not ventured to guess at this point; it would be a project of no mean size to effect such a unit.

Whether the expense of such a development is justified depends upon the value to be placed upon a fuel saving of about 2:1 maximum, with (say) about 1.5:1 for some simplified transmission system which approached the conditions over a major portion of the schedule.

X. FIVE-TON VEHICLE WITH COMPRESSION IGNITION ENGINE

In order to examine the possible fuel economies to be achieved when employing the compression-ignition principle, a hypothetical 5-ton vehicle powered by a GM 6-71E engine was examined.

The data employed in this instance had, in general, to be predicted. The road resistance was made up as shown in Fig. 14, and 1.5, 2.0, and 3 times this employed in the calculations as before, while the engine-performance curves were derived from "GM Diesel's Additional Engines" by K. L. Hulsing and C. E. Ervin, SAE Transactions, Vol. 67, 1959, pp. 596-617 in the following manner:

(1) From data in the above publication a frictional horsepower curve and blower-power cruve were constructed.

(2) With the aid of (1), IHP curves for full load were plotted and extrapolated as required, and percent IHP versus fuel flow obtained as in Fig. 15 in conjunction with such part-load performance data as were given in the reference. Some extrapolation of the results were necessary at this point, and these are best done on an IHP basis.

(3) Using the results from the plotted and extrapolated curves of Fig. 15, the data were again reduced to a BHP basis at engine speeds of 500, 1000, 1400, 1800, 2100, 2400, and 2700 rpm and plotted on an rpm base in Fig. 16, which also includes the SFC data; the performance from this map for this investigation was obtained.

The basic data obtained from the reference work are given in Table XIV.

Plotting of the data of Table XIV led to the estimated BHP performance and fuel data referred to and shown in Table XV and Fig. 17 over the extended speed range required for the analysis.

The specifications of the vehicle that will be employed with the engine data of Table XV are:

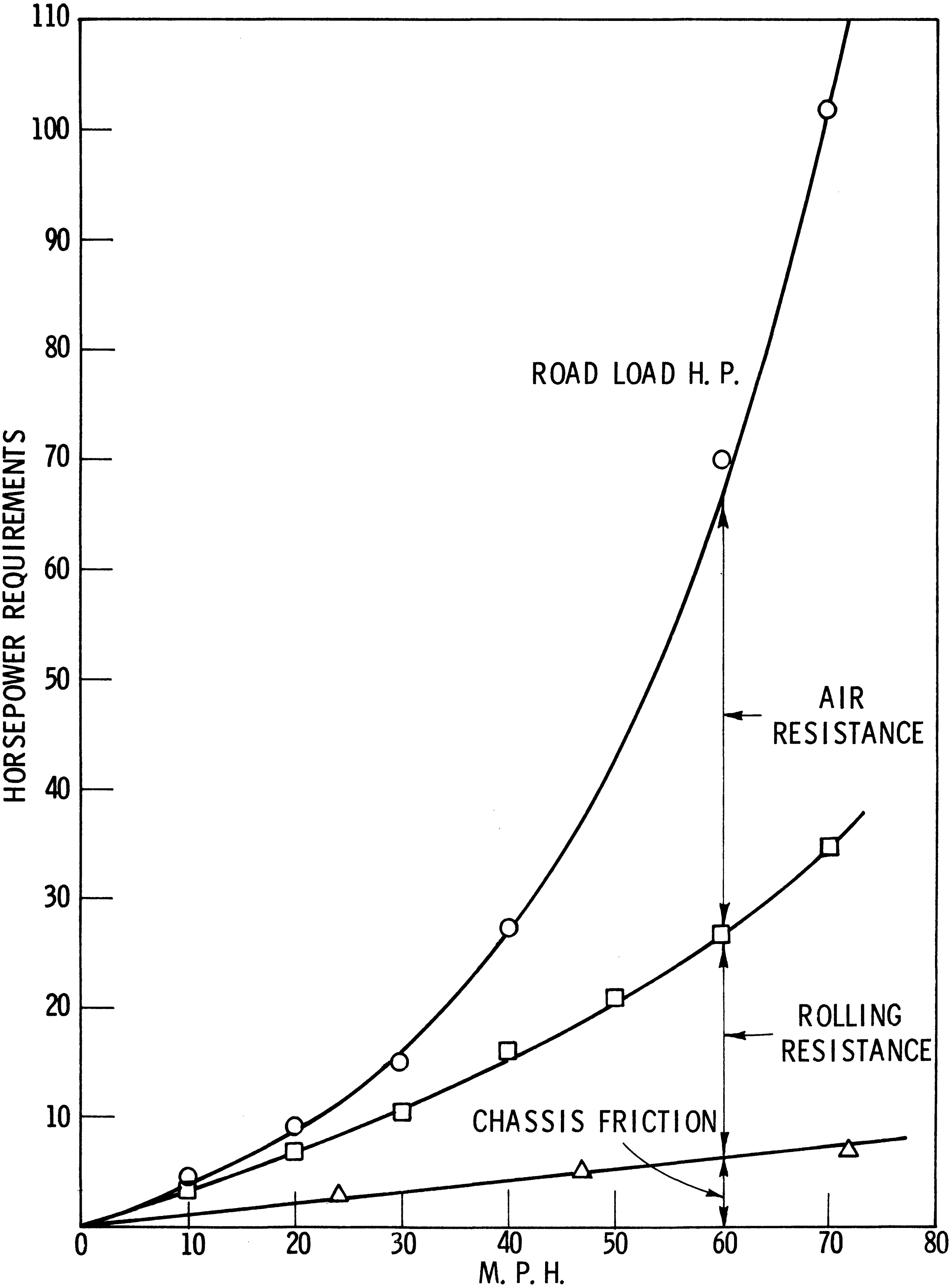

Fig. 14. Road resistance of five-ton vehicle.

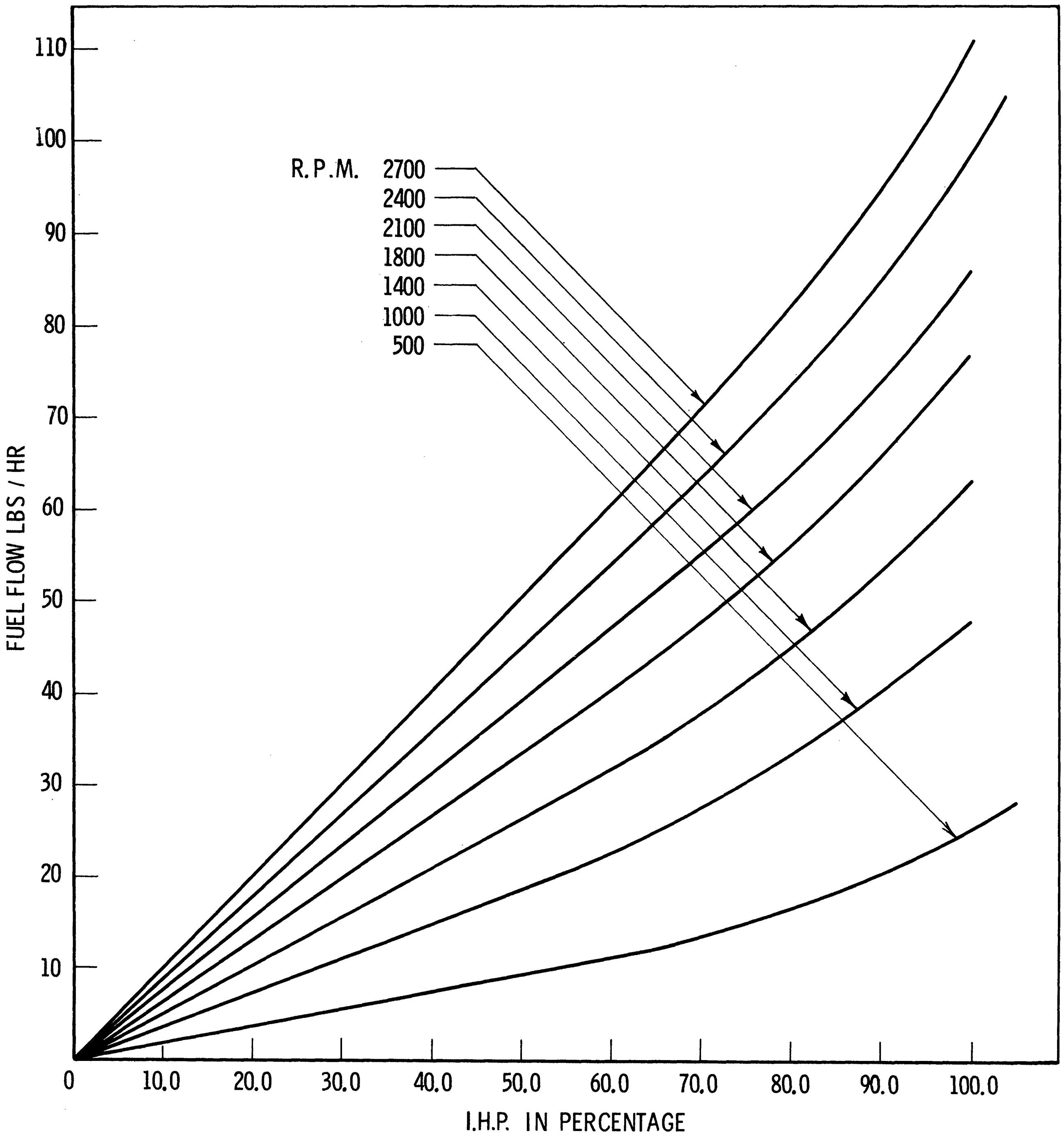

Fig. 15. Percentage indicated horsepower vs. fuel flow.

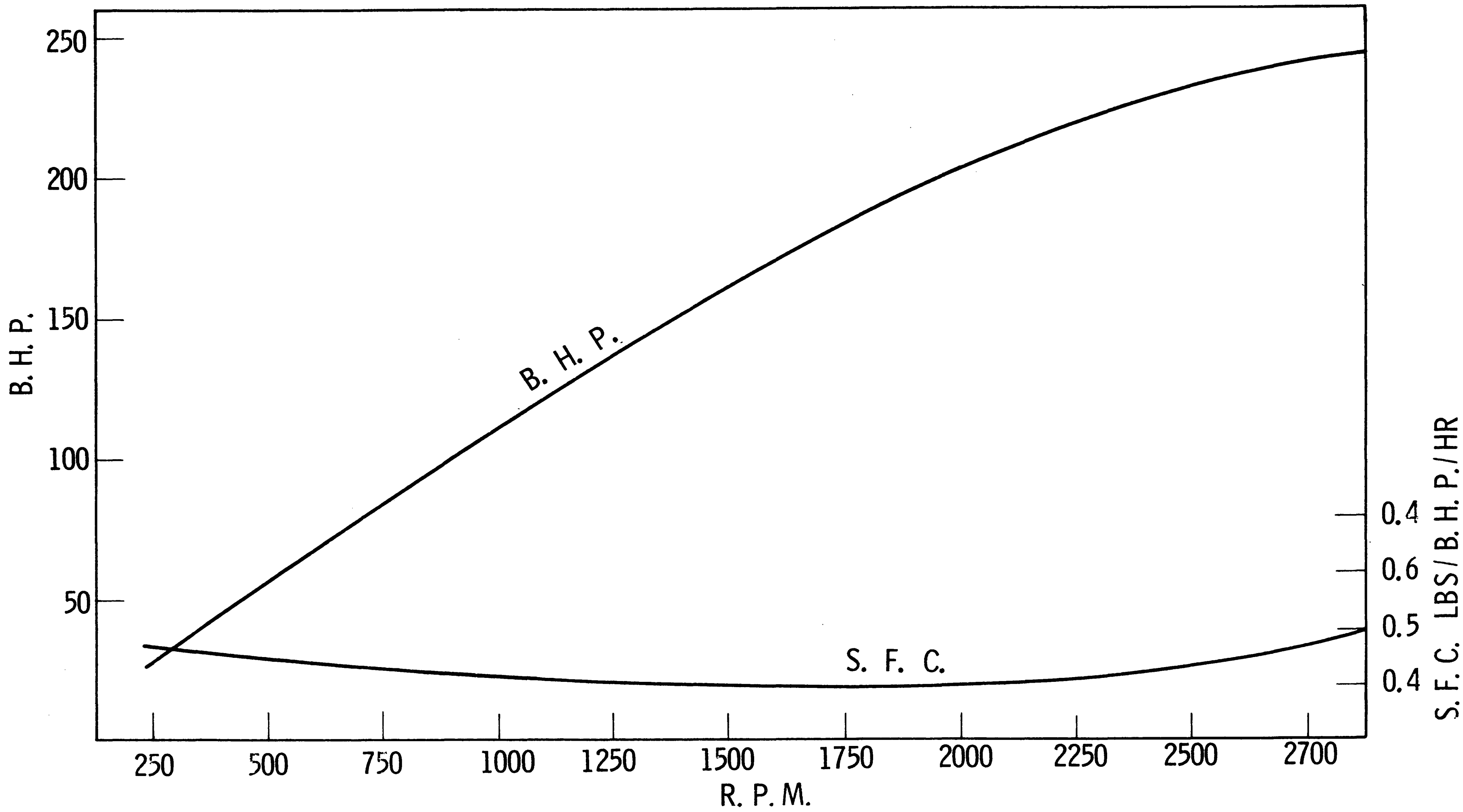

Fig. 16. Final brake horsepower and specific fuel consumption curves for engine.

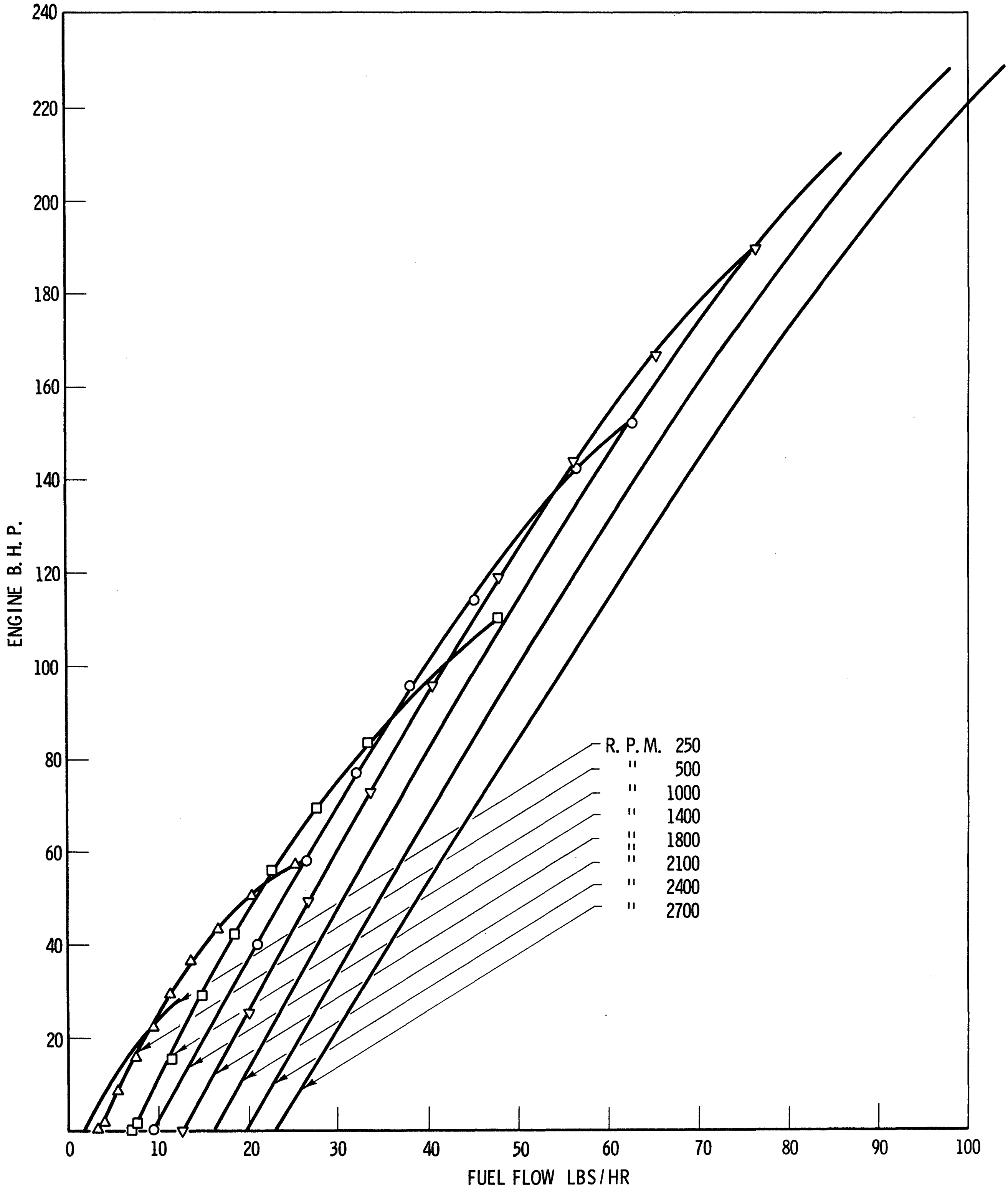

Fig. 17. Brake horsepower vs. fuel flow map for GM6-71E engine.

TABLE XIV

GM6-71E ENGINE PERFORMANCE

RPM	BHP	BSFC lb/BHP/hr	Fuel Flow, lb/hr	Blower, hp	Friction, hp	IHP	Percent IHP	ISFC lb/IHP/hr
			Part-Load Performance					
	210	0.41	86.2	14.0	40	264	100	0.326
	180	0.40	72.1	14.0	40	234	88.6	0.309
	150	0.408	61.3	14.0	40	204	77.4	0.300
2100	120	0.430	41.7	14.0	40	174	66.0	0.297
	90	0.478	43.1	14.0	40	144	54.5	0.299
	70	0.535	37.5	14.0	40	124	47.0	0.302
	60	0.574	32.9	14.0	40	114	43.2	0.289
	152	0.402	61.0	5	30	187	100	0.326
	130	0.392	51.1	5	30	165	87	0.310
	110	0.390	43.0	5	30	145	76.4	0.297
1400	90	0.400	36.0	5	30	125	65.8	0.288
	70	0.420	29.4	5	30	105	55.3	0.280
	60	0.438	26.4	5	30	95	50.0	0.278
	50	0.454	22.7	5	30	85	44.6	0.268
			Full-Load Performance					
2700	240	0.457	110.0			315.0	100	0.349
2400	228	0.430	98.0			290.0	100	0.338
2100	210	0.41	86.2			264.0	100	0.326
2000	203	0.405	82.2			253.8	100	0.324
1800	190	0.40	76.0			235.5	100	0.323
1600	172	0.395	68.0			212.5	100	0.320
1400	152	0.402	61.0			187.0	100	0.326
1200	130	0.409	53.2			160.5	100	0.331
1000	109	0.421	45.9			134.5	100	0.341
500	57.5	0.438	25.2			70.0	100	0.360

TABLE XV

EXTENDED PERFORMANCE AT ALL LOADS AND SPEEDS OF THE GM6-71E ENGINE

RPM	BHP	Fuel Flow, lb/hr	BSFC lb/BHP/hr	Blower plus Friction, hp
2700	240	110.0	0.457	75.0
	177	82.0	0.463	
	114	61.0	0.535	
	51	40.5	0.793	
	19.5	30.5	1.56	
2400	228	98.0	0.43	62.0
	170	73.5	0.432	
	112	54.5	0.486	
	54	36.2	0.67	
	25	27.2	1.09	
2100	210	86.0	0.410	54.0
	184	74.0	0.402	
	157	63.8	0.406	
	131	55.5	0.424	
	104	47.5	0.456	
	78	39.5	0.506	
	52	32.0	0.616	
	25	24.0	0.962	
1800	190.5	77.0	0.404	45.5
	166.5	65.5	0.393	
	143.5	56.5	0.394	
	119.5	47.8	0.400	
	96.5	40.5	0.420	
	72.5	33.8	0.466	
	49.5	27.0	0.545	
	25.5	20.0	0.79	
1400	152.0	63.0	0.414	35.0
	143.0	56.5	0.374	
	114.0	45.3	0.397	
	96.0	38.0	0.396	
	77.0	32.0	0.416	
	58.0	26.5	0.456	
	40.0	21.1	0.528	
	21.0	15.6	0.744	
1000	110.5	47.8	0.432	25.5
	96.5	40.4	0.419	
	83.5	33.4	0.400	
	69.5	27.6	0.397	
	56.0	22.6	0.403	
	42.5	18.6	0.436	
	29.0	15.0	0.510	
	15.5	11.5	0.741	
500	57.5	25.2	0.438	12.5
	50.4	20.5	0.407	
	43.5	16.7	0.384	
	36.5	13.6	0.372	
	29.5	11.4	0.386	
	22.4	9.5	0.424	
	15.5	7.5	0.484	
	8.5	5.6	0.658	

Gross vehicle weight: 10,000 lb

Vehicle height: 7 ft-0 in.

Vehicle width: 6 ft-0 in.

Tire size: 11 x 22 in.

Assumed rolling radius: 21.2 in.

Rear axle ratio: 4.75:1

	1st	2nd	3rd	4th
Transmission ratios:	5.90	2.95	1.97	1.0
Transmission efficiencies, %:	85.0	88.0	91.0	94.0
DR_o:	28.0	14.49	9.38	4.75

The above gear ratios and efficiencies are hypothetical; 4th gear ratio was selected to give a vehicle speed of 60 mph at an engine speed of 2400 rpm.

Employing the data shown, Fig. 18 can be constructed, as for the M-151 vehicle, and comparisons can now be made as before. Using a slip factor of 5%, the engine speed for any road speed is given by Eq. (3).

$$\text{Engine rpm} = 8.42 \times DR_o \times \text{mph} . \tag{3}$$

There is one difference between Figs. 10 and 18; the latter has various transmission-efficiency curves plotted on it from 100 down to 80%. This permits selection of any desired efficiency rather than the fixed values of Fig. 10. The use of the chart changes slightly as a result, the horsepower value is taken to the right to the intersection of the desired efficiency curve. This point of intersection is then taken vertically to the 100% line then back horizontally to the BHP axis for the engine horsepower.

The performance with the assumed engine and transmission, employed in a conventional manner, is read out of Fig. 18 and recorded in Table XVI for all the various terrain surfaces and gear ratios available.

Repeating the process for the engine and variable transmission giving minimum fuel consumption, the data of Table XVII are obtained, of which Table XVIII and Fig. 19 give engine performance only.

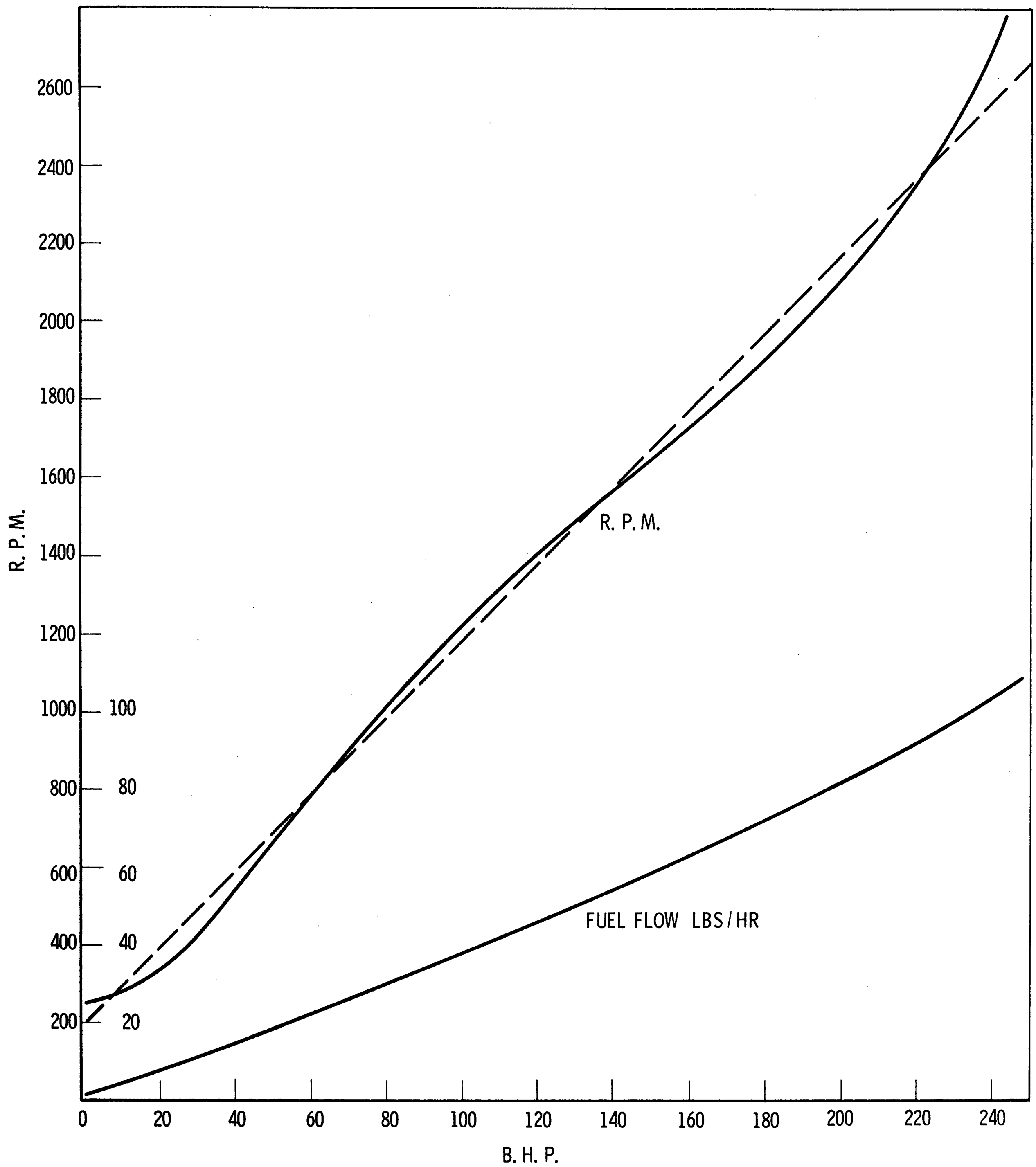

Fig. 19. Flexible engine performance.

TABLE XVI

STANDARD SYSTEM PERFORMANCE AT FOUR ROAD RESISTANCES FOR FIVE-TON VEHICLE

(a) Pavement

mph	First Gear			Second Gear			Third Gear			Fourth Gear		
	BHP	RPM	Fuel Flow, lb/hr	BHP	RPM	Fuel Flow, lb/hr	BHP	RPM	Fuel Flow, lb/hr	BHP	RPM	Fuel Flow, lb/hr
2	0.35	470	3.0	--	--	--	--	--	--	--	--	--
4	0.80	940	6.6	--	--	--	--	--	--	--	--	--
5				1.2	590	4.5	1.1	395	2.8	1.0	200	1.6
6	1.5	1420	9.5	--	--	--	--	--	--	--	--	--
8	2.5	1880	13.8	--	--	--	--	--	--	--	--	--
10	3.5	2360	20.3	4.0	1180	8.8	3.8	790	6.8	3.7	400	3.6
12	4.9	2830	27.4	--	--	--	--	--	--	--	--	--
15				6.1	1770	13.6	7.2	1190	10.1	7.0	600	6.0
20				10.7	2360	23.0	10.0	1590	13.2	9.9	800	8.0
25				13.8	2950	32.6	14.5	1990	18.8	13.5	1000	10.5
30							18.5	2380	25.5	17.8	1200	12.9
35							23.0	2790	33.5	22.0	1400	15.0
40										29.0	1600	19.0
45										38.5	1800	22.9
50										49.8	2000	29.5
55										63.5	2200	36.5
60										78.0	2400	44.0
65										94.5	2600	52.8
70										110.0	2800	62.0

TABLE XVI (Continued)

(b) Secondary Roads—1.5 x Pavement

mph	First Gear			Second Gear			Third Gear			Fourth Gear		
	BHP	RPM	Fuel Flow, lb/hr	BHP	RPM	Fuel Flow, lb/hr	BHP	RPM	Fuel Flow, lb/hr	BHP	RPM	Fuel Flow, lb/hr
2.5	1.0	560	4.0	--	--	--	--	--	--	--	--	--
5	2.1	1170	8.5	2.0	590	4.6	1.9	395	2.9	1.9	200	1.9
7.5	4.0	1740	13.0	--	--	--	--	--	--	--	--	--
10	5.5	2360	20.8	5.4	1180	9.5	5.2	790	6.9	4.7	400	4.0
12.5	8.0	2950	31.0	--	--	--	--	--	--	--	--	--
15				10.1	1770	14.2	9.8	1190	10.6	8.5	600	6.5
20				15.1	2360	23.9	14.8	1590	14.6	14.0	800	9.2
25				20.8	2950	35.0	20.2	1990	20.2	19.0	1000	12.0
30							26.4	2380	27.2	24.8	1200	15.1
35							34.2	2790	37.0	32.1	1400	18.5
40										42.4	1600	22.5
45										53.2	1800	27.2
50										71.5	2000	36.3
55										89.4	2200	44.5
60										111.5	2400	54.3
65										135.2	2600	64.5
70										161.0	2800	78.5

TABLE XVI (Continued)

(c) Cross Country—2.0 x Pavement

mph	First Gear			Second Gear			Third Gear			Fourth Gear		
	BHP	RPM	Fuel Flow, lb/hr	BHP	RPM	Fuel Flow, lb/hr	BHP	RPM	Fuel Flow, lb/hr	BHP	RPM	Fuel Flow, lb/hr
2.5	1.5	560	4.2	--	--	--	--	--	--	--	--	--
5	3.4	1170	9.0	3.3	590	5.0	3.1	395	3.0	3.0	200	2.0
7.5	5.4	1740	13.0	--	--	--	--	--	--	--	--	--
10	8.2	2360	20.6	8.1	1180	10.2	8.0	790	7.8	7.9	400	4.8
12.5	11.3	2950	31.8	--	--	--	--	--	--	--	--	--
15				13.5	1770	15.2	13.2	1190	11.7	13.0	600	7.3
20				20.8	2360	25.8	20.5	1590	16.3	19.4	800	10.5
25				27.3	2950	37.8	27.2	1990	22.8	27.0	1000	14.1
30							36.0	2380	30.5	34.0	1200	17.8
35							46.5	2790	40.8	43.0	1400	21.8
40										57.0	1600	27.2
45										73.5	1800	33.2
50										96.7	2000	43.8
55										122.2	2200	54.2
60										152.0	2400	67.0
65										182.8	2600	81.5
70										216.0	2800	96.6

TABLE XVI (Concluded)

(d) Cross Country—3.0 x Pavement

mph	First Gear			Second Gear			Third Gear			Fourth Gear		
	BHP	RPM	Fuel Flow, lb/hr	BHP	RPM	Fuel Flow, lb/hr	BHP	RPM	Fuel Flow, lb/hr	BHP	RPM	Fuel Flow, lb/hr
2.5	2.3	560	4.6	--	--	--	--	--	--	--	--	--
5	5.0	1170	9.5	4.7	590	5.8	4.5	395	3.9	4.4	200	2.5
7.5	8.4	1740	14.0	--	--	--	--	--	--	--	--	--
10	12.2	2360	22.6	11.5	1180	11.1	12.1	790	8.9	11.0	400	5.5
12.5	15.8	2950	32.5	--	--	--	--	--	--	--	--	--
15				20.6	1770	17.5	20.3	1190	13.6	19.0	600	9.0
20				31.4	2360	28.8	30.3	1590	19.0	82.0	800	13.1
25				42.7	2950	41.0	39.0	1990	24.7	38.8	1000	17.5
30							52.7	2380	30.2	50.0	1200	22.4
35							68.5	2790	47.8	64.6	1400	28.4
40										84.5	1600	34.8
45										110.0	1800	44.8
50										144.0	2000	58.2
55										183.8	2200	75.5
60										229.0	2400	98.8
65										--	2600	--
70										--	2800	--

TABLE XVII

FLEXIBLE SYSTEM PERFORMANCE AT FOUR ROAD RESISTANCES

MPH	BHP	RPM	Fuel Flow, lb/hr	Overall Drive Ratio Required	BHP	RPM	Fuel Flow, lb/hr	Overall Drive Ratio Required
			(a) Pavement				(c) Cross Country—2.0 x Pavement	
Idle	-	250	1.8	-	-	250	1.8	-
2.5	0.5	250	1.8	11.90	1.3	250	1.9	11.90
5.0	1.4	250	1.9	5.94	3.0	250	2.3	5.94
7.5	2.4	250	2.2	3.96	4.9	250	2.8	3.96
10.0	3.9	250	2.6	2.97	8.3	250	3.9	2.97
12.5	5.3	250	3.0	2.38	11.1	300	4.5	2.85
15.0	7.3	250	3.6	1.98	13.7	350	5.6	2.77
20.0	9.2	250	4.2	1.49	20.7	400	8.4	2.37
25.0	13.8	300	5.6	1.43	27.5	500	10.5	2.38
30.0	18.0	400	7.6	1.58	36.3	550	13.8	2.18
35.0	23.0	450	9.0	1.53	46.5	650	17.6	2.20
40.0	30.0	500	11.5	1.49	60.5	800	23.2	2.37
45.0	39.8	600	15.0	1.58	78.5	1050	30.9	2.77
50.0	51.2	700	19.5	1.66	101.5	1350	39.6	3.20
55.0	65.3	950	25.5	2.05	130.0	1430	50.8	3.08
60.0	80.0	1000	31.8	1.98	161.0	1750	62.6	3.46
65.0	98.0	1350	38.0	2.47	194.0	1900	76.8	3.47
70.0	114.0	1400	44.5	2.38	228.0	2400	94.8	4.06
			(b) Secondary Roads—1.5 x Pavement				(d) Cross Country—3.0 x Pavement	
Idle	-	250	1.8	-	-	250	1.8	-
2.5	1.0	250	1.9	11.90	2.1	250	2.1	11.90
5.0	2.3	250	2.1	5.94	4.8	250	2.8	5.94
7.5	3.2	250	2.4	3.95	8.3	250	3.8	3.96
10.0	5.5	250	3.0	2.97	11.8	300	4.3	3.57
12.5	8.4	250	3.8	2.38	15.5	350	6.1	3.33
15.0	10.0	250	4.2	1.98	20.0	400	7.8	3.16
20.0	15.2	350	6.2	2.08	29.0	550	11.5	3.26
25.0	20.7	450	8.2	2.14	41.5	600	15.7	2.85
30.0	26.4	500	10.0	1.98	51.0	700	19.3	2.77
35.0	34.0	600	12.9	2.04	68.0	1100	26.4	3.73
40.0	45.0	750	17.0	2.23	89.0	1200	34.8	3.56
45.0	59.5	850	22.8	2.24	115.5	1400	45.0	3.69
50.0	76.0	1000	30.0	2.37	152.2	1750	59.2	4.15
55.0	87.5	1100	34.5	2.38	196.5	2150	70.8	4.64
60.0	116.7	1400	45.5	2.77				
65.0	143.7	1500	55.8	2.74				
70.0	170.8	1950	66.5	3.30				

TABLE XVIII

MINIMUM FUEL FLOW FLEXIBLE ENGINE REQUIREMENTS

RPM	BHP	Fuel Flow, lb/hr
Idle	0.0	1.8
250	2.0	2.0
250	4.0	2.6
250	6.0	3.2
250	8.0	3.8
250	10.0	4.5
250	14.0	5.8
375	26.0	10.0
500	37.0	14.0
750	57.0	22.0
1000	74.5	29.5
1200	100.0	39.0
1400	123.0	48.0
1600	143.0	55.5
1800	160.0	63.0
2100	203.0	81.2
2400	228.0	94.5
2700	238.0	103.0

The data of these tables have been obtained using an overall efficiency of the transmission of 90%.

The dotted line of Fig. 19 is seen to follow the trend of the engine rpm quite closely; the error by using this straight line relationship would be of negligible mangitude.

XI. SYSTEM COMPARISON

The information contained in these performance tables permits comparing the Battlefield Day requirements for the two compression-ignition systems. In order to do so, the operating schedules (Section VIII-A) will again be employed and the necessary data are collected together in Tables XIX, XX, and XXI.

Repeating this tabulation for the flexible system the data of Tables XX and XXI are obtained.

Examination of the data of Table XXI again shows that at minimum consumption the flexible engine consumes almost one-half the fuel of a conventional engine and transmission even when a compression-ignition engine of the General Motors type is used, which for light loads at high speeds is paralized somewhat by high blower plus friction horsepower losses.

Actual vehicles fitted with the compression-ignition engine and conventional transmission have demonstrated on many occasions two-to-one increase in miles per gallon over that of the spark-ignition type when fitted to the same vehicle. The calculations covered by this report indicate the possibility of almost a four-to-one increase in miles per gallon when using a flexible compression-ignition engine system in place of a conventional spark-ignition unit coupled to a standard transmission.

TABLE XIX

STANDARD SYSTEM BATTLEFIELD DAY REQUIREMENTS FOR FIVE-TON VEHICLE

Surface	MPH	Hours	Gear	RPM	Fuel Flow lb/hr	Fuel Flow Total, lb
Hard Pavement	Idle	1.6	-	350	2.6	4.16
	0-10	3.36	2nd	350-1180	5.4	18.15
	10-20	5.92	3rd	790-1590	10.1	59.80
	20-30	3.36	4th	800-1200	10.5	35.30
	30-40	1.6	4th	1200-2400	15.6	25.0
	50-60	0.16	4th	2000-2400	36.7	5.9
	Total Hours = 16			Total Fuel Flow		= 148.31
Secondary Roads	Idle	1.6	-	350	2.6	4.16
	0-10	3.36	2nd	350-1180	5.6	18.80
	10-20	5.92	3rd	790-1590	10.7	63.30
	20-30	3.36	4th	800-1200	12.1	40.60
	30-40	1.6	4th	1200-1600	18.7	29.90
	50-60	0.16	4th	2000-2400	45.1	7.21
	Total Hours = 16			Total Fuel Flow		= 163.97
Cross Country 2 x Pavement	Idle	1.6	-	350	2.6	4.16
	0-10	3.36	1st	250-2360	9.9	33.20
	10-20	5.92	2nd	1180-2360	17.1	101.50
	20-30	3.36	3rd	1590-2380	23.2	77.80
	30-40	1.6	4th	1200-1600	22.3	35.70
	50-60	0.16	4th	2000-2400	55.0	8.80
	Total Hours = 16			Total Fuel Flow		= 261.16
Cross Country 3 x Pavement	Idle	1.6	-	350	2.6	4.16
	0-10	3.36	1st	350-2360	10.66	35.80
	10-20	5.92	2nd	1180-2360	19.10	113.20
	20-30	3.36	3rd	1590-2380	24.60	82.50
	30-40	1.6	4th	1200-1600	28.50	45.60
	50-60	0.16	4th	2000-2400	77.50	12.41
	Total Hours = 16			Total Fuel Flow		= 293.67

Total fuel for 48-hr BFD, 1/3 pavement, 1/3 secondary, and 1/3 cross country (2 x pavement) = 573.5 lb

Total fuel for 48-hr BFD, 1/3 pavement, 1/3 secondary, and 1/3 cross country (3 x pavement) = 606.0 lb

TABLE XX

FLEXIBLE SYSTEM BATTLEFIELD DAY REQUIREMENTS FOR FIVE-TON VEHICLE

Surface	MPH	Hours	Gear Ratio	RPM	Fuel Flow lb/hr	Fuel Flow Total, lb
Hard Pavement	Idle	1.6	--	250	1.80	2.88
	0-10	3.36	14.5 -2.97	250	2.1	7.05
	10-20	5.92	2.97-1.49	250	3.5	20.70
	20-30	3.36	1.49-1.59	250- 400	5.8	19.48
	30-40	1.60	1.59-1.48	400- 500	9.4	15.05
	50-60	0.16	1.66-1.98	700-1000	25.6	4.10
	Total Hours = 16				Total Fuel Flow =	69.26
Secondary Roads	Idle	1.6	--	250	1.80	2.88
	0-10	3.36	14.5 -2.97	250	2.25	7.56
	10-20	5.92	2.97-2.08	250- 350	4.50	26.60
	20-30	3.36	2.08-1.98	350- 500	8.10	27.20
	30-40	1.60	1.98-2.23	500- 750	13.30	21.30
	50-60	0.16	2.37-2.77	1000-1400	36.70	5.88
	Total Hours = 16				Total Fuel Flow =	91.24
Cross Country 2 x pavement	Idle	1.6	--	250	1.80	2.88
	0-10	3.36	14.5 -2.97	250	2.6	8.74
	10-20	5.92	2.97-2.37	250- 400	5.6	33.10
	20-30	3.36	2.37-2.18	400- 550	10.9	36.60
	30-40	1.60	2.18-2.37	550- 800	18.2	29.10
	50-60	0.16	3.21-3.46	1350-1750	51.0	8.16
	Total Hours = 16				Total Fuel Flow =	118.58
Cross Country 3 x pavement	Idle	1.6	--	250	1.80	2.88
	0-10	3.36	14.5 -3.56	250- 300	2.96	9.94
	10-20	5.92	3.56-3.27	300- 550	7.87	46.50
	20-30	3.36	3.27-2.77	550- 700	15.50	52.00
	30-40	1.60	2.77-3.56	700-1200	26.80	42.90
	50-55	0.16	4.16-4.63	1750-2150	65.00	10.40
	Total Hours 16				Total Fuel Flow =	164.62

TABLE XXI

COMPARISON OF STANDARD AND FLEXIBLE SYSTEMS FOR FIVE-TON VEHICLE
(Fuel requirements for 48-hr power plant—GM6-71E)

Schedule	Engine and Transmission System, lb	
	Conventional	Flexible
33-1/3% Pavement 33-1/3% Secondary Roads 33-1/3% Cross Country (2 x Pavement)	573.5	280.0
33-1/3% Pavement 33-1/3% Secondary Roads 33-1/3% Cross Country (3 x Pavement)	606.0	325.0
25% Pavement 35% Secondary Roads 40% Cross Country (2 x Pavement)	597.0	290.6
25% Pavement 35% Secondary Roads 40% Cross Country (3 x Pavement)	635.6	345.8

XII. TRANSMISSION REQUIREMENTS FOR COMPRESSION-IGNITION ENGINE

In order to achieve the economies predicted for the flexible engine system, the only important element changed is the transmission. The engine is identical for each system, developing the same power at the same speed for the same fuel consumption. The fuel saved comes from the reduction in engine speed that is possible for a given power output.

To reduce engine speed relative to vehicle speed, a lower overall drive ratio between engine and wheels must be employed. Looking at the requirements for the two power systems examined for the 5-ton vehicle, the data of Table XXII are obtained for speeds up to 70 mph.

It is seen that the conventional system in 1st gear on pavement can only employ up to a maximum of about 1/70 full power output at full engine speed. In such a case the frictional losses are about twenty times the useful power being generated, i.e., for every pound of useful fuel 20 lb are wasted in friction. It is not until 4th gear is employed, and even then high road speed is also necessary, that a reasonably good relationship between useful fuel and friction fuel is obtained.

If cross country operation is examined, it is seen that the engine is now working up near its capacity at high speed and the proportional fuel flow is improved. It follows that the savings to be made are reduced as the engine load increases.

These observations are not new; it has been well known for a long time that high speed and economy cannot be achieved simultaneously. In these calculations the actual sacrifice made to achieve high speed has been brought into the open for perhaps the first time for those not intimately connected to vehicle development.

The engine and transmission are designed to meet certain top-speed conditions, conditions which in the schedule of operations employed in this analysis are only existant for a total of 1% of the 48-hour BFD. The transmission is then totally unsuited for operation over about 80% of the total time period.

The flexible engine concept reduces engine speed, and thus frictional losses to a minimum. As a result the fuel savings over the above 80% period are considerable and at the same time there is but a small loss in the maximum performance viz., 55 mph maximum speed with flexibility against 60 mph for the conventional system when operating on level ground of three times pavement resistance. There is no loss in maximum speed at any of the other

TABLE XXII

COMPARISON OF TRANSMISSION SYSTEM REQUIREMENTS

System	Gear and Ratio	Engine Requirements											
		Pavement			Secondary Roads			Cross Country					
								2 x Pavement			3 x Pavement		
		Vehicle, mph	Engine, rpm	BHP	Vehicle, mph	Engine, rpm	BHP	Vehicle, mph	Engine, rpm	BHP	Vehicle, mph	Engine, rpm	BHP
C.I. Engine and Conventional Transmission	1st 28.0 :1.0	2-10	470-2360	0- 3.5	2-10	470-2360	0- 5.5	2-10	470-2360	0- 8.2	2-10	470-2360	0- 12.2
	2nd 14.49:1.0	5-20	590-2360	0- 10.7	5-20	590-2360	0- 15.1	5-20	590-2360	0- 20.8	5-20	590-2360	0- 31.4
	3rd 9.38:1.0	5-30	395-2380	0- 18.5	5-30	395-2380	0- 26.4	5-30	395-2380	0- 36.0	5-30	395-2380	0- 52.7
	4th 4.75:1.0	5-70	200-2800	0-110.0	5-70	200-2800	0-161.0	5-70	200-2800	0-216.0	5-60	200-2400	0-229.0*
Flexible C.I. Engine and Variable Transmission	1.5 :12.0	0-70	250-1400	0-114.0									
	1.98:12.0				0-70	250-1950	0-171.0						
	2.2 :12.0							0-70	250-2400	0-228.0			
	2.7 :12.0										0-55	250-2150	0-196.5**

*At 3 times Pavement resistance maximum speed limited to 60 mph.
**At 3 times Pavement resistance maximum speed limited to 55 mph.

ground conditions examined. This sacrifice is minor and the question can be raised as to whether any sacrifice is made anyway since it can be asked "Where and under what conditions could 70 mph be maintained over rought terrain cross country?"

By looking at Table XX it is seen that the flexible engine requires overall gear ratios of 14.5 to 1.5 (approximately) for complete conformity with the calculations. Now as in the case of the spark-ignition engine previously considered, it is probable that some high gear ratio would be required for starting from rest, particularly on hills. If such was provided, say for speeds from 0-5 mph, and then from about 5 mph on up the flexible system came into operation, the range of overall ratios would be reduced to about 6.0 to 1.5:1.0, with the great majority of the operation being within the range of 4.5 to 1.5 for all the various ground conditions considered. If the three-to-one ground data were eliminated, the range could be cut to 3.5 to 1.5.

It is possible that such a range could be handled with a first gear conventional reduction plus a form of hydrostatic transmission. In such a case it is true that the full savings would not be achieved, but it is possible, today, that a worthwhile saving of fuel could be made by using the system in the most favorable combination that could be worked out.

It seems that a new look at transmissions in the light of this investigation would be justified on the following basic principles

(1) Economy of Fuel

(2) Logistic Problem

(3) Range of Operation

(4) Reduced Repair and Maintenance of Power Plant

XIII. DISADVANTAGES OF FLEXIBLE SYSTEM

This proposed system of operation, as is common to most changes, does not present a completely clear-cut decision to be made. To achieve the objective of fuel economy, etc., some sacrifices must be made in other directions. In this case the major sacrifice would be in the field of the vehicles acceleration. The maximum speed would be unaffected, but the time to reach that speed would be increased considerably. This would be of considerably consequence to most drivers of today's passenger cars on the freeways. How this would affect military convoys only those with such experience could judge.

In order to illustrate this point the data of Table XXIII are provided for the M-151 vehicle. This table records, for both conventional and flexible systems, the operating horsepower for each engine speed, i.e., the point at which the vehicle would be performing under the contemplated idealized conditions, together with the maximum BHP that would be available if the throttle were suddenly opened wide at that same speed. The difference in power then represents that available for accelerating the vehicle.

TABLE XXIII

POWER AVAILABLE FOR ACCELERATION M-151 VEHICLE

Engine,	Conventional System, BHP			Flexible System, BHP		
rpm	Min	Max	Δ	Min	Max	Δ
250	0.1	3.4	3.3	2.8	3.4	0.6
500	0.3	7.1	6.8	5.7	7.1	1.4
1000	2.5	17.0	14.5	12.0	17.0	5.0
1400	4.6	28.5	23.9	20.0	28.5	8.5
1800	8.0	36.5	28.5	29.0	36.5	7.5
2200	12.3	45.5	33.2	35.0	35.5	10.5
2600	19.5	51.5	32.0	43.5	51.5	8.0
3000	29.5	55.5	26.0	53.0	55.5	2.5
3400	39.3	59.2	19.9	54.5	59.2	3.7
3800	52.0	60.0	8.0	60.0	60.0	0.0
4200	61.0	61.0	0.0	61.0	61.0	0.0

Comparing the two sets of data, it is seen that the difference in these accelerating powers for the two cases is in the order of about 3 or 4:1 on the average. It follows that the fuel-consumption increase shown for the M-151 unit between the two systems (174.0 lb/48 hr), represents the penalty to be paid for a 3:1 increase in vehicle acceleration. By reducing this saving in fuel, increase in acceleration is possible. Also as is well known, by further increasing maximum BHP, additional increase in acceleration of the standard unit is possible, at the expense of further increase in fuel, over and above that of the existing vehicle.

The selection of the best operating combination can only be made by those closely connected with the actual overall vehicle operational requirements, the problem of fuel supply, and the effects that the range of operation has on the general problems encountered in the field. It is considered that the present trend of the automotive industry in vehicle development, both passenger car and trucks (i.e., high speeds and higher accelerations with transmissions to suit these conditions) may not be the best basis for the design of military vehicles to meet their average operating schedule.

Lack of rapid acceleration seems to be the outstanding disadvantage of the flexible system. Its importance versus savings must be judged by competent authorities. It is, of course, quite probable that some other problems may exist, increased costs, complexity, etc.—these cannot be evaluated until the transmission problem has been examined and a proposed design prepared.

It is believed that Figs. 10 and 18, can be added to in such a way that the instantaneous acceleration resulting from wide open throttle conditions could be added without much difficulty. In addition, the time of acceleration from x to y mph could also be added to the same chart if necessary. Alternatively, these acceleration values could be given separately if thought desirable.

No reason is seen why the fuel flow during acceleration and deceleration could not also be plotted without complicating the problem to an impossible extent. With such data a fairly exact prediction of actual vehicle operation should be possible.

XIV. FUTURE INVESTIGATIONS

It is believed that this analysis should be continued by working out an example of an engine coupled to an automatic transmission of the torque-converter type giving the position of that combination relative to those already examined.

XV. CONCLUSIONS

It can be concluded from the data presented in this report that a typical modern vehicle fitted with an internal combustion engine (and also a gas turbine, it is believed, though this has not been investigated) and connected to a typical modern transmission of either the conventional stick shift or automatic variety produces a combination which is conducive to excessive fuel consumption compared to the minimum that could be obtained given the most efficient combination of units.

The various conclusions, both for and against, are as follows:

(1) The ideal flexible system could be designed to use about one half the present fuel quantities in a 48-hour day.

(2) In order to achieve the savings indicated, a new approach to the transmission problem must be made.

(3) Existing engines were employed in the analysis. Nothing in the way of new engine concepts are involved in the reduction of fuel flow.

(4) To achieve the reduced flow the present type of engine would need some improvements in the direction of satisfactory slow-speed operation without stalling, and with smoothness of operation.

(5) It is probable that some new development in controls may be necessary; this will depend upon the transmission design, when worked out.

(6) A distinct sacrifice in acceleration would be involved to achieve the indicated economy.

(7) Some sacrifice in the maximum available economies shown here can be made which would be reflected in improved acceleration, and still leave a major fuel saving available.

(8) The fuel economy indicated of about 50% is an overall one taking into consideration all the various conditions encountered in a BFD of 48-hours. It is not the economy at any one isolated point.

(9) The general engine operating conditions will be improved and should result in increased life and reduced maintenance.

(10) By suitable design, with some sacrifice in the maximum fuel saving possible, the range of variability of the transmission could be reduced greatly with perhaps considerable simplification of the unit.

(11) The design of a suitable overdrive unit attached to a two or three speed transmission and special rear axle probably could achieve a large percentage of the possible gains for the M-151 vehicle.

(12) There is a distinct possibility that the successful solution of the low-speed engine operation, which would be necessary to achieve the objective, would involve some increase in the rotating weights to eliminate torque reversal on the transmission.

(13) The sacrifice of say 15% in maximum vehicle speed (for the two cases examined) would reduce considerably the range of variability of the transmission without loss in the gains to be expected; in fact some improvement seems possible.

(14) If the "flexible" concept is compared with the "responsive" one of Refs. 1 and 3, it is seen that where fuel economy is of major consideration the flexible system will do much more than the responsive one.

(15) The "responsive engine" needs considerable development in order to be a practicable power plant. It does not reduce fuel quantities, but it does eliminate some, and in an ideal case all, of the transmission problems. It provides torque multiplation as engine speed reduces.

(16) The "flexible system" employs existing engines with little or no change (slower speed operation being the major requirement). This system, however, adopts the engine fuel-flow characteristics to the vehicle requirements in the most efficient manner, via the use of a transmission of special design or by a conventional gearbox plus overdrive. If some sacrifice in maximum fuel savings is accepted, probably a 40% saving in place of 50% (approx.) could be achieved relatively easily.

(17) An engine developed specifically for economy of operation coupled to the flexible system would not achieve any additional major gains, since the engine operation over the majority of the operating schedule is at a point of maximum economy anyway. Some small gains could be made at the high-speed, high-load conditions only.

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