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Technical Report

THE FLEXIBLE ENGINE AND ITS ACCELERATION PROBLEMS

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ABSTRACT

This report presents the results of a study of the acceleration from zero to maximum speed of the M-151 vehicle, using the standard engine (1) coupled to the standard transmission, and (2) coupled to an ideal flexible engine transmission.

The possibilities of using a flexible engine were investigated by operating three vehicles under conditions approximating Battlefield Day conditions. The slow-speed performance of the engine indicates that, if a successful flexible system is to be achieved, greater attention must be given to developments in the ignition system, carburetor, valve timing, manifolding, etc.

I. OBJECT

The object of this study was to record the results obtained when estimating the acceleration of the M-151 vehicle fitted with the perfectly flexible engine.[1]

II. INTRODUCTION

Reference 1 presented the results of an investigation of the fuel economies under Battlefield Day conditions of a perfectly flexible engine of the same performance characteristics as the L-141 engine. We demonstrated that operating the vehicle under terms of strict economy results in considerable loss of acceleration. In investigating the M-151 vehicle, the only change was that the transmission automatically accommodated the engine to the most desirable speed for minimum fuel consumption at all times. At full load and at high speed the F/A ratio was left unchanged so as not to impair the standard engine performance in the interests of economy. The results of these imposed limitations is that acceleration of the M-151 vehicle is poor, but that further fuel economies are possible by a small sacrifice in high-speed output by using a somewhat reduced F/A ratio instead of the rich F/A ratio used at full output. Such an adjustment would hardly affect the acceleration.

This report presents the results of additional calculations with the perfectly flexible engine, and compares the acceleration characteristics of a vehicle with standard transmission with the acceleration characteristics of a vehicle with a perfectly flexible engine.

III. METHOD OF CALCULATION

The relationship between time, velocity, and acceleration for small increments dt of time is given by

Acceleration = change of velocity/time

$$\alpha = \frac{dv}{dt} \text{ ...Eq. (1)} \qquad (1)$$

α = acceleration, fps^2

dv = increment of velocity, fps

dt = time increment, sec.

Force required for acceleration $= \frac{w}{g}\alpha = F$, lb

F = force acting on mass

w = weight accelerated, lb

g = gravitational acceleration

The power supplied by the engine is given by

Power = work done/unit time

$$= F\frac{dx}{dt}$$

dx = distance moved through, ft

dt = time for dx, ft sec

$$= \frac{w}{g}\alpha\frac{dx}{dt} = 550 \text{ d(hp) ft lb/sec.}$$

But,

$$\frac{dx}{dt} = \text{velocity}$$

$$\therefore \alpha = \frac{550 \text{ d(hp)}}{v \times \frac{w}{g}} \text{ ft/sec}^2\text{...Eq. (2)} \qquad (2)$$

d(hp) = increase in hp available for acceleration.

Using Equation (2), the acceleration α can be calculated at any instant when the velocity is v fps and a change d(hp) occurs in the engine output in excess of the road requirements.

Equations (1) and (2) can be written in the finite difference form:

$$\Delta t = \frac{\Delta v}{\alpha}, \tag{3}$$

$$\alpha = \frac{17700 \times \Delta\, hp}{vw} \tag{4}$$

Using finite differences, the time to accelerate from v_1 to v_2 fps is given by $\sum \Delta t$ or

$$t_{v_1 \to v_2} = \sum_{v_1 \to v_2} \frac{\Delta v}{\alpha} \tag{5}$$

The maximum performance of the vehicle can be calculated theoretically using Equations (3)-(5). Such calculations represent the actual acceleration from any steady speed to some higher desired speed which is achieved by suddenly applying full throttle and maintaining it until the desired speed is reached. The sequence of events is then a given hp_{v_1} at speed v_1 fps for the initial steady operation followed by the application of the maximum engine power $hp_{v_1 max}$ the instant acceleration begins, which is the full-throttle output at the same rpm as the steady speed. This is followed by the gradual change in hp_{max} as engine speed increases as the vehicle accelerates until the desired velocity is reached. Of course, as vehicle speed increases the road resistance also increases; thus the available hp for acceleration is always given by

$$\text{Available hp} = hp_{max} - hp_{road}.$$

In Ref. 1, Fig. 1 records the ground hp at all speeds for the L-141 vehicle, and Fig. 10 is a plot of hp_{max} versus engine speed. It follows that the value of Δ hp for any initial condition is the difference between the engine hp under the desired steady road speed and the hp_{max}; as acceleration occurs the available hp changes with speed according to these two diagrams. This performance is then divided into suitable elements of Δt and the step-by-step calculation process repeated as necessary.

One step of the calculation can be illustrated by Fig. 1, which shows the road resistance hp, i.e., the steady input of hp required to maintain constant velocity, and the maximum hp available at full throttle for all speeds.

Divide the speed scale into a series of equal increments, say 2.5 mph; take as an example the element for 10-12.5 mph; then at point 10 mph, $hp_{R\ 10}$ is the road resistance, while $hp_{max\ 10}$ is the maximum hp available. Similarly, at 12.5 mph we have $hp_{R\ 12.5}$ and $hp_{max\ 12.5}$. Since it is assumed that during

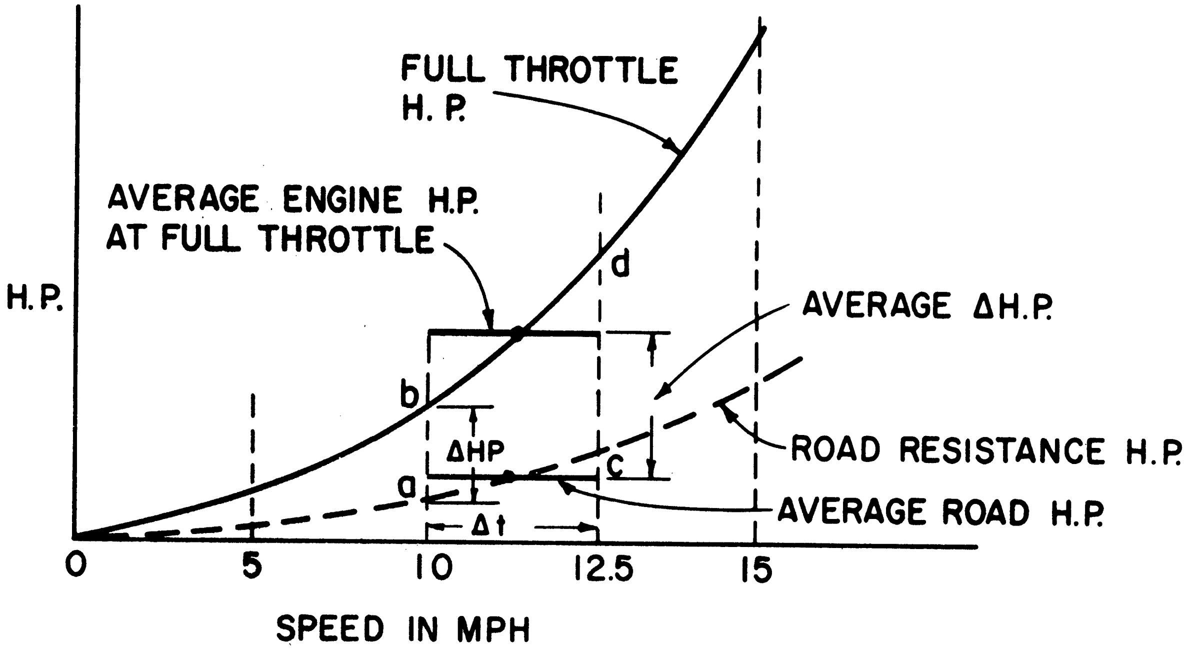

Fig. 1. Method of approximation.

any elements of time Δt the Δ hp, etc., is also constant, the above values of output, etc., are averaged as shown in Fig. 1, and the elements are treated as being subjected to an average Δ hp, as shown for the time Δt from 10 to 12.5 mph. Equation (2) then gives the average acceleration for the element: the time Δt is given by

$$v_{12.5} = v_{10} + \alpha\,\Delta t$$

$$\Delta t = \frac{v_{12.5} - v_{10}}{\alpha}$$

and the distance traveled by

$$S = v_{10}\,\Delta t + \frac{1}{2}\,\alpha(\Delta t)^2.$$

Thus acceleration, distance, and time for any range of speeds, loads, etc., can be determined by a series of calculations.

IV. RESULTS

The data used in Calculations for the M-151 vehicle are given in Tables I-IV, and the following conditions were investigated

1. Standard Vehicle on
    - a. Pavement
    - b. 1.5 x Pavement
    - c. 2.0 x Pavement
    - d. 3.0 x Pavement
2. Flexible Engine Operation of M-151
    - a. Pavement
    - b. 1.5 x Pavement
    - c. 2.0 x Pavement
    - d. 3.0 x Pavement

TABLE I

HP REQUIREMENTS ON PAVEMENT

mph	hp to Overcome Resistance	mph	hp to Overcome Resistance
2.5	0.1	35.0	12.3
5.0	0.3	37.5	14.7
7.5	0.5	40.0	17.3
10.0	0.96	42.5	20.5
12.5	1.30	45.0	23.9
15.0	1.90	47.5	28.0
17.5	2.70	50.0	32.1
20.0	3.50	52.5	36.6
22.5	4.80	55.0	41.0
25.0	6.00	57.5	46.5
27.5	7.50	60.0	51.0
30.0	8.56	62.5	56.9
32.5	10.70	65.0	62.0

TABLE II

EFFICIENCY EMPLOYED IN DIFFERENT GEAR RATIOS

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

TABLE III

ENGINE BHP AND FUEL FLOW

rpm	bhp_{max}	Fuel Flow, lb/hr at max hp
250	4.5	3.0
500	7.3	6.0
1000	17.0	12.0
1400	28.4	16.5
1800	35.5	19.5
2200	45.0	24.0
2600	51.0	28.5
3000	54.0	30.0
3400	59.0	35.0
3800	60.0	37.5
4200	60.0	40.0

TABLE IV

FLEXIBLE ENGINE PERFORMANCE

Pavement Resistance, hp	bhp_{max} for Minimum Fuel	Fuel Flow, lb/hr	Pavement Resistance, hp	bhp_{max} for Minimum Fuel	Fuel Flow, lb/hr
0.0	0.0	0.0	26.0	33.0	18.5
2.0	3.5	3.0	28.0	35.0	19.0
4.0	5.0	4.5	30.0	38.0	21.0
6.0	7.5	6.0	32.0	42.0	22.5
8.0	11.0	9.5	34.0	45.0	24.0
10.0	13.0	10.5	36.0	47.0	25.5
12.0	17.0	12.0	38.0	48.0	26.0
14.0	21.0	14.0	40.0	49.0	27.0
16.0	25.0	15.0	45.0	51.0	28.0
18.0	26.0	15.5	50.0	54.0	30.0
20.0	28.0	16.5	55.0	59.0	35.0
22.0	30.0	17.0	60.0	60.0	37.5
24.0	32.0	18.0			

Gear changes were made at appropriate points (see Table V). For example, at 10 mph on pavement the acceleration in 1st gear ends and the start of operation in 2nd gear begins. The data at 10 mph in 1st gear are used to evaluate the step just completed, and the 2nd gear speed is used for the beginning of the next step from 10 to 15 mph. The gear shift is considered to be instantaneous when the velocity reaches 10 mph.

In this manner the time, acceleration, distance, fuel consumption, etc., can be calculated, and the standard and flexible units compared.

The calculations were run on a computer; a sample of the final machine tabulation is shown in Table V, which covers the speed range from 17.5 to 35 mph on pavement with the standard vehicle in 2nd gear at 17.5 mph, in 3rd at 20-32.5, and in 4th at 35.0 mph, as is indicated by the change in engine rpm.

The data used in evaluating this vehicle are those given in Ref. 1; data obtained from the present calculations are given in Table VI.

TABLE V

SAMPLE MACHINE TABULATION OF RESULTS

mph	Vel., fps	V_{avg}, fps	rpm	Road, hp	hp_{max}	Accel. α, ft/sec^2	α_{avg}	Time, sec	Total Time, sec	Fuel Rate, lb/sec x 10^3	Fuel Rate, avg	Fuel Used, lb	Total Fuel, lb	Distance Traveled, ft	Total Distance, ft
17.50	25.67		3366.69	2.65	55.94	11.99			1.71	9.61			9.78		32.14
		27.50					3.51	1.04			3.06	3.19		32.55	
20.00	29.33		2023.50	3.36	37.45	7.02			2.76	6.12			12.97		64.69
		31.17					6.97	.53			6.51	3.42		18.32	
22.50	33.00		2276.44	4.60	41.54	6.92			3.28	6.91			16.39		83.00
		34.83					6.78	.54			7.30	3.95		20.84	
25.00	36.67		2529.38	5.75	44.19	6.63			3.82	7.70			20.34		103.84
		38.50					6.39	.57			7.90	4.53		24.18	
27.50	40.33		2782.32	7.19	45.17	6.16			4.40	8.11			24.88		128.02
		42.17					5.97	.61			8.28	5.09		28.15	
30.00	44.00		3035.26	8.21	46.23	5.78			5.01	8.46			29.96		156.18
		45.83					5.62	.65			8.89	5.80		32.29	
32.50	47.67		3288.19	10.26	47.34	5.46			5.66	9.33			35.77		188.47
		49.50					1.69	2.17			3.21	6.96		115.40	
35.00	51.33		2119.45	11.55	31.54	3.38			7.84	6.41			42.73		303.87

V. PERFORMANCE COMPARISON

Graphs of the two types of engines under each of the road conditions investigated are shown in Figs. 2-9:

Standard Vehicle on Pavement	Fig. 2
Flexible Vehicle on Pavement	Fig. 3
Standard Vehicle 1.5 x Pavement	Fig. 4
Flexible Vehicle 1.5 x Pavement	Fig. 5
Standard Vehicle 2.0 x Pavement	Fig. 6
Flexible Vehicle 2.0 x Pavement	Fig. 7
Standard Vehicle 3.0 x Pavement	Fig. 8
Flexible Vehicle 3.0 x Pavement	Fig. 9

For comparative purposes the important data have been compiled in Tables VI and VII for acceleration up to the maximum speed possible under the assumed conditions. Some columns contain two sets of values: The first gives the same speed range as the standard unit; the second gives values up to the maximum possible vehicle speed. Exact maximum speed in each case is difficult to obtain, since it is a variable for the two conditions, standard drive and maximum economy power, because both engine rpm and hp vary at the limiting value.

Table VII records the differences between time, distance, and fuel of the flexible system compared to the standard one. The flexible vehicle takes 3-4 times as long to accelerate, requires 1.5-4.0 times the distance, and uses 1.4-2.3 times as much fuel in the process.

It is difficult to calculate accurately the initial acceleration, time, etc., because the slowest engine speed at which satisfactory performance can be secured with the L-141 engine is about 600 rpm (see Appendix, page 24). In the calculations it must be assumed that the engine rpm is not zero when the mph is zero, otherwise no power would be available. It was considered that the lowest engine speed that could be employed was 500 rpm and that 1.5 hp was developed to give the required traction plus slip of the clutch as necessary for a start. These assumptions prevent accurate determination of the actual acceleration below the 2.5 mph. Fortunately the effect of these inaccuracies upon the total values is quite small.

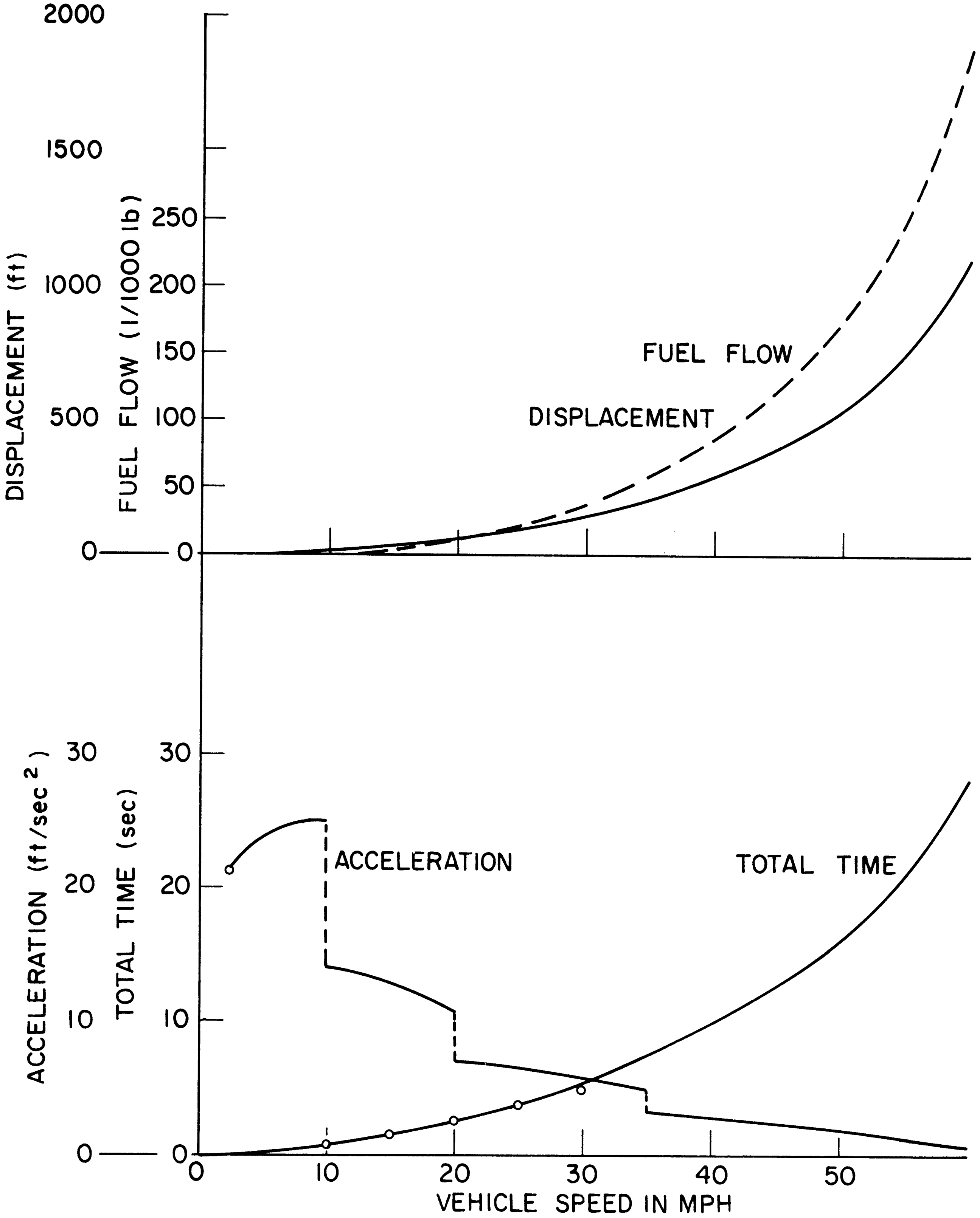

Fig. 2. Performance curves, standard vehicle on pavement.

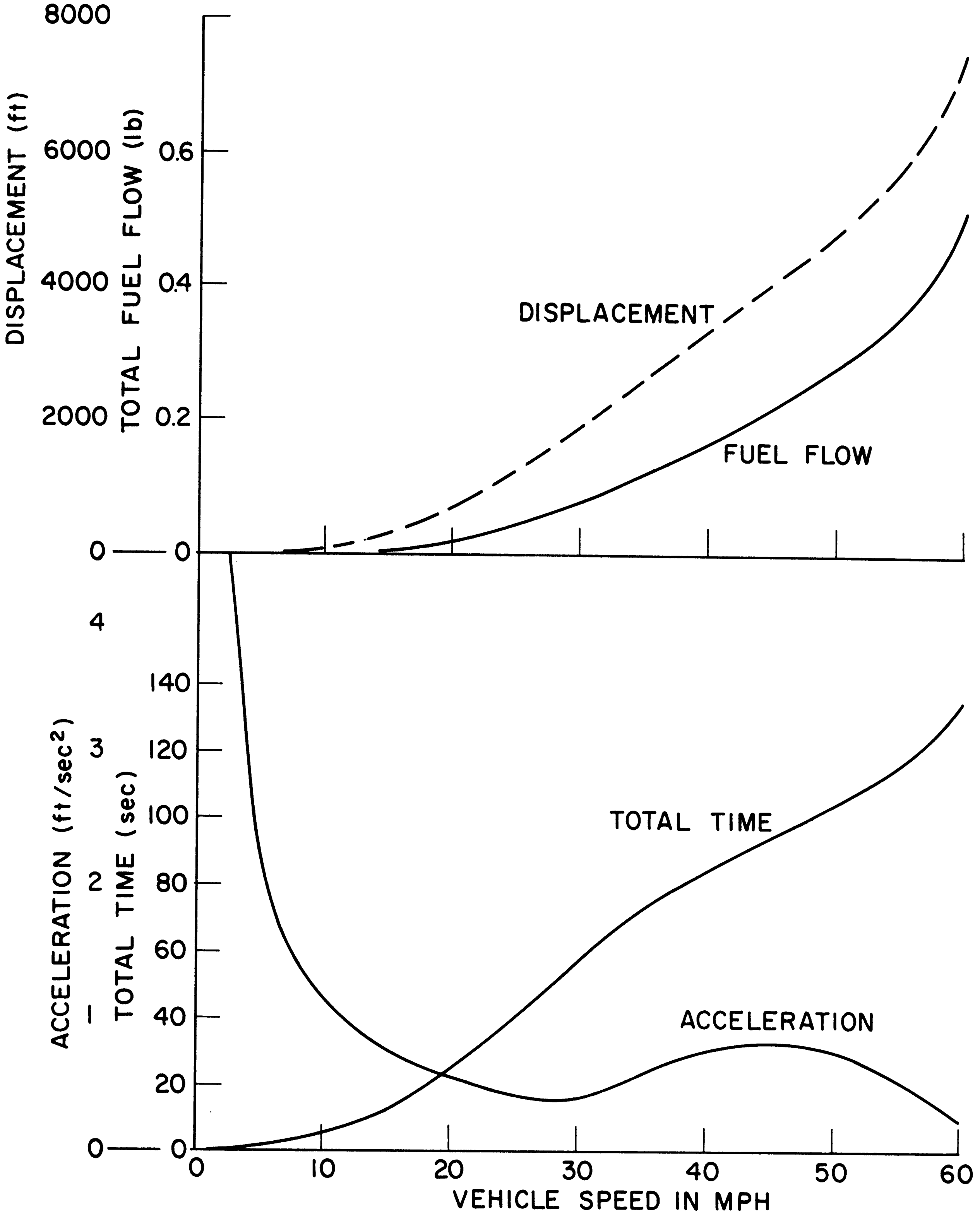

Fig. 3. Performance curves, flexible vehicle on pavement.

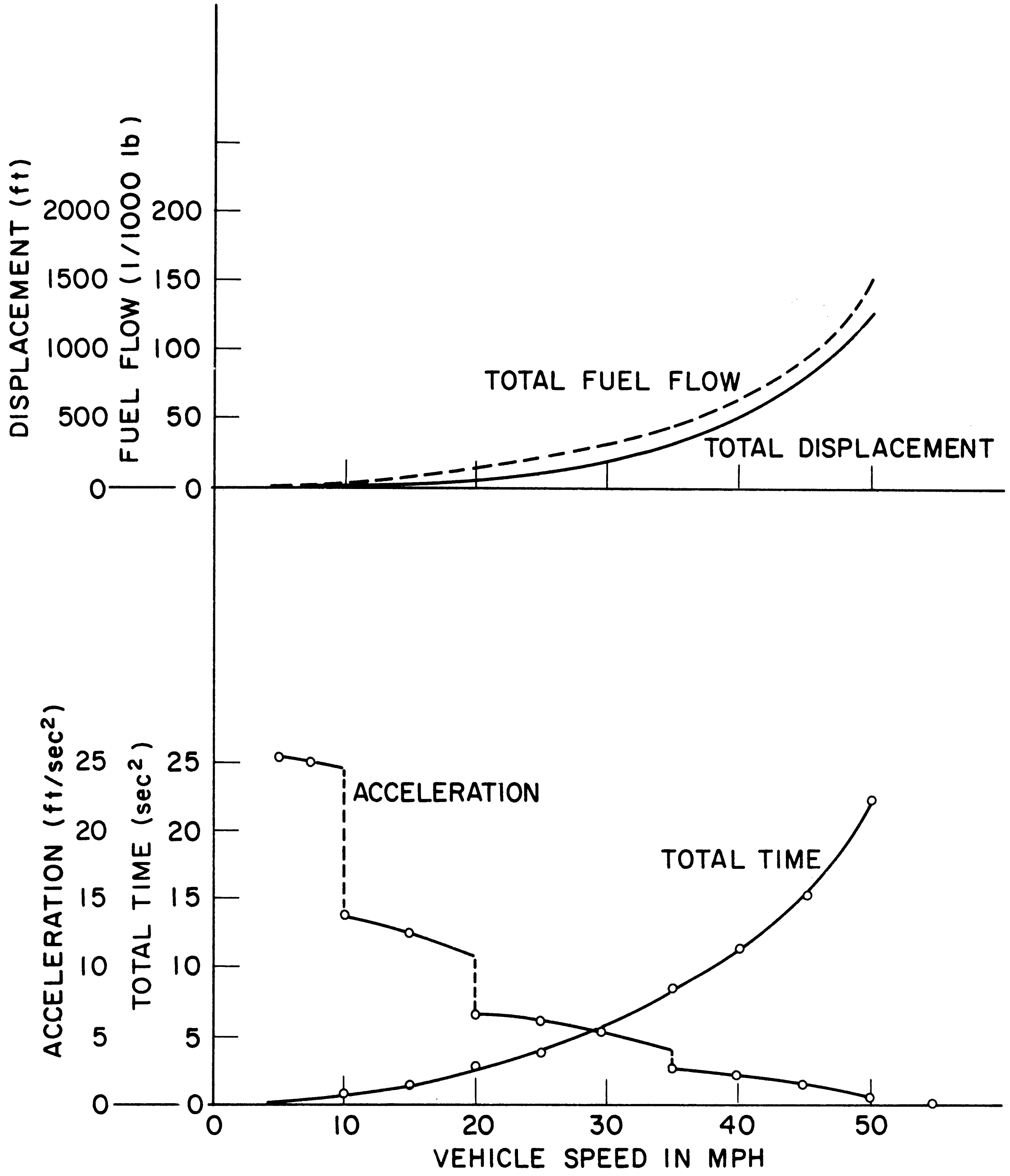

Fig. 4. Performance curves, standard vehicle, 1.5 times pavement resistance.

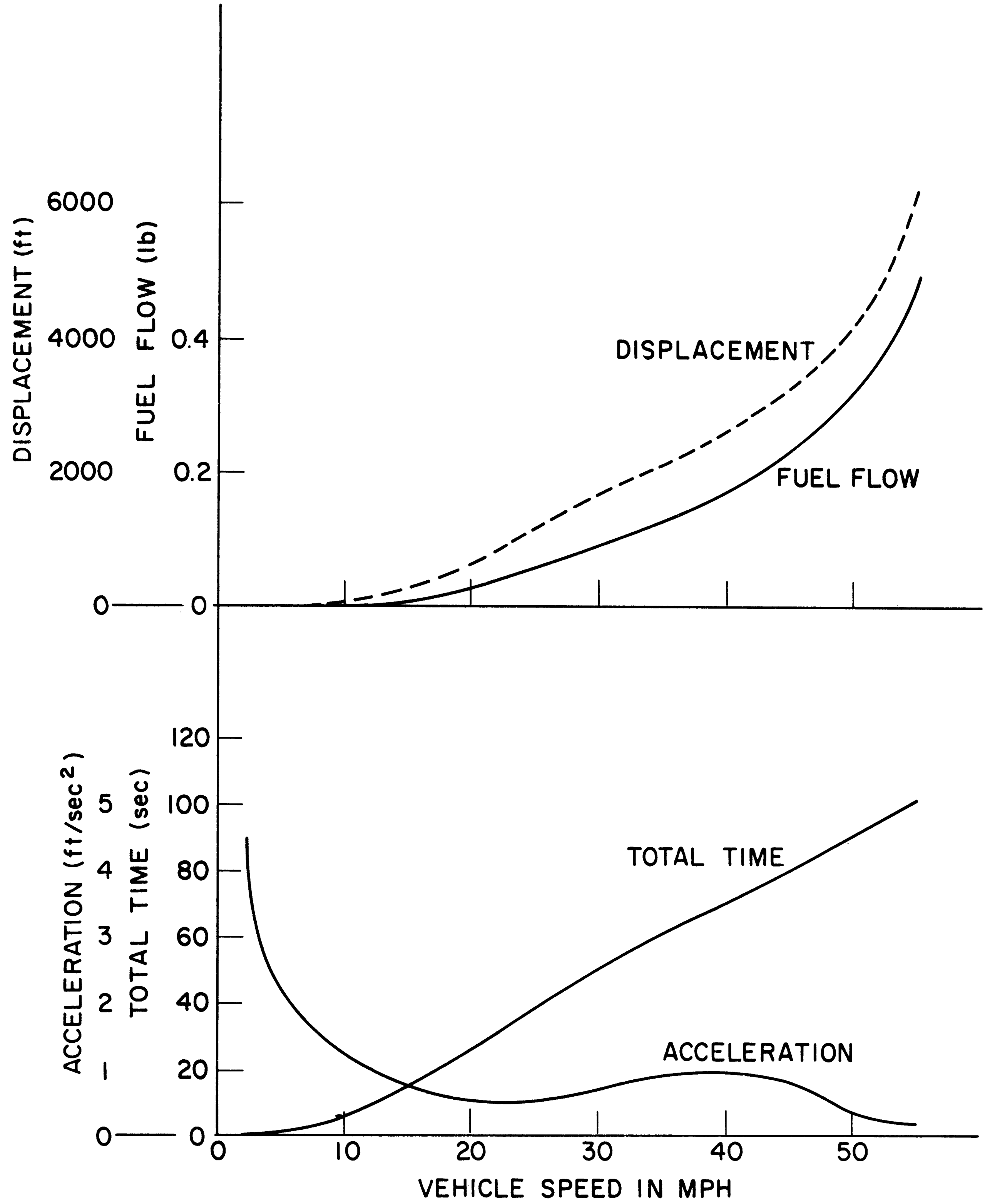

Fig. 5. Performance curves, flexible vehicle, 1.5 times pavement resistance.

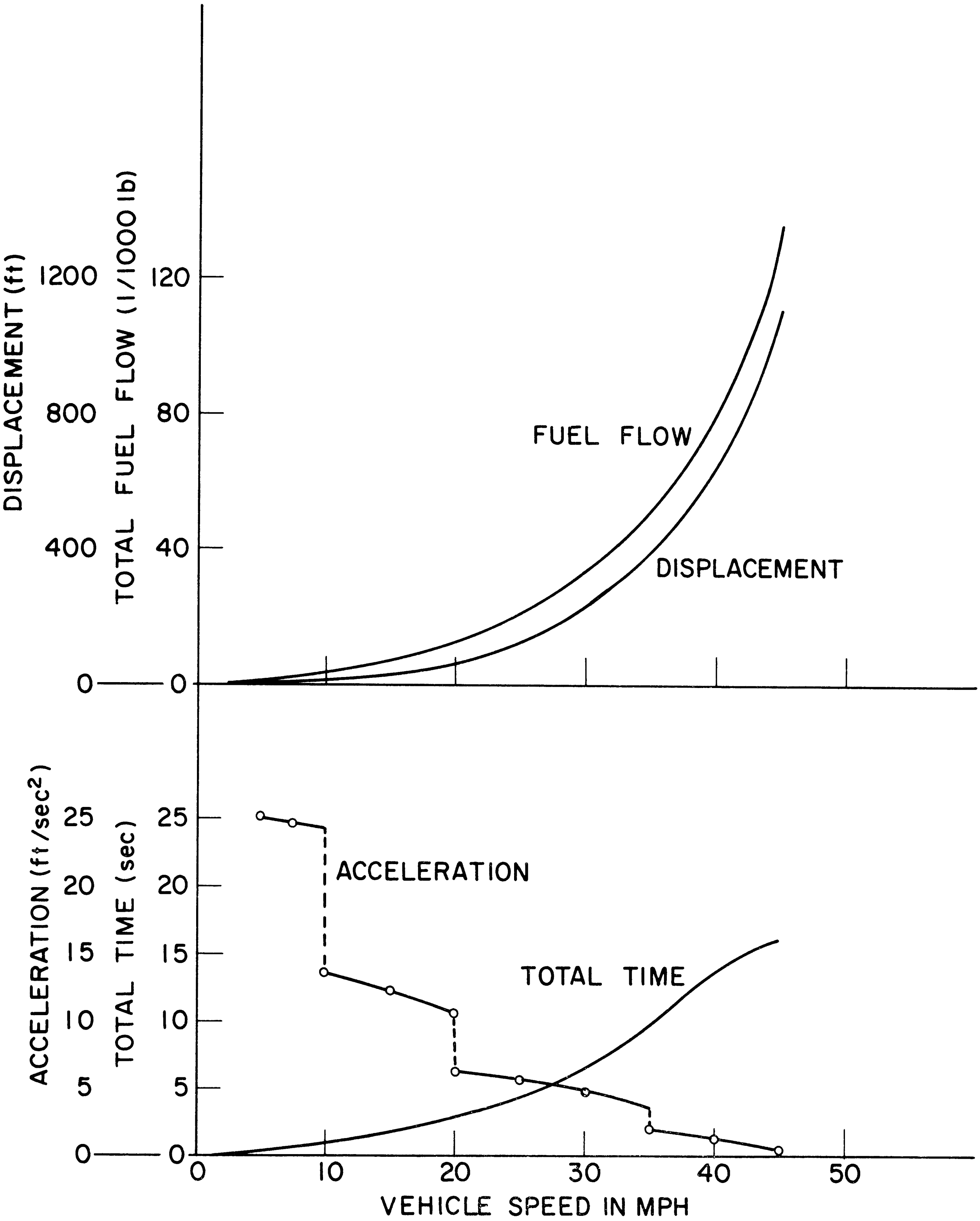

Fig. 6. Performance curves, standard engine, 2.0 times pavement resistance.

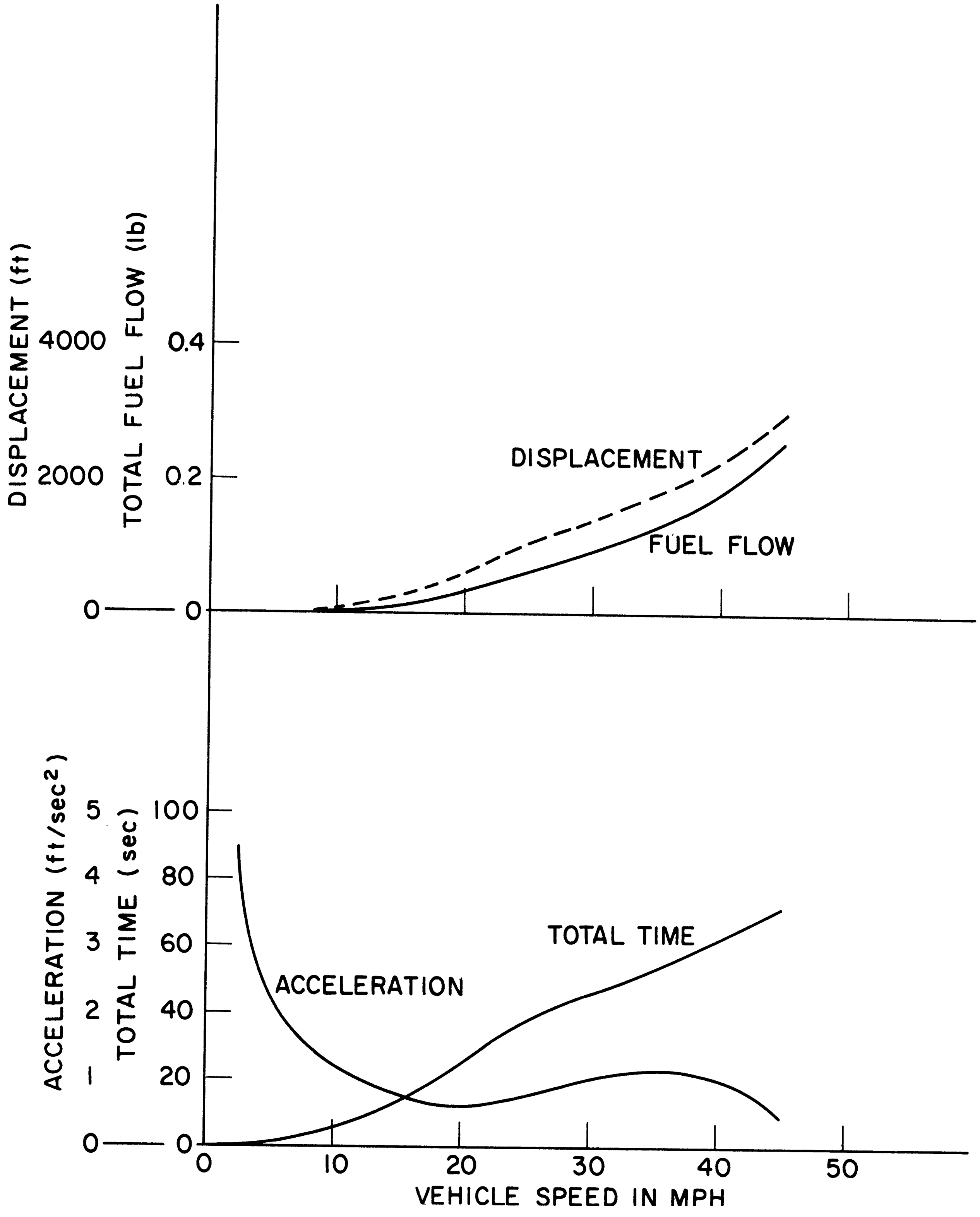

Fig. 7. Performance curves, flexible engine, 2.0 times pavement resistance.

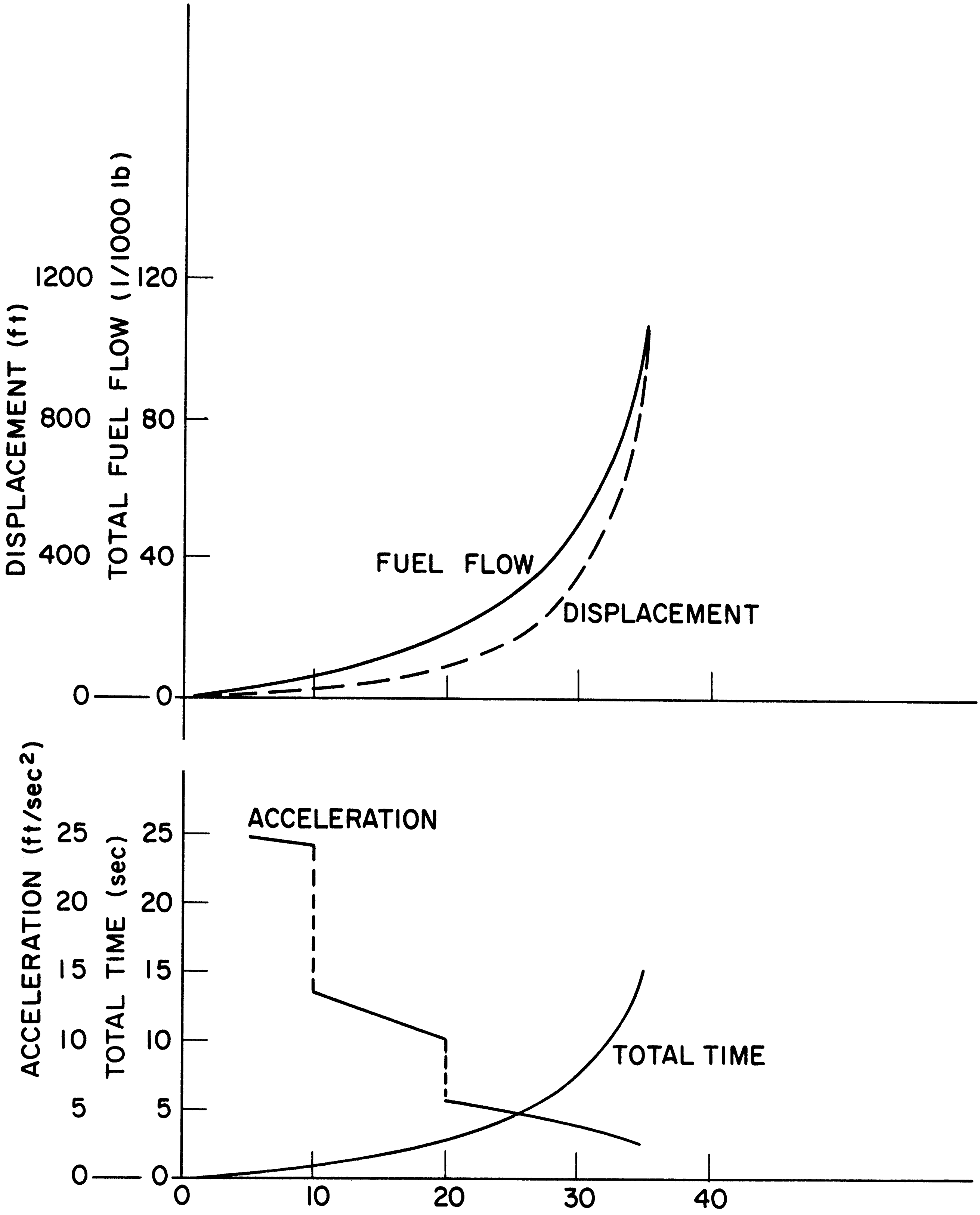

Fig. 8. Performance curves, standard engine, 3.0 times pavement resistance.

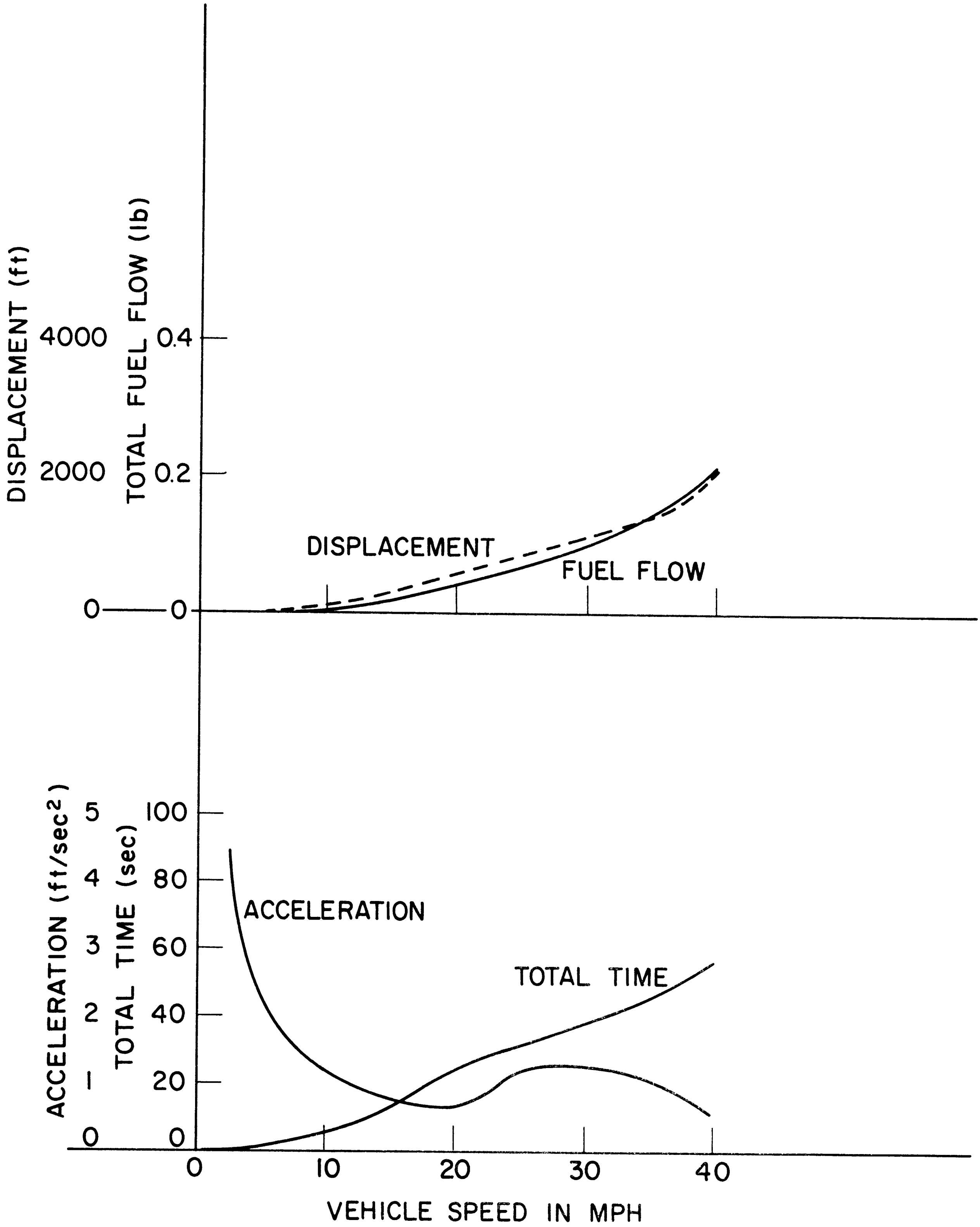

Fig. 9. Performance curves, flexible engine, 3.0 times pavement resistance.

TABLE VI

COMPARATIVE PERFORMANCE OF STANDARD AND FLEXIBLE SYSTEMS

Vehicle	Road Surface	Maximum Acceleration Reached, fps^2	Total Time, sec	Distance Traveled, ft	Fuel Flow for Period, lb	Specific Fuel Flow, ft/lb of Fuel	Speed Range, mph
Standard	Pavement	25.0	28.0	1900	0.225	8450	0-60
Flexible	Pavement	4.5	136.0	7600	0.52	14600	0-60
Standard	1.5 x Pavement	25.0	22.5	1300	0.155	8400	0-50
Flexible	1.5 x Pavement	4.5	91	4200	0.325	12900	0-50
			101	6300	0.50	12600	0-55
Standard	2.0 x Pavement	25.0	15.2	1120	0.136	8240	0-45
Flexible	2.0 x Pavement	4.5	72.0	3000	0.26	11550	0-45
Standard	3.0 x Pavement	25.0	15.5	990	0.109	9090	0-35
Flexible	3.0 x Pavement	4.5	46.0	1430	0.15	9540	0-35
			57.0	2100	0.215	9770	0-40

TABLE VII

RELATIVE PERFORMANCE OF FLEXIBLE SYSTEM

Acceleration, mph		Increase Relative to Standard Unit			Resistance
From	To	Time	Distance	Fuel	
0	60	4.85	4.0	2.3	Pavement
0	50	4.05	3.23	2.1	1.5 x Pavement
0	45	4.73	2.68	1.9	2.0 x Pavement
0	35	2.97	1.45	1.38	3.0 x Pavement

VI. DISCUSSION

To obtain a correct picture of the merits of a flexible engine as compared with the standard system, one would have to make a complete appraisal of the operating regime of the vehicle. Reference 1 analyzed the 48-hr Battlefield Day; based on fuel economy alone, the flexible unit scored approximately a 2:1 advantage over the standard system. In that analysis, however, the need for acceleration, etc., did not enter; so that, in fact, based on present results, the flexible system has some definite limitations not readily apparent from the earlier report. One would have to have a tape recording of a typical day's operation or an estimated program of events including starts, accelerations, stops, duration at certain speeds, etc., in order to obtain an accurate estimate of the relative merits of the two systems.

Obviously, the situation depends a great deal upon the events that occur in any time interval: Periods of continued stops, starts, and accelerations could reduce the 2:1 advantage demonstrated in Ref. 1 to almost a 1:1 equality, as judged by the data of Table VII. We believe that under normal conditions the flexible system will have a definite advantage as far as fuel economy is concerned, but this advantage will be achieved only at a considerable sacrifice in pick-up ability.

The data in this report suggest that the next step should be to examine the transmission possibilities to see if, by suitable design and gear changing, the higher acceleration factors can be re-established, while the economy of the flexible system is still preserved. Although such a step might result in reducing the fuel economy from 2:1 to a less ideal 1.5:1 approximately, an overall advantage may be secured in the process.

It should be kept in mind that all studies to date on the flexible engine have included the same engine characteristics outlined in this report; no attempts have been made to eliminate the increased F/A ratio for vehicles under maximum load and at high speed which is wasteful of fuel for the small increase in power secured.

Column 7, Table VI, gives a specific fuel flow: This is the distance traveled per pound of fuel burned during the acceleration period. Of course, the greater this distance is, the greater the overall economy will be; but, as we shall see, the acceleration time will also be greater. This time factor is greatest when the engine hp is the lowest (on pavement), and it is reduced as the engine hp is increased. This is to be expected, because it is at low resistance that the standard transmission utilizes the engine output in the least favorable manner. However, even at the 3.0:1 pavement resistance the flexible system has about a 7% advantage over the standard system so far as ft/lb are concerned.

VII. CONCLUSIONS

The ideal flexible engine system, as applied to the M-151 vehicle without changing the engine characteristics, has the following advantages over the standard engine and transmission system:

1. It reduces fuel consumption during the 48-hr Battlefield Day by as much as one-half.

2. It increases the time of acceleration from 0-60 mph on pavement in the ratio of 4.8:1.

3. It increases the distance traveled in reaching 60 mph by 4:1.

4. It increases the fuel burned during the acceleration period by 2.3:1.

These conclusions suggest that a new appraisal of the system be made, in which acceleration, etc., are included in the 48-hr Battlefield Day.

VIII. APPENDIX

I. Engine Developments Required

If the M-151 engine is to approach even closely the ideal of flexibility, certain improvements must be made. To ascertain some of these improvements, instrumentation was applied to three different vehicles for the purpose of obtaining various driver reactions under simulated flexible conditions.

The main requirement for flexibility, as determined in Ref. 1, is that the engine operate at the lowest speed under all conditions of vehicle performance. As Fig. 12 and Table VII of Ref. 1 show, a large percentage of engine operating time, particularly on pavement, occurs at relatively low speeds when compared with the standard transmission. For example, in the 35 mph range the speed must be reduced from 1500-1800 rpm to about 500 rpm.

The object of our experiments was to gather as much information as possible regarding low-speed operation of existing equipment. Since the M-151 vehicle can be considered a light one, we decided to experiment with vehicles in this same class:

1. Triumph Herald, a small, 4-cylinder engine of light weight and high speed, giving maximum hp at about 5000 rpm.

2. Chevrolet (1956 model with stick transmission) a 6-cylinder engine with a peak rpm of about 4000.

3. M-151 4-cylinder engine with stick transmission, with a peak rpm of 3600 approx.

Of these three vehicles, (1) would be considered the most likely to show the greatest effects of slow speed; (2) and (3) would probably be about the same, although (2) would be expected to be somewhat better than (3) by virtue of the six cylinders.

The standard carburator and ignition system of each vehicle was adjusted to the lowest speed at which the engine could idle smoothly without danger of stalling: Triumph, 500 rpm; Chevrolet, 500 rpm; M-151, 550 rpm.

Then, equipped with an electronic tachometer, each vehicle was operated on the level road, on such hills as are locally available, and in all gear ratios in order to determine the slowest speed at which vehicle jerk became noticeable. All three vehicles were operated under the same conditions, and the results were recorded.

A. TRIUMPH

On level road, on hills, and in all gears, the Triumph began to "buck" noticeably at speeds of 450-550 rpm; the lower speed could be approached only slowly if complete stall was not to occur. All tests indicated that the bucking occurred because either the ignition system failed to provide satisfactory ignition, or the carburetor failed to supply combustible mixture, or both, at speeds lower than the conventional idle speed. In other words, to achieve a satisfactorily low operating speed the engine's idling ability must be improved by changes in the ignition system, carburetor, valve-timing, manifolding, etc.

B. CHEVROLET

The same conclusions were reached for the Chevrolet as for the Triumph. Despite its 6-cylinder engine, the Chevrolet was able to idle at speeds only slightly, if at all, lower than the Triumph's idling speed.

C. M-151 VEHICLE

Fairly extensive tests were conducted on the M-151, since this is the vehicle under consideration. The results of these tests are presented on Table VIII. The lowest engine idling speed was 550 rpm.

Observe that in this case substantially the same conclusions were reached as for the other two vehicles, the only exception being that on the steeper downhill runs higher speeds were recorded because of the driving component from the vehicle.

II. Conclusions

Before the flexible engine system can be completely effective, the engine's performance at low speeds must be improved. Since low-speed operation can occupy a considerable portion of the Battlefield Day, the possibilities for fuel economy are greatest under these conditions. Therefore some effort to reduce idling speed is justified. However, improvements to slow-speed performance usually affect the high-speed output adversely. This factor must be taken into account.

Before any development work is undertaken, a hypothetical case should be examined. The effect on the overall results of any improvements in acceleration and in low-speed operation should be calculated by the methods presented in this paper. to determine how far such efforts to improve low-speed operation should be carried before funds are expended.

TABLE VIII

M-151 VEHICLE PERFORMANCE AT LOW SPEEDS

Road Surface	Year	Lowest Engine Speed	Comments
Level Blacktop	1st	675	
	2nd	700	
	3rd	650	
	4th	675	
Level Gravel	1st	700	
	2nd	725	
	3rd	625	
	4th	675	
Uphill 20° Blacktop	1st	650	
	2nd	625	
	3rd	600	
	4th	625	
Downhill 20° Blacktop	1st	750	These results affected by the vehicle driving engine.
	2nd	750	
	3rd	800	
	4th	825	
Gravel 12° Incline Uphill	1st	675	
	2nd	650	
	3rd	650	
	4th	600	
Gravel 12° Downhill	1st	675	
	2nd	675	
	3rd	650	
	4th	550	

REFERENCE

1. Vincent, E. T., The Flexible Engine, ORA Report No. 05847-3-F, University of Michigan, May, 1964.