THE UNIVERSITY OF MICHIGAN
COLLEGE OF ENGINEERING
Department of Mechanical Engineering

Technical Report

VEHICLE PERFORMANCE EMPLOYING MINIMUM RESPONSIVENESS WITH AN EXISTING TRANSMISSION

E. T. Vincent
N. Tokuda

ORA Project 05847

under contract with:

U. S. ARMY
DETROIT PROCUREMENT DISTRICT
CONTRACT NO. DA-20-018-AMC-0729-T
DETROIT, MICHIGAN

administered through:

OFFICE OF RESEARCH ADMINISTRATION ANN ARBOR

January 1964

TABLE OF CONTENTS

LIST OF TABLES

LIST OF TABLES (Concluded)

LIST OF FIGURES

ABSTRACT

This report covers the calculation of a compression ignition engine of the turbocharged type having a minimum responsiveness. The degree of responsiveness to be employed being such that at no point of the vehicle's operating schedule will the performance be inferior to a present typical engine and transmission with torque converter and lockup.

An engine with a 1.68:1 responsiveness, as defined in the text, is found to give a performance superior at all speeds except the ones at which the match is made and at the points of full power.

The Battlefield Day (BFD) fuel requirement data are presented below.

Type of Engine	Fuel/24 hr lb
Turbocharged compression ignition engine in lockup	1039.8
Turbocharged compression ignition engine in torque converter	1361.7
Turbocharged compression ignition engine in combinations of lockup and torque converter	1142.5
1.68:1 responsive engine with 5% stall operation	1084.1
Turbocharged engine with torque converter and 5% stall operation	1513.0

The conditions to be met by the turbocharger to achieve the 1.68:1 responsiveness are examined and found to be the provision of an exhaust manifold pressure control and variable turbine geometry. The range of air flow required appears to be within the capabilities of a well designed centrifugal compressor. It follows that the development for both engine and turbocharger should be at a minimum since the engine performance factors have been kept at about the maximum already achieved under R and D contracts.

I. INTRODUCTION

There is a distinct possibility that an engine with some degree of responsiveness will, when coupled to an existing shift-type of transmission, give such superior driver feel and response that the installation of such an engine in a vehicle would not only improve the performance but reduce driver fatigue as well. This same reaction has already been demonstrated with other items of equipment, such as tractors, etc., employing engines with but slight torque curve changes. If this can be demonstrated for the type of vehicle now being considered, the problem of developing a completely responsive engine with no transmission over a speed range of at least 10 to 12:1 is unnecessary, and the problem is greatly simplified.

In this report, the magnitude of the responsiveness is understood to be the magnitude by which the torque, and thus the BMEP (brake mean effective pressure), will increase as the engine speed is reduced from 100% to 33-1/3%, a 3:1 range. Thus, for a responsiveness of 3, the BMEP at 1/3 speed will be three times that at full speed; in other words, the horsepower will be constant; this is sometimes called 100% responsive. It follows that a responsiveness of 2 will have twice the BMEP at 1/3 speed as at full speed, and the power will be 2/3 that of full load, or 66.6% responsive, and so on. In other words, an engine speed range of 3:1 is assumed to be capable of development in a reasonable time, the balance of any speed control being obtained with a transmission.

This reaction could be illustrated simply in the following manner. Figure 1 shows a typical level road resistance curve for an automobile together with the maximum horsepower available from the engine at all speeds. Looking at the curves for speed "a" mph, there is available "x" hp from the engine with "y" hp required to maintain the speed constant at "a" mph. Plainly, the vehicle under such conditions responds freely to throttle changes, since (x-y) hp is available for acceleration or additional load due to any reason.

Now, consider the case when the road speed is "b" mph; steady state on a level road can be maintained, but acceleration to any other speed is very slow since the available horsepower is only $(x'-y')$, a very small amount. At this point, any large increase in load cannot be compensated for by increased engine horsepower; operation of the throttle gives a flat feeling to the driver, and a gear shift is indicated. It does not take much change in horsepower, as shown by the dotted curve in Fig. 1, to restore to a great extent the feeling of good control to the driver. For example, if $x'-y' = 1$ when the engine horsepower x' is 200, then if the engine horsepower x'' was only 202, $x''-y'$ is double $x'-y'$, and the acceleration possible is also doubled. At a point such as this, a 10% increase in available power can make a tre-

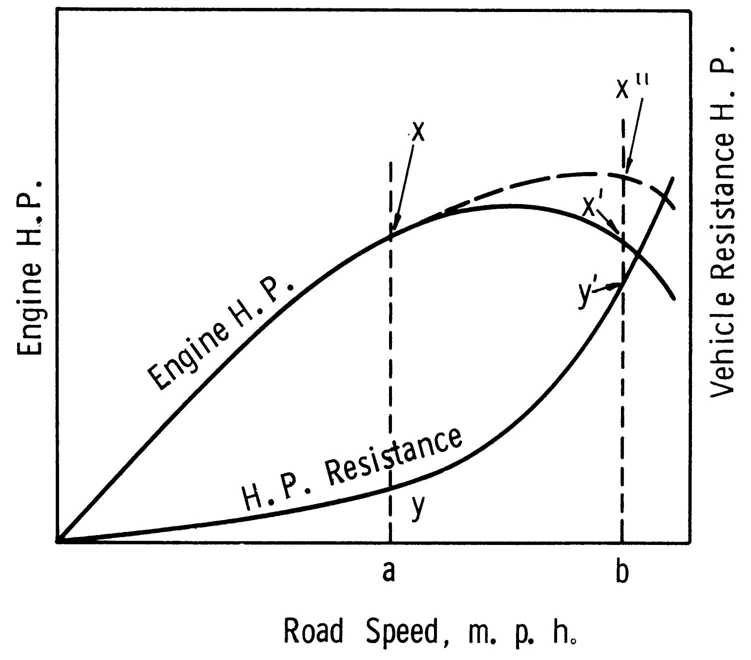

Fig. 1. Typical resistance and horsepower curves.

mendous difference in operator response as far as gear changing, etc., is concerned. The same is true under any other conditions where the available horsepower is close to the resistance. Of course a 10% increase in horsepower at any speed is also a 10% increase in torque or BMEP, the terms usually employed for such cases.

The type of change considered here is not a major one as far as magnitude is concerned, but in place of the 1 to 10% illustrated above it is believed that it is possible to consider an increase of 1.5 up to 2.0 times the engine torque at low engine-speed when the unit is loaded down and the point of gear shifting is reached.

It will be assumed that the operator will stay in any one ratio so long as the vehicle responds and feels adequately under control. If the full engine-speed is 3000 rpm, probably the operator would not tend to change gears provided that the feeling of good control still existed down to say 1000 rpm. It follows that if a responsiveness of 2:1 could be achieved from 3000 to 1500 rpm the vehicle would (if an automobile) feel as lively at 1500 rpm as at 3000 rpm since the same horsepower would be available at the two road speeds. In fact, it would give an improved response since the horsepower will be unchanged at the low speed but the road resistance will be reduced. Alternatively, if the vehicle was loaded down by increased load or the addition of a loaded trailer so that the engine speed was pulled down to 1500 rpm, there would still be a feeling of adequate control since the horsepower available could still be more than sufficient for the load applied; in fact, it would be more than twice that normally available at that speed, the actual magnitude depending upon the shape of the torque curves, fan losses, etc.

Turning to the immediate problem in hand, viz., estimating the minimum responsiveness necessary to simplify vehicle operation without excessive driver fatigue or sacrifice in performance, the following analysis is employed.

This examination is based upon the following units:

1. Engine.—The power plant is to be a turbocharged compression ignition engine of 500 hp at 3000 rpm.

2. Transmission.—Power Train, Model XTG-411-1 Hydraulic Torque Converter Planetary Gear, All Torque Shifting.

The above selection was based upon the availability of complete engine performance as estimated in Fig. 16, Ref. 1, plus transmission data supplied by U.S. Army Tank-Automotive Center, reproduced in Fig. 2. Using the engine data of Fig. 16, Ref. 1, the present performance data at full output of the conventional engine for the various speeds is recorded in Fig. 3.

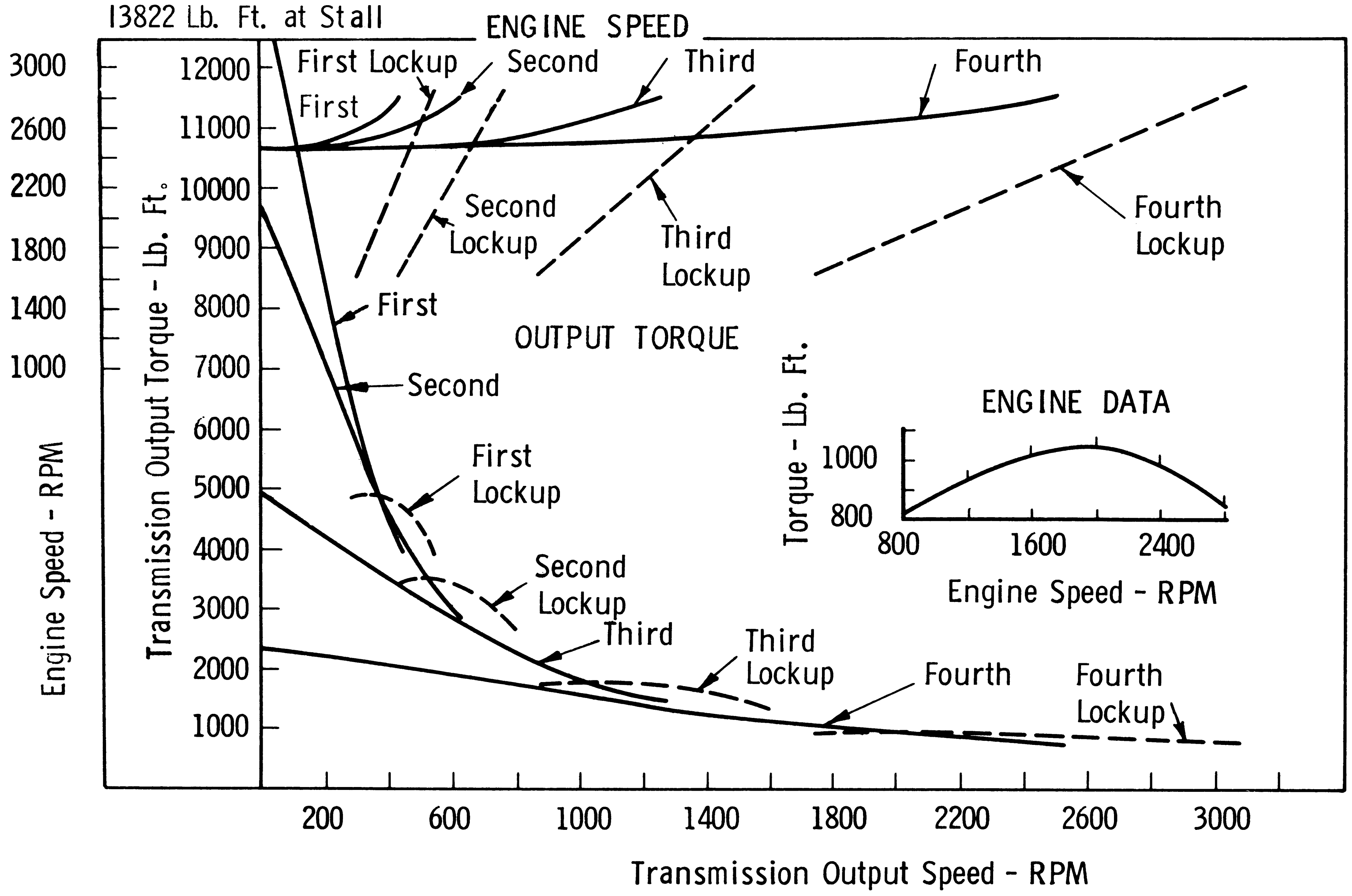

Fig. 2. XTG-411-1 transmission performance.

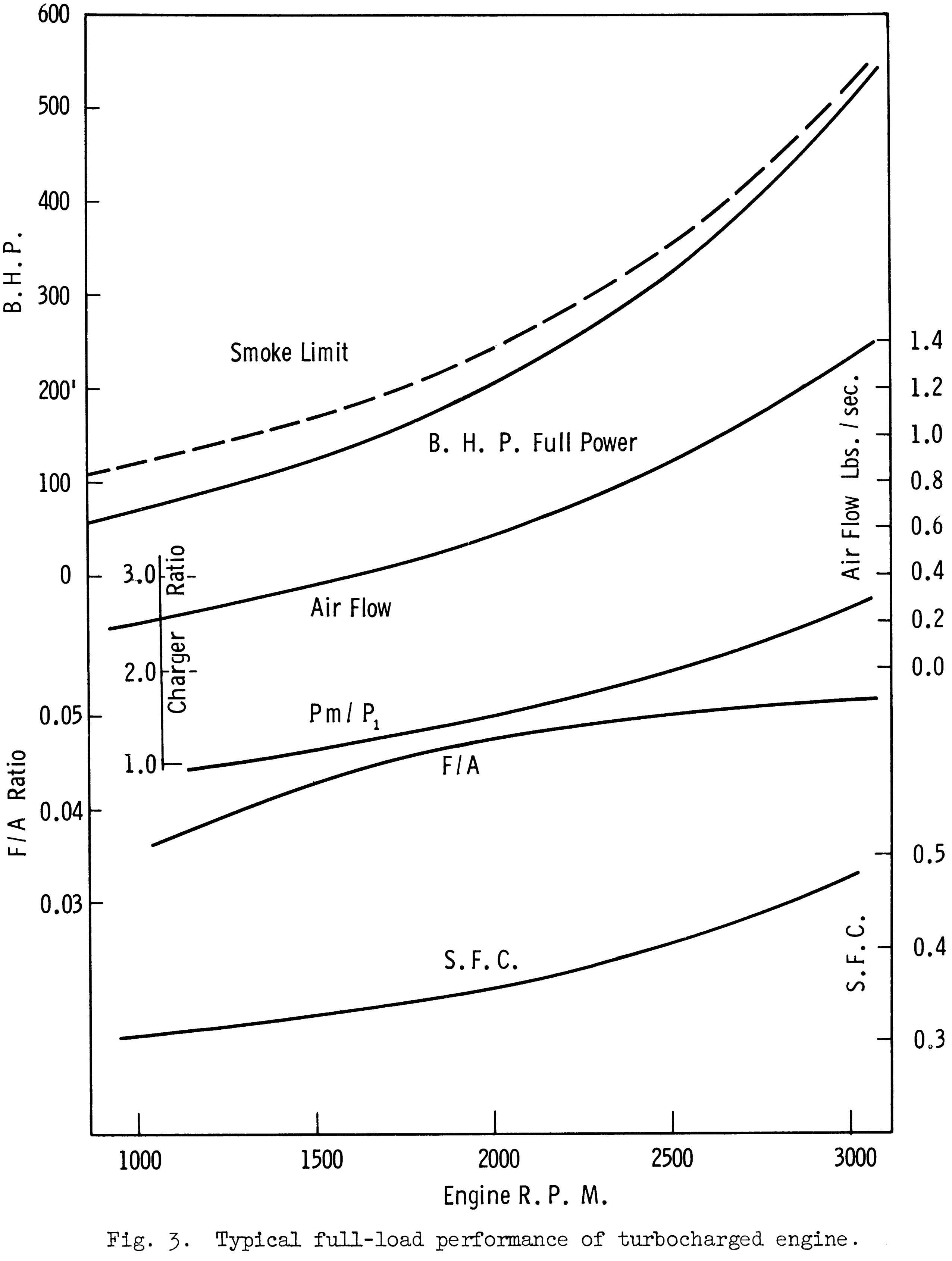

Fig. 3. Typical full-load performance of turbocharged engine.

II. ESTIMATE OF VEHICLE PERFORMANCE

Using the above data the following analysis is to be made:

a. Overall vehicle performance at full load with presently installed engine using both the torque converter system and lockup transmission, and a comparison made with the performance of a responsive engine from the viewpoint of vehicle tractive force.

b. Overall vehicle performance both full and part load by present engine and torque converter and lockup system, and a comparison with the performance by a responsive engine based upon a viewpoint of fuel economy.

c. Fuel consumption over a Battlefield Day with conventional engine and a minimum responsive one.

III. METHOD OF CALCULATION

The following calculations are based upon a vehicle having the following specifications.

Vehicle weight: 43 tons

Pitch diameter of sprocket: 22.19 in.

Final drive ratio: 5.4:1

Maximum coefficient of friction: 80%

Rolling resistance (first-class roads)

mph	lb/ton
2	67.0
3	67.5
4	68.0
5	68.0
6	68.0
7	68.5
8	69.0
9	70.0
10	73.5
15	72.0
16	69.0
17	68.0
18	67.0
19	67.0
20	67.0
30	70.0

The Battlefield Day (BFD) calculations are based upon the following schedule of operations and resistances (Table I).

The first schedule for the conventional engine is the same as that usually employed for BFD calculations. The second schedule for both the conventional and responsive engines has reduced the 40% time at twice first-class road resistance to 35% and added a 5% period in which the vehicle could be stalled by some obstacle. At this time the engine is operating at its maximum horsepower but at minimum engine speed (of say 1000 rpm) in order to minimize ground slip while at the same time giving high torque to the track.

TABLE I

BATTLEFIELD DAY SCHEDULES

Vehicle Speed, mph	Rolling Resistance	Time % of BFD: Conventional Engine Only	Time % of BFD: Conventional and Responsive Engine with Stall
15, 16, 17, 18, 19, 20	1.57 times that of 1st class roads	20.0	20.0
2, 3, 4, 5, 6, 7, 8, 9, 10	2.0 times that of 1st class roads	40.0	35.0
0 - engine idle	0.0	40.0	40.0
0 - maximum hp at minimum rpm	Vehicle stalled by obstacle, etc.	0.0	5.0

The relations between vehicle speed, resistance, engine torque, power, and rpm on various slopes are as follows. (Due to the low speeds of vehicle operation, air-drag has been neglected as well as acceleration requirements.)

The vehicle is assumed to be off the road upon a slope of $\alpha°$ to the horizontal as shown in Fig. 4. Then

$$\text{Force in track} = \text{Weight reaction along slope} + \text{Resistance of vehicle against motion}$$

$$= W \sin \alpha + \mu_{gvo} W \cos \alpha$$

where

W = weight of vehicle in lb

μ_{gvo} = coefficient of rolling resistance on ground at V mph and zero slope

α = slope in degrees

If the transmission sprocket has a diameter of D ft, then the torque on the sprocket shaft must be

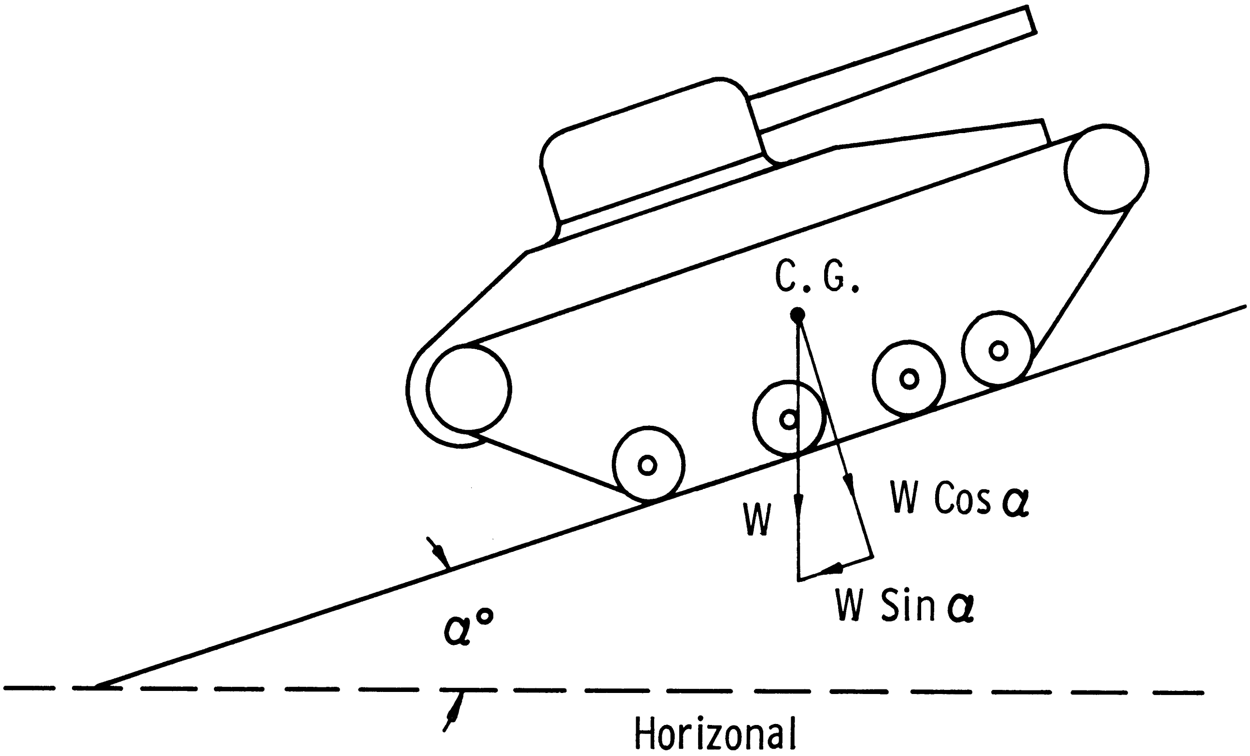

Fig. 4. Forces with vehicle on slope of α.

$$\text{Sprocket shaft torque} = \text{force in track} \times D/2$$

$$= \frac{WD}{2} (\sin \alpha + \mu_{gvo} \cos \alpha) \text{lb ft.} \qquad (1)$$

The data supplied record that the rolling resistance at low speeds (off-the-road operation on poor terrain) is twice that of a first-class road. Assuming that the same applies to the road resistance when climbing, it follows that on a first-class level road

$$\text{Sprocket shaft torque } (T_s) = \mu_{fvo} W \frac{D}{2} \text{ or } \mu_{fvo} = \frac{2T_s}{WD} \qquad (2)$$

where

T_s = torque on sprocket in lb ft

μ_{fvo} = coefficient of rolling resistance on a level first-class road at V mph

The value of μ_{fvo} is given in the previous pages in terms of lb/ton weight. It follows that off the road the value of μ_{gvo} will be given by $\mu_{gvo} = (1.57 \text{ to } 2.0)\mu_{fvo}$ depending upon the speed; Table II then gives the rolling resistance of the vehicle being examined under the various speed conditions.

TABLE II

ROLLING RESISTANCES ON LEVEL GROUND

Vehicle Speed, mph	1st Class Road, μ_{fvo}		Off the Road, μ_{gvo}	
	lb/ton	lb/lb	lb/ton	lb/lb
2	67.0	0.0335	134.0	0.067
3	67.5	0.0338	135.0	0.0675
4	68.0	0.0340	136.0	0.0680
5	68.0	0.0340	136.0	0.0680
6	68.0	0.0340	136.0	0.0680
7	68.5	0.0343	137.0	0.0685
8	69.0	0.0345	138.0	0.0690
9	70.0	0.0350	140.0	0.0700
10	73.5	0.0368	147.0	0.0735
15	72.0	0.0360	113.1	0.0566
16	69.0	0.0345	108.4	0.0542
17	58.0	0.0340	106.8	0.0534
18	67.0	0.0335	105.2	0.0526
19	67.0	0.0335	105.2	0.0526
20	67.0	0.0335	105.2	0.0526
30	70.0	0.0350	110.0	0.055

If an equivalent rolling resistance/ton is employed (defined as $\mu_{gv\alpha}$), that is, the equivalent rolling resistance of the vehicle on ground at a slope of α at V mph, we may write

$$\mu_{gv\alpha} = (\sin\alpha + \mu_{gvo} \cos\alpha)$$

and for off-the-road operation

$$\frac{\text{Total rolling resistance on slope } \alpha \text{ at V mph}}{\text{Total rolling resistance on slope } \alpha = 0 \text{ at V mph}} = \frac{\sin\alpha + \mu_{gvo} \cos\alpha}{\mu_{gvo}}$$

or

$$\text{Vehicle resistance on slope } \alpha \text{ at V mph} = \frac{\sin\alpha + \mu_{gvo} \cos\alpha}{\mu_{gvo}} R_{gvo} \qquad (3)$$

where

R_{gvo} = resistance on level ground at V mph.

The value of the ratio $\sin\alpha + \mu_{gvo} \cos\alpha/\mu_{gvo}$ for each value of the slope is shown in Table III. Observe that the variation of this ratio with vehicle speed is of a very minor order for slopes of low magnitude, but it increases with the slope.

Collecting together the relations between engine, transmission, and track we have:

A. RESISTANCES

$$\text{Vehicle resistance at V mph on first-class level road} = R_{fvo} = \mu_{fvo} W$$

where

W = weight of vehicle in lb

μ_{fvo} = rolling resistance per lb on first-class level road at velocity of V mph

$$\text{Vehicle resistance on level ground off the road} = R_{gvo} = 1.57 - 2.0\ R_{fvo}$$

$$= \mu_{gvo} W$$

TABLE III

RESISTANCE FACTOR $\frac{\sin \alpha + \mu_{gvo} \cos \alpha}{\mu_{gvo}}$ FOR VARIOUS SLOPES

α	Resistance Factor	Miles per Hour															
		2	3	4	5	6	7	8	9	10	15	16	17	18	19	20	30
0°	μ_{gvo}	.0670	.0675	.0680	.0680	.0680	.0685	.0690	.0700	.0735	.0566	.0542	.0534	.0526	.0526	.0526	.055
	$\sin \alpha$	.017	.017	.017	.017	.017	.017	.017	.017	.017	.017	.017	.017	.017	.017	.017	.017
1°	$\mu_{gvo} \cos \alpha$	.067	.0675	.068	.068	.068	.0685	.0690	.0700	.0735	.0566	.0542	.0534	.0526	.0526	.0526	.055
	$\frac{\mu_{gvo} \cos \alpha + \sin \alpha}{\mu_{gvo}}$	1.255	1.261	1.252	1.252	1.252	1.25	1.246	1.244	1.232	1.3	1.314	1.32	1.323	1.323	1.323	1.31
		.035	.035	.035	.035	.035	.035	.035	.035	.035	.035	.035	.035	.035	.035	.035	.035
2°	as above	.067	.0675	.068	.068	.068	.0685	.0690	.0700	.0735	.0566	.0542	.0534	.0526	.0526	.0526	.055
		1.52	1.52	1.515	1.515	1.515	1.511	1.507	1.501	1.476	1.618	1.645	1.655	1.665	1.665	1.665	1.639
		.052	.052	.052	.052	.052	.052	.052	.052	.052	.052	.052	.052	.052	.052	.052	.052
3°	as above	.0669	.0674	.0679	.0679	.0679	.0684	.0689	.0699	.0734	.0656	.0541	.0534	.0525	.0525	.0525	.0549
		1.774	1.769	1.764	1.764	1.764	1.756	1.751	1.74	1.706	1.915	1.958	1.973	1.986	1.986	1.986	1.943
		.070	.070	.070	.070	.070	.070	.070	.070	.070	.070	.070	.070	.070	.070	.070	.070
4°	as above	.0668	.0673	.0678	.0678	.0678	.0683	.0688	.0698	.0733	.0564	.0540	.0532	.0524	.0524	.0524	.0548
		2.04	2.033	2.028	2.028	2.028	2.018	2.01	1.995	1.95	2.23	2.29	2.31	2.327	2.327	2.327	2.27
		.087	.087	.087	.087	.087	.087	.087	.087	.087	.087	.087	.087	.087	.087	.087	.087
5°	as above	.0667	.0672	.0677	.0677	.0677	.0682	.0687	.0697	.0732	.0563	.0539	.0531	.0523	.0523	.0523	.0547
		2.294	2.28	2.278	2.278	2.278	2.265	2.256	2.24	2.18	2.53	2.60	2.62	2.65	2.65	2.65	2.575
		.174	.174	.174	.174	.174	.174	.174	.174	.174	.174	.174	.174	.174	.174	.174	.174
10°	as above	.066	.0665	.0670	.0670	.0670	.0675	.068	.069	.0725	.0556	.0532	.0524	.0516	.0516	.0516	.054
		3.58	3.562	3.542	3.542	3.542	3.53	3.51	3.487	3.35	4.05	4.19	4.24	4.29	4.29	4.29	4.15
		.259	.259	.259	.259	.259	.259	.259	.259	.259	.259	.259	.259	.259	.259	.259	.259
15°	as above	.0647	.0652	.0657	.0657	.0657	.0662	.0667	.0677	.0712	.0544	.052	.0512	.0504	.0504	.0504	.0528
		4.83	4.805	4.775	4.775	4.775	4.75	4.72	4.665	4.498	5.54	5.73	5.81	5.89	5.89	5.89	5.67
		.342	.342	.342	.342	.342	.342	.342	.342	.342	.342	.342	.342	.342	.342	.342	.342
20°	as above	.063	.0635	.064	.064	.064	.0645	.065	.066	.0695	.0533	.0509	.0501	.0493	.0493	.0493	.0517
		6.05	6.01	5.97	5.97	5.97	5.935	5.90	5.83	5.6	6.98	7.24	7.35	7.44	7.44	7.44	7.16
		.423	.423	.423	.423	.423	.423	.423	.423	.423	.423	.423	.423	.423	.423	.423	.423
25°	as above	.061	.0615	.062	.062	.062	.0625	.063	.064	.0675	.0521	.0497	.0489	.0481	.0481	.0481	.0505
		7.22	7.18	7.14	7.14	7.14	7.08	7.04	6.95	6.68	8.38	8.72	8.84	8.96	8.96	8.96	8.61

Vehicle resistance on slope $\alpha°$ off the road at V mph $= R_{gv\alpha} = \left(\frac{\mu_{gvo}\cos\alpha+\sin\alpha}{\mu_{gvo}}\right) R_{gvo}$

$$= \mu_{gvo}\left(\frac{\mu_{gvo}\cos\alpha+\sin\alpha}{\mu_{gvo}}\right) W \text{ lb.}$$

B. TORQUE

When driven by a sprocket of diameter D in. with a track resistance of R lb the sprocket torque is given by

$$\text{Sprocket torque} = \frac{D}{24} \times R \text{ lb ft} = T_s$$

then for

(a) First-class level road

$$T_{s_f} = \frac{D}{24} R_{fvo}$$

$$= \mu_{fvo}\frac{WD}{24} \text{ lb ft.} \tag{4}$$

(b) Off-road level ground

$$T_{s_g} = \frac{D}{24} R_{gvo}$$

$$= \mu_{gvo}\frac{WD}{24} \text{ lb ft.} \tag{5}$$

(c) Off road on slope of $\alpha°$

$$T_{s_\alpha} = \frac{D}{24} R_{gv\alpha}$$

$$= \mu_{gvo}\left(\frac{\mu_{gvo}\cos\alpha+\sin\alpha}{\mu_{gvo}}\right)\frac{WD}{24}$$

$$= \frac{\mu_{gvo}\cos\alpha+\sin\alpha}{\mu_{gvo}} T_{s_g} . \tag{6}$$

C. TRANSMISSION TORQUE

The transmission output torque for the vehicle under the various conditions will be given by

$$\begin{aligned}\text{Transmission output torque} &= T_{TO}\\ &= \text{sprocket torque x } \frac{1}{DR_f x \eta_D}\\ &= \frac{\text{appropriate } T_s(f, g, \text{ or } \alpha)}{DR_f x \eta_D} \qquad (7)\end{aligned}$$

where

DR_f = final drive ratio

η_D = final drive efficiency.

D. ENGINE OUTPUT TORQUE

The engine torque will depend upon transmission losses and is given by

$$\begin{aligned}\text{Engine output torque} &= T_E\\ &= \frac{T_{TO}}{GR_T x \eta_T} \qquad (8)\end{aligned}$$

where

GR_T = gear ratio of transmission

η_T = transmission efficiency.

E. SPEEDS

The speed in rpm at the various locations is given below for any vehicle speed in miles per hour, accompanied with a ground slip of 10%.

$$\text{Sprocket speed } (N_s) = \frac{\text{mph x } 5280 \text{ x } 12}{60 \text{ x } \pi \text{ x } D \text{ x } \eta_s} \text{ rpm}$$

$$N_s = 373 \text{ x } \frac{\text{mph}}{D} \qquad (9)$$

when

η_s = ratio of ground to track speed

= 0.90 (10% slip)

Transmission output speed N_{TO} = sprocket speed x DR_f

$$N_{TO} = 373 \frac{\text{mph} \times DR_f}{D} \text{ rpm} \qquad (10)$$

Engine speed (N_E) = transmission speed x GR_T

$$N_E = 373 \frac{\text{mph} \times DR_f}{D} GR_T \qquad (11)$$

where

GR_T = gear ratio of transmission.

Let

$$DR_f \times GR_f = DR_o$$

= overall drive ratio

then

$$\text{Engine speed } (N_E) = 373 \frac{\text{mph}}{D} DR_o \text{ rpm.} \qquad (12)$$

When examining the case of a torque-converter transmission, the engine speed can be obtained directly from the test data for any given set of conditions (Fig. 2).

F. HORSEPOWER REQUIREMENTS

The horsepower requirements at the various points of interest are as follows:

$$\text{Ground hp applied by track} = \text{resistance} \times \frac{\text{mph} \times 5280}{60 \times 33000 \times \eta_s}$$

$$= 1.905 \times 10^{-4}\, T_E \times N_E.$$

The values to be employed for the various ground conditions are given in Eq. (3) and Table III.

$$\text{Engine horsepower} = \frac{T_E x 2\pi x N_E}{33000}$$

$$= 1.905 \text{ x } 10^{-4}\ T_E \text{ x } N_E\ . \qquad (13)$$

In most cases, the engine horsepower can best be calculated via the ground resistances by using the transmission output torque and the overall transmission efficiency, as below:

$$\text{Engine horsepower} = \frac{2\pi\ N_E}{33000}\ \frac{T_{TO}}{GR_T x \eta_T}\ . \qquad (14)$$

IV. VEHICLE PERFORMANCE OF PROPOSED SYSTEM

The performance of a given vehicle can be predicted from the above equations. In the present instance, the vehicle, engine, and transmission, given on page 3 of this report, will be examined under the various possible systems of operation, torque converter, and lockup to obtain a reference point; the minimum required conditions of responsiveness will then be investigated (for possible engines of the near future) to fulfill, or exceed, the present performance of the assumed combination. To this end the highest torque at transmission output of the present setup, in converter or lockup, will be employed to determine the minimum responsive engine condition; this will set the conditions that the engine must meet, its range of power requirements, etc., to be the equivalent of the present engine and transmission.

Tables IV and V show the vehicle resistances for first-class and off-the-road conditions at 2-10 mph and again at 15-30 mph using the data of pages 9 and 10.

With the above resistances, the ground and sprocket horsepower requirements for off-the-road operation are calculated via Eqs. (8), (12), and (13) with the aid of Eqs. (15)-(18). The results are shown for the various speeds, gear ratios, slopes, etc., in Tables VI-XI.

TABLE IV

GROUND RESISTANCE, 2-10 MPH

Ground Conditions	α	Pounds per Ton								
		2	3	4	5	6	7	8	9	10
First Class Road	0°	67.0	67.5	68.0	68.0	68.0	68.5	69.0	70.0	73.5
Off the Road	0°	134.0	135.0	136.0	136.0	136.0	137.0	138.0	140.0	147.0
	1°	168.1	170.2	170.2	170.2	170.2	171.1	172.0	174.0	180.9
	2°	203.5	205.1	206.1	206.1	206.1	207.0	208.0	210.0	216.9
	3°	237.5	238.6	239.9	239.9	239.9	240.5	241.8	243.5	250.7
	4°	273.0	274.2	276.0	276.0	276.0	276.1	277.5	279.1	286.5
	5°	307.2	307.8	309.5	309.5	309.5	310.2	311.2	313.4	320.1
	10°	479.5	481.0	482.0	482.0	482.0	483.5	484.8	488.0	492.0
	15°	646.5	648.2	649.5	649.5	649.5	650.1	651.1	652.5	660.1
	20°	810.0	811.0	812.0	812.0	812.0	812.1	814.0	816.0	822.0

TABLE V

GROUND RESISTANCE, 15-30 MPH

Ground Conditions	α	Pounds per Ton						
		15	16	17	18	19	20	30
First Class Road	0°	72.0	69.0	68.0	67.0	67.0	67.0	70.0
Off the Road	0°	113.1	108.4	106.8	105.2	105.2	105.2	110.0
	1°	147.1	142.5	141.1	139.3	139.3	139.3	144.0
	2°	184.0	178.4	176.9	175.3	175.3	175.3	180.1
	3°	216.7	212.1	210.9	209.0	209.0	209.0	213.7
	4°	252.2	248.1	247.0	244.9	244.9	244.9	249.6
	5°	286.2	281.8	280.0	278.9	278.9	278.9	283.1
	10°	458.0	454.0	453.0	451.2	451.2	451.2	456.0
	15°	626.5	620.5	621.0	620.0	620.0	620.0	623.0
	20°	790.0	785.0	786.0	783.0	783.0	783.0	787.0

TABLE VI

GROUND HORSEPOWER REQUIREMENTS, 2-10 MPH

Ground Conditions	α	Miles per Hour								
		2	3	4	5	6	7	8	9	10
First Class Road	0°	15.3	23.2	31.25	38.9	46.7	54.9	62.2	72.2	84.2
Off the Road	0°	30.7	46.4	62.2	77.8	92.4	109.8	126.5	144.5	168.5
	1°	38.5	58.5	78.0	97.4	117.0	137.2	157.7	179.5	207.0
	2°	46.6	70.5	94.4	117.9	141.5	166.0	190.5	216.5	248.1
	3°	54.4	82.0	109.8	137.1	164.6	192.8	221.5	251.0	287.0
	4°	62.5	94.2	126.5	157.9	189.5	221.5	254.1	288.0	328.0
	5°	70.4	105.7	141.7	177.0	212.5	248.6	285.0	323.2	367.0
	10°	109.8	165.3	220.7	275.5	331.0	387.5	444.0	503.0	563.0
	15°	148.0	222.8	297.0	371.0	445.5	520.8	597.0	673.0	756.0
	20°	185.5	278.7	372.0	464.0	557.0	651.0	745.0	841.0	941.0

TABLE VII

SPROCKET HORSEPOWER REQUIREMENTS, 2-10 MPH

Ground Conditions	α	Miles per Hour								
		2	3	4	5	6	7	8	9	10
First Class Road	0°	16.9	25.5	34.4	42.8	51.4	60.4	68.4	79.4	92.7
Off the Road	0°	33.8	50.8	68.4	85.6	102.8	120.8	139.1	159.0	185.4
	1°	42.4	64.4	85.8	107.2	128.6	151.0	173.5	197.5	227.5
	2°	51.3	77.5	103.8	129.6	155.6	182.5	209.5	238.0	273.0
	3°	59.8	90.2	120.8	150.8	181.0	212.0	243.5	276.0	315.8
	4°	68.8	103.6	139.2	173.5	208.5	243.5	279.5	316.8	361.0
	5°	77.4	116.2	156.0	194.7	233.5	273.2	313.5	355.5	403.5
	10°	120.7	181.6	242.5	303.0	363.0	426.0	488.0	-	-
	15°	162.6	245.0	326.2	408.0	490.0	-	-	-	-
	20°	207.2	306.2	409.0	509.5	-	-	-	-	-

TABLE VIII

SPROCKET AND TRANSMISSION SPEEDS, 2-10 MPH

Speeds, rpm	Miles per Hour								
	2	3	4	5	6	7	8	9	10
Sprocket, N_S	33.6	50.4	67.2	84.0	100.8	117.5	134.4	151.1	168.1
Transmission, N_T	181.6	272.2	363.0	453.8	544.2	635.5	726.0	816.5	908.0

TABLE IX

GROUND HORSEPOWER REQUIREMENTS, 15-30 MPH

Ground Conditions	α	Miles per Hour						
		15	16	17	18	19	20	30
First Class Road	0°	123.5	124.5	132.5	138.0	145.8	153.5	240.0
Off the Road	0°	194.0	195.4	208.0	217.0	229.0	241.0	377.5
	1°	252.5	257.0	275.0	287.0	303.0	319.0	494.0
	2°	316.0	321.8	344.5	361.0	381.5	401.5	618.0
	3°	372.0	382.8	410.5	430.5	455.0	479.0	734.0
	4°	433.0	447.5	481.0	504.0	533.0	560.5	-
	5°	491.5	508.0	545.0	574.0	606.0	638.0	-
	10°	786.0	819.0	882.0	930.0	982.0	-	-
	15°	1075.0	1120.0	-	-	-	-	-
	20°	1356.0	1416.0	-	-	-	-	-

TABLE X

SPROCKET HORSEPOWER REQUIREMENTS, 15-30 MPH

Ground Conditions	α	Miles per Hour						
		15	16	17	18	19	20	30
First Class Road	0°	135.8	137.0	145.7	151.9	160.4	168.9	264.0
Off the Road	0°	213.2	215.0	228.8	238.8	252.0	265.0	415.2
	1°	277.5	282.8	302.2	315.7	333.0	351.0	544.0
	2°	347.5	353.8	379.0	397.0	419.5	441.5	680.0
	3°	419.0	421.0	451.5	473.5	499.9	526.5	807.0
	4°	476.0	492.0	528.5	554.0	-	-	-
	5°	539.0	558.0	-	-	-	-	-
	10°	-	-	-	-	-	-	-
	15°	-	-	-	-	-	-	-
	20°	-	-	-	-	-	-	-

TABLE XI

SPROCKET AND TRANSMISSION SPEEDS, 15-30 MPH

Speeds, rpm	Miles per Hour 15	16	17	18	19	20	30
Sprocket, N_s	252.0	269.0	286.0	305.0	319.5	336.0	504.5
Transmission, N_T	1360.0	1452.0	1545.0	1646.0	1725.0	1814.0	2723.0

$$\text{Ground horsepower at track} = 0.002662 \times \mu_{fvo} \times W \times \text{mph} \quad (15)$$

$$\text{Sprocket horsepower, 10\% slip} = 0.002930 \times \mu_{fvo} \times W \times \text{mph} \quad (16)$$

$$\text{Sprocket speed } (N_s) = 373 \times \frac{\text{mph}}{D} \quad (17)$$

where

$D = 22.19$ in.

$N_s = 16.81 \times \text{mph}$

$$\text{Transmission output speed } (N_T) = 16.81 \times \text{mph} \times DR_f$$

$$= 90.8 \times \text{mph}. \quad (18)$$

The input to the final drive will depend upon the efficiency of this drive unit; assuming an efficiency of 0.90 for the 2-10 mph data and 93% for the 15-30 mph values, the transmission output requirements are given in Table XII.

With the transmission output horsepower and speed available, the curves of the Model XTG-411-1 Power Train, shown in Fig. 2, can be employed for the engine performance characteristic at the 2-10 mph when employing the torque converter; these results are set out in Tables XIII-XVI employing Fig. 5, calculated from the data supplied, for the efficiency in both converter and lockup conditions.

When the transmission is used in the lockup drive at various vehicle speeds the engine rpm and horsepower requirements are as shown in Tables XVII-XIX.

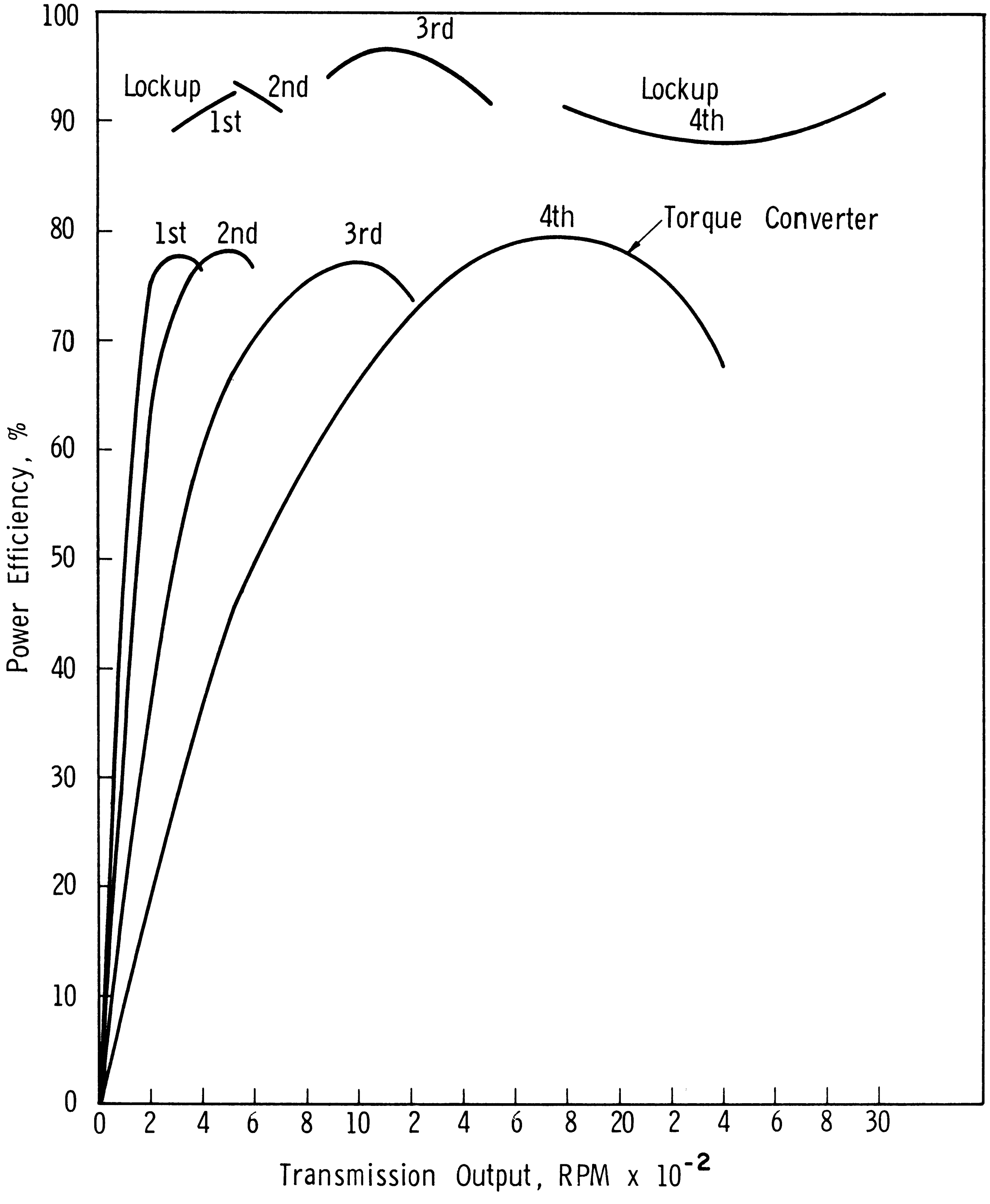

Fig. 5. Efficiency data for XTG-411-1 transmission

TABLE XII

TRANSMISSION OUTPUT HORSEPOWER, 2-30 MPH

Ground Conditions	α	Miles per Hour															
		2	3	4	5	6	7	8	9	10	15	16	17	18	19	20	30
First Class Road	0°	18.8	28.3	38.2	47.5	57.2	67.2	76.0	88.2	103.0	146.0	147.4	156.6	163.2	172.5	181.5	284.0
Off the Road	0°	37.5	56.5	76.0	95.1	114.1	134.1	154.5	176.5	206.0	229.5	231.5	246.0	257.0	271.2	285.0	446.0
	1°	47.1	71.6	95.3	119.1	142.9	167.5	192.8	219.5	253.0	298.7	304.0	325.3	340.0	358.2	378.0	585.0
	2°	57.0	86.2	115.4	144.0	173.0	203.0	233.0	264.8	307.0	374.0	380.5	408.0	427.5	451.0	475.0	730.5
	3°	66.5	100.2	134.2	167.6	201.0	235.5	271.0	307.0	351.0	451.0	453.0	486.0	510.0	537.0	567.0	-
	4°	76.4	115.2	154.6	192.9	231.8	270.5	311.0	352.0	402.0	512.0	530.0	568.0	-	-	-	-
	5°	86.0	129.2	173.3	216.5	259.5	304.0	348.5	395.2	448.5	580.0	600.0	-	-	-	-	-
	10°	134.1	202.0	269.8	337.0	404.0	474.0	543.0	-	-	-	-	-	-	-	-	-
	15°	180.8	272.5	363.0	454.0	546.0	-	-	-	-	-	-	-	-	-	-	-
	20°	230.5	341.0	455.0	566.0	-	-	-	-	-	-	-	-	-	-	-	-

TABLE XIII

FIRST GEAR TORQUE-CONVERTER OPERATION, 2-4 MPH

		Miles per Hour								
		2	3	4	5	6	7	8	9	10
Engine speed, rpm		2485	2540	2640	-	-	-	-	-	-
Transmission efficiency, %		72.5	76.0	77.5	-	-	-	-	-	-
					Engine Horsepower					
First Class Road	α = 0°	25.9	37.2	49.3		Engine overspeeds at all other vehicle speeds.				
Off the Road	= 0°	51.7	74.3	98.6	-	-	-	-	-	-
	= 1°	64.9	94.2	123.0	-	-	-	-	-	-
	= 2°	78.6	113.4	149.0	-	-	-	-	-	-
	= 3°	91.7	131.9	173.2	-	-	-	-	-	-
	= 4°	105.4	151.5	199.5	-	-	-	-	-	-
	= 5°	118.6	170.0	223.7	-	-	-	-	-	-
	= 10°	184.9	265.8	348.0	-	-	-	-	-	-
	= 15°	249.0	358.5	468.5	-	-	-	-	-	-
	= 20°	317.8	448.3	587.0	-	-	-	-	-	-

TABLE XIV

SECOND GEAR TORQUE-CONVERTER OPERATION, 2-7 MPH

		Miles per Hour								
		2	3	4	5	6	7	8	9	10
Engine speed, rpm		2450	2480	2520	2590	2660	2800	-	-	-
Transmission efficiency, %		55.0	71.0	76.0	77.5	77.0	75.0	-	-	-
					Engine Horsepower					
First Class Road	α = 0°	34.2	39.9	50.3	61.2	74.3	89.6	-	-	-
Off the Road	= 0°	68.2	79.6	100.0	122.5	146.5	179.0	-	-	-
	= 1°	85.6	100.9	125.5	153.6	185.4	223.2	-	-	-
	= 2°	103.5	121.5	151.9	185.6	224.5	270.7	-	-	-
	= 3°	120.9	141.2	176.5	216.1	261.0	314.0	-	-	-
	= 4°	138.9	162.2	203.5	248.8	301.0	360.5	-	-	-
	= 5°	156.3	182.0	228.0	279.0	337.0	405.2	-	-	-
	= 10°	238.5	284.5	355.0	434.5	524.0	632.0	-	-	-
	= 15°	328.5	384.0	478.0	586.0	708.0	-	-	-	-
	= 20°	419.0	480.0	599.0	730.0	-	-	-	-	-

TABLE XV

THIRD GEAR TORQUE-CONVERTER OPERATION, 2-10 MPH

		Miles per Hour								
		2	3	4	5	6	7	8	9	10
Engine speed, rpm		2450	2450	2450	2450	2460	2500	2530	2560	2590
Transmission efficiency, %		36.0	47.0	56.5	64.0	68.5	72.3	75.0	77.0	77.7
		Engine Horsepower								
First Class Road	α = 0°	52.2	60.2	67.6	74.2	83.5	92.9	101.4	114.6	132.5
Off the Road	= 0°	104.2	120.3	134.6	148.5	166.6	185.5	206.0	229.2	265.0
	= 1°	130.9	152.5	168.8	186.0	208.6	231.7	257.0	285.0	325.5
	= 2°	158.4	183.5	204.2	225.0	252.8	280.5	310.5	343.8	395.0
	= 3°	184.8	213.2	237.7	262.0	293.5	325.5	361.1	399.0	451.5
	= 4°	212.2	240.0	274.0	301.4	338.2	374.0	414.5	457.0	517.0
	= 5°	239.0	275.0	307.0	338.2	379.0	420.2	464.8	514.0	577.0
	= 10°	372.5	430.0	478.0	526.5	590.0	656.0	723.0	-	-
	= 15°	502.0	580.0	643.0	710.0	798.0	-	-	-	-
	= 20°	640.0	726.0	-	-	-	-	-	-	-

TABLE XVI

FOURTH GEAR TORQUE-CONVERTER OPERATION, 2-10 MPH

		Miles per Hour								
		2	3	4	5	6	7	8	9	10
Engine speed, rpm		2450	2450	2450	2450	2450	2455	2460	2470	2480
Transmission efficiency, %		16.5	23.0	32.5	40.5	46.5	51.0	54.5	58.5	61.5
		Engine Horsepower								
First Class Road	α = 0°	114.0	123.1	117.5	117.2	123.0	131.8	139.5	150.7	167.4
Off the Road	= 0°	227.5	245.8	233.8	234.5	245.3	263.0	283.5	301.5	335.0
	= 1°	285.8	311.4	293.0	294.0	307.0	328.5	354.0	375.0	411.3
	= 2°	345.8	375.0	354.8	355.3	372.0	398.1	427.5	452.5	499.0
	= 3°	403.4	436.0	412.5	413.5	432.5	462.0	497.5	524.5	570.3
	= 4°	463.0	501.0	475.5	476.0	498.5	530.0	571.0	602.0	653.0
	= 5°	522.0	562.0	533.0	534.0	558.0	596.0	640.0	-	-
	= 10°	814.0	-	-	-	-	-	-	-	-
	= 15°	-	-	-	-	-	-	-	-	-
	= 20°	-	-	-	-	-	-	-	-	-

TABLE XVII

FIRST GEAR LOCKUP, 2-6 MPH

		Miles per Hour								
		2	3	4	5	6	7	8	9	10
Engine speed, rpm		950	1400	1870	2350	2800	-	-	-	-
Transmission efficiency, %		85.0	87.5	90.0	91.8	92.5	-	-	-	-
					Engine Horsepower					
First Class Road	α = 0°	22.1	32.3	42.5	51.8	61.8	-	-	-	-
Off the Road	= 0°	44.2	64.6	84.5	103.6	123.3	-	-	-	-
	= 1°	55.4	81.8	106.0	129.9	154.4	-	-	-	-
	= 2°	67.1	98.5	128.3	156.9	187.0	-	-	-	-
	= 3°	78.2	114.5	149.0	182.7	217.1	-	-	-	-
	= 4°	89.9	131.6	172.0	210.0	251.0	-	-	-	-
	= 5°	101.2	147.6	192.5	236.0	280.5	-	-	-	-
	= 10°	157.9	230.5	299.5	367.0	436.5	-	-	-	-
	= 15°	216.0	311.0	403.0	495.0	590.0	-	-	-	-
	= 20°	271.0	389.8	506.0	616.0	-	-	-	-	-

TABLE XVIII

SECOND GEAR LOCKUP, 2-9 MPH

		Miles per Hour								
		2	3	4	5	6	7	8	9	10
Engine speed, rpm		650	1000	1335	1650	2000	2340	2670	3000	-
Transmission efficiency, %		91.0	93.0	94.0	93.5	92.5	92.0	91.5	91.0	-
					Engine Horsepower					
First Class Road	α = 0°	20.7	30.4	40.7	50.3	61.8	73.0	83.0	96.8	-
Off the Road	= 0°	41.2	60.7	80.9	101.7	123.3	145.8	168.8	194.0	-
	= 1°	51.8	76.9	101.5	127.4	154.3	182.1	210.7	241.0	-
	= 2°	62.7	92.6	122.9	154.0	187.0	220.7	254.7	291.0	-
	= 3°	73.1	107.6	143.0	179.3	217.2	256.0	296.0	337.0	-
	= 4°	84.0	123.8	164.7	206.1	250.4	294.0	339.7	386.5	-
	= 5°	94.6	138.8	184.5	231.5	280.3	330.5	380.8	434.0	-
	= 10°	147.5	217.0	287.2	360.0	436.3	515.5	593.0	-	-
	= 15°	198.7	292.7	386.7	485.2	590.0	-	-	-	-
	= 20°	253.3	366.5	484.5	605.0	-	-	-	-	-

TABLE XIX

THIRD GEAR LOCKUP, 6-10 MPH

		Miles per Hour								
		2	3	4	5	6	7	8	9	10
Engine speed, rpm		-	-	-	-	1000	1166	1334	1449	1665
Transmission efficiency, %		-	-	-	-	87.0	89.0	91.0	92.0	94.0
						Engine Horsepower				
First Class Road	α = 0°	-	-	-	-	65.8	75.6	83.6	95.9	109.6
Off the Road	= 0°	-	-	-	-	131.1	150.8	170.0	191.9	219.2
	= 1°	-	-	-	-	164.2	188.4	212.0	238.5	269.2
	= 2°	-	-	-	-	198.8	228.1	256.2	288.0	326.7
	= 3°	-	-	-	-	231.0	264.8	298.0	333.7	373.7
	= 4°	-	-	-	-	266.1	304.2	342.0	383.0	428.0
	= 5°	-	-	-	-	298.0	342.0	383.2	430.0	477.5
	= 10°	-	-	-	-	464.2	533.0	597.0	-	-
	= 15°	-	-	-	-	627.5	-	-	-	-
	= 20°	-	-	-	-	-	-	-	-	-

The use of 4th gear lockup in the 2-10 mph range is not considered too practicable; because the highest engine speed reached would be only about 900 rpm for the 10 mph (the test data supplied for this gear ratio goes down to only 1600 rpm) a large extrapolation would thus be involved. However, for an idea of the magnitudes involved at this low speed, a transmission efficiency of about 92% is estimated, under which the horsepower required will vary from 120 for the first class road to 487.5 off the road on a 20° slope; a responsiveness of at least 3:1 would be necessary for this.

Repeating the above calculations for the speed range of 15-30 mph the data of Tables XX-XXII are obtained.

The heavy lines in all the above tables block off those conditions under which horsepower in excess of 500 are involved, regardless of speed.

From the data of these tables, graphs have been plotted showing the engine horsepower requirements for all ground slopes up to the 500 hp level for the vehicle speed ranges given on pages 9 and 10. Superimposed on these diagrams is a line for various degrees of responsiveness, values for 1.0, 2.0 and 3.0 being shown, together with the normal type, turbocharged, full power output of the 500 hp engine as well as its smoke limit; in addition, the SFC (Specific Fuel Consumption) of the unit for these conditions is also shown. The fuel requirements of the present system under all operating conditions are thus available. These results are given in Figs. 6-15.

These data are now replotted in Fig. 16 showing the various methods of operation on one diagram, torque converter and lockup conditions. The problem

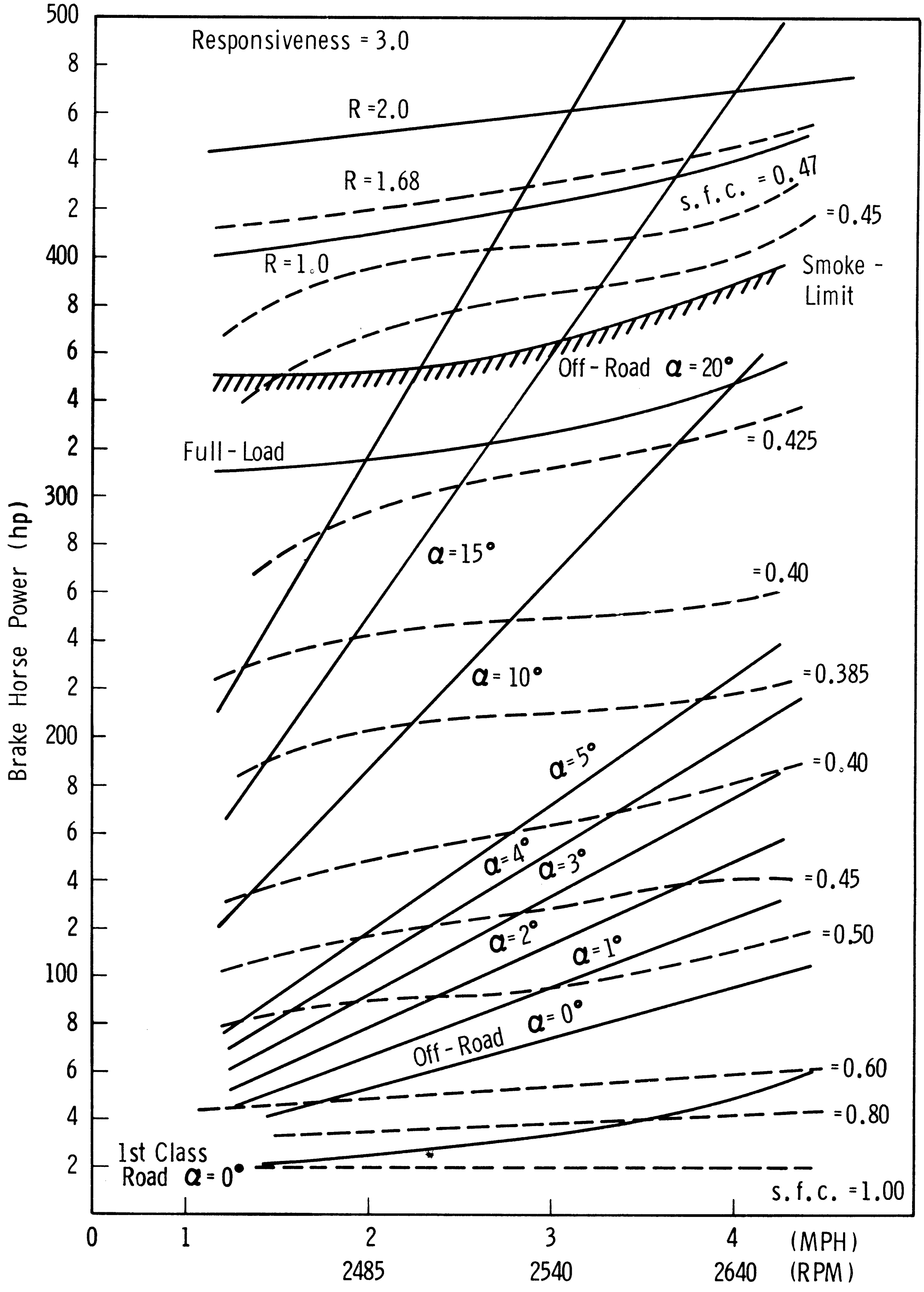

Fig. 6. First gear torque-converter operation, 2-4 mph.

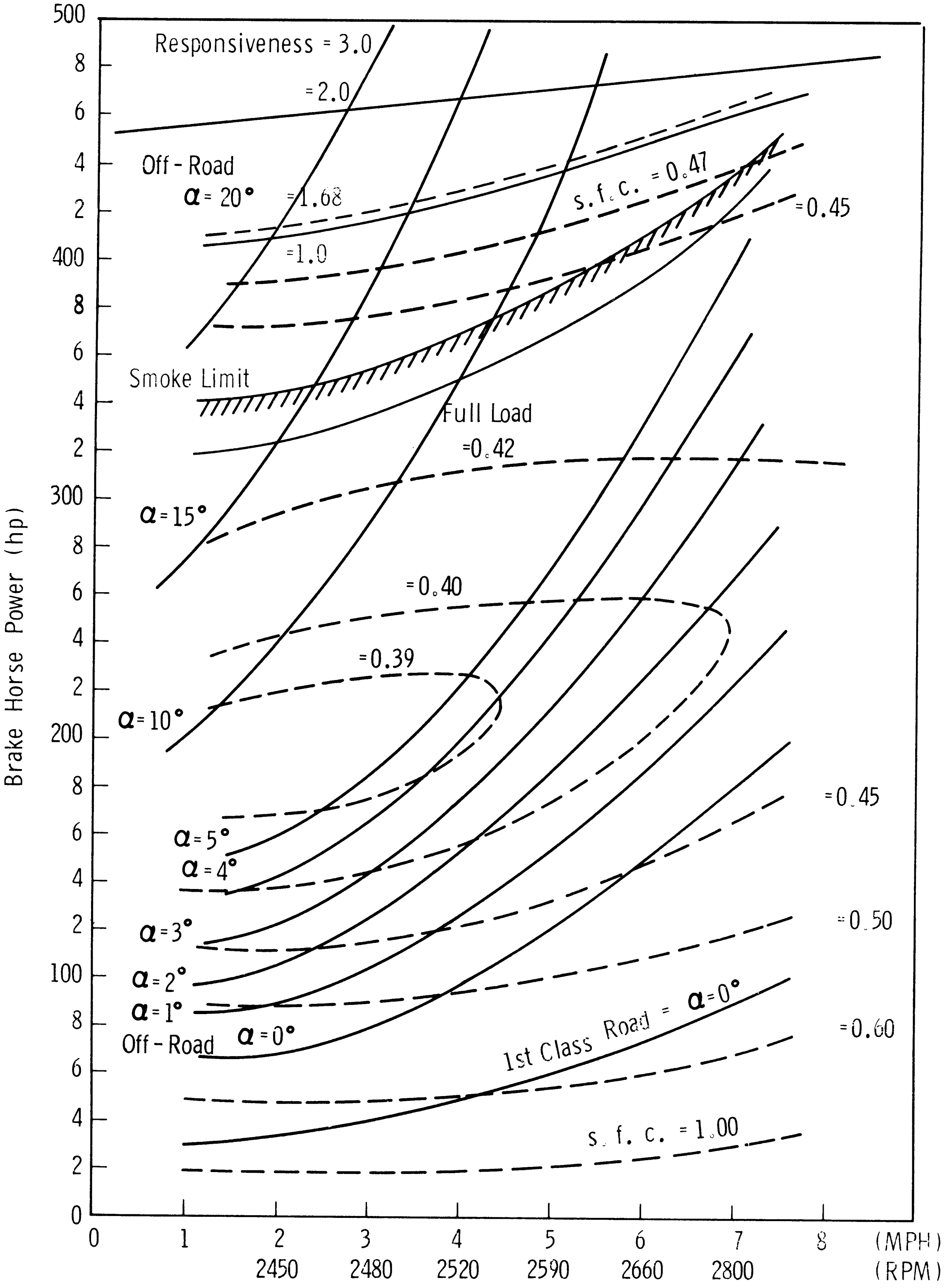

Fig. 7. Second gear torque-converter operation, 2-7 mph.

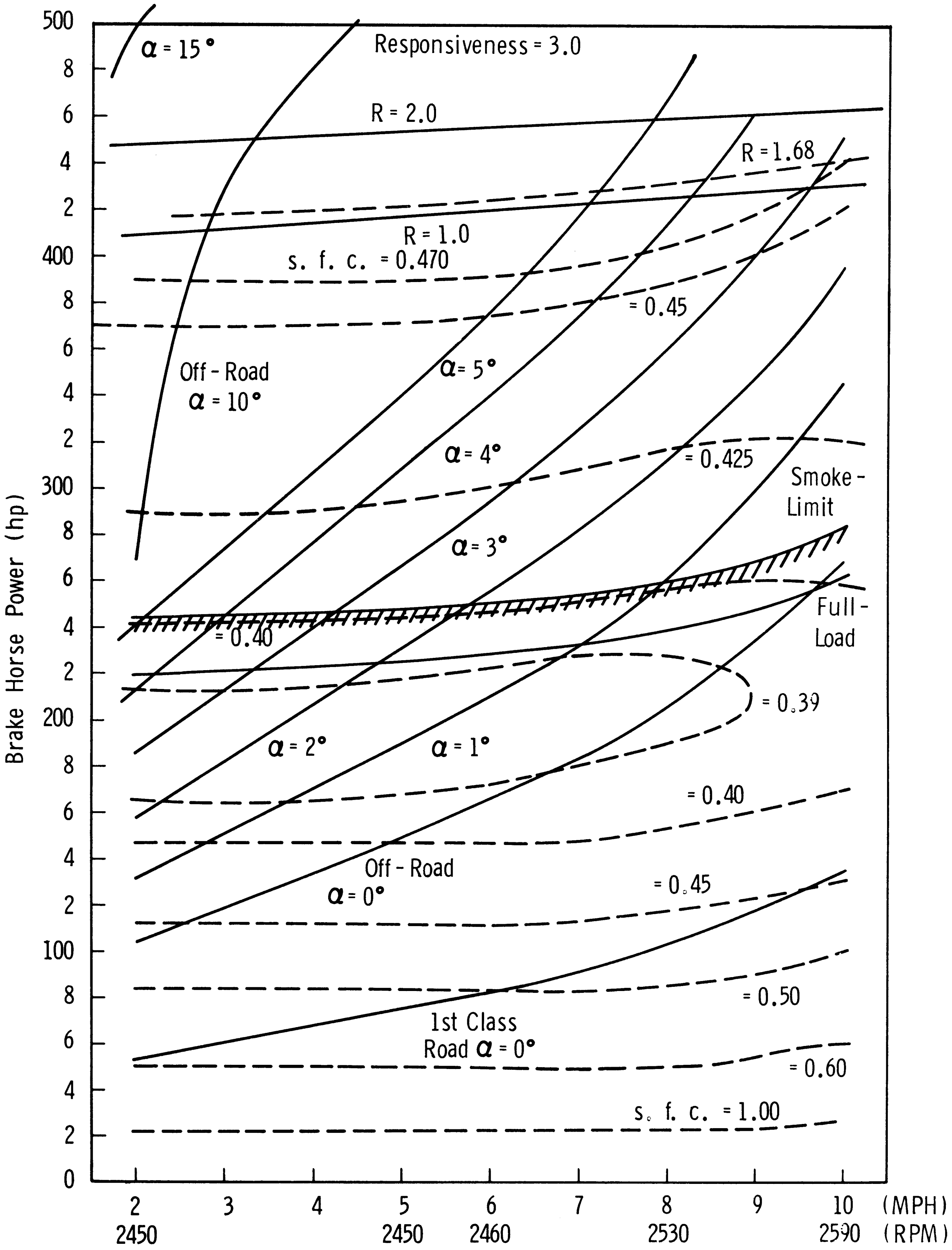

Fig. 8. Third gear torque-converter operation, 2-10 mph.

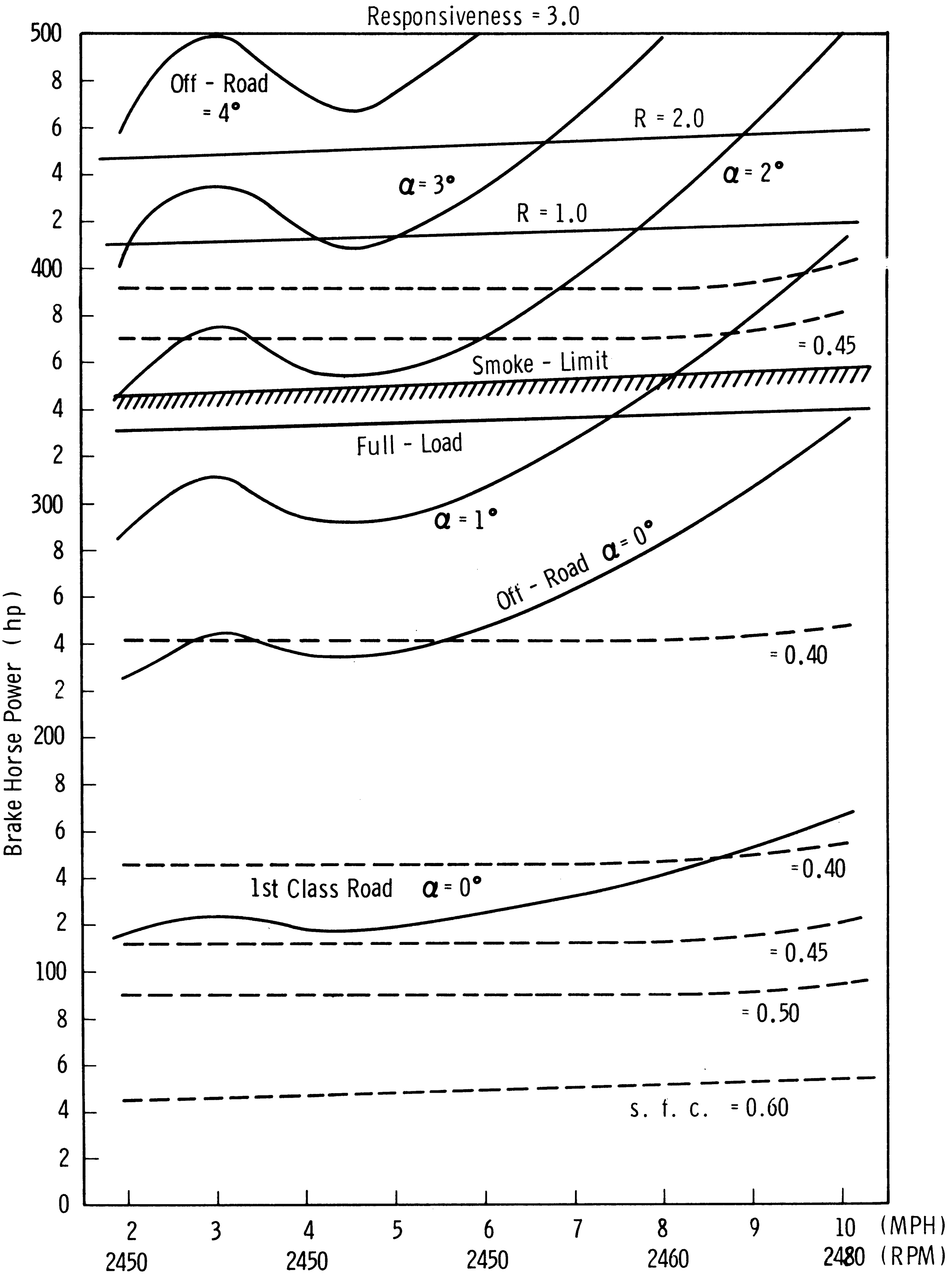

Fig. 9. Fourth gear torque-converter operation, 2-10 mph.

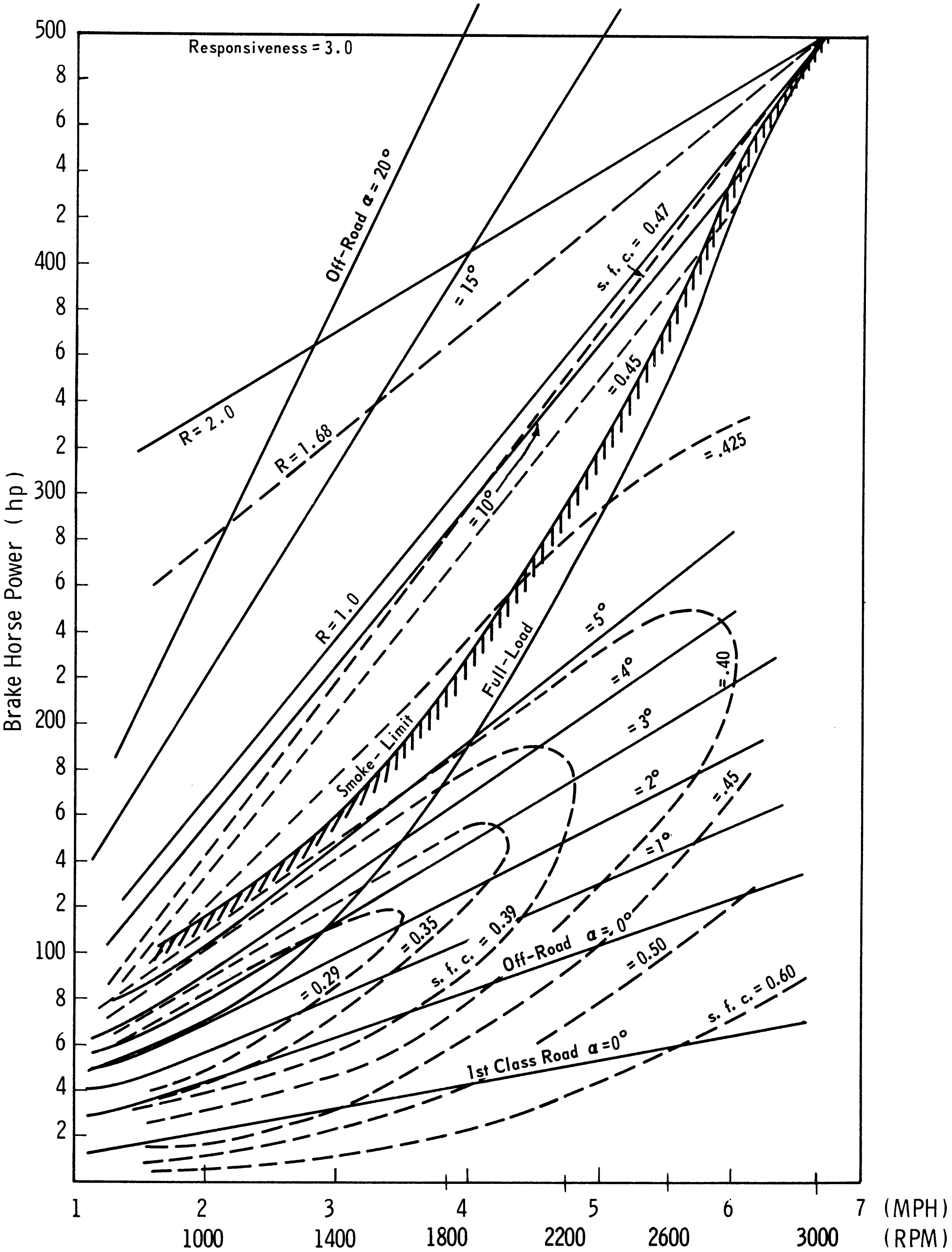

Fig. 10. First gear lockup operation, 2-6 mph.

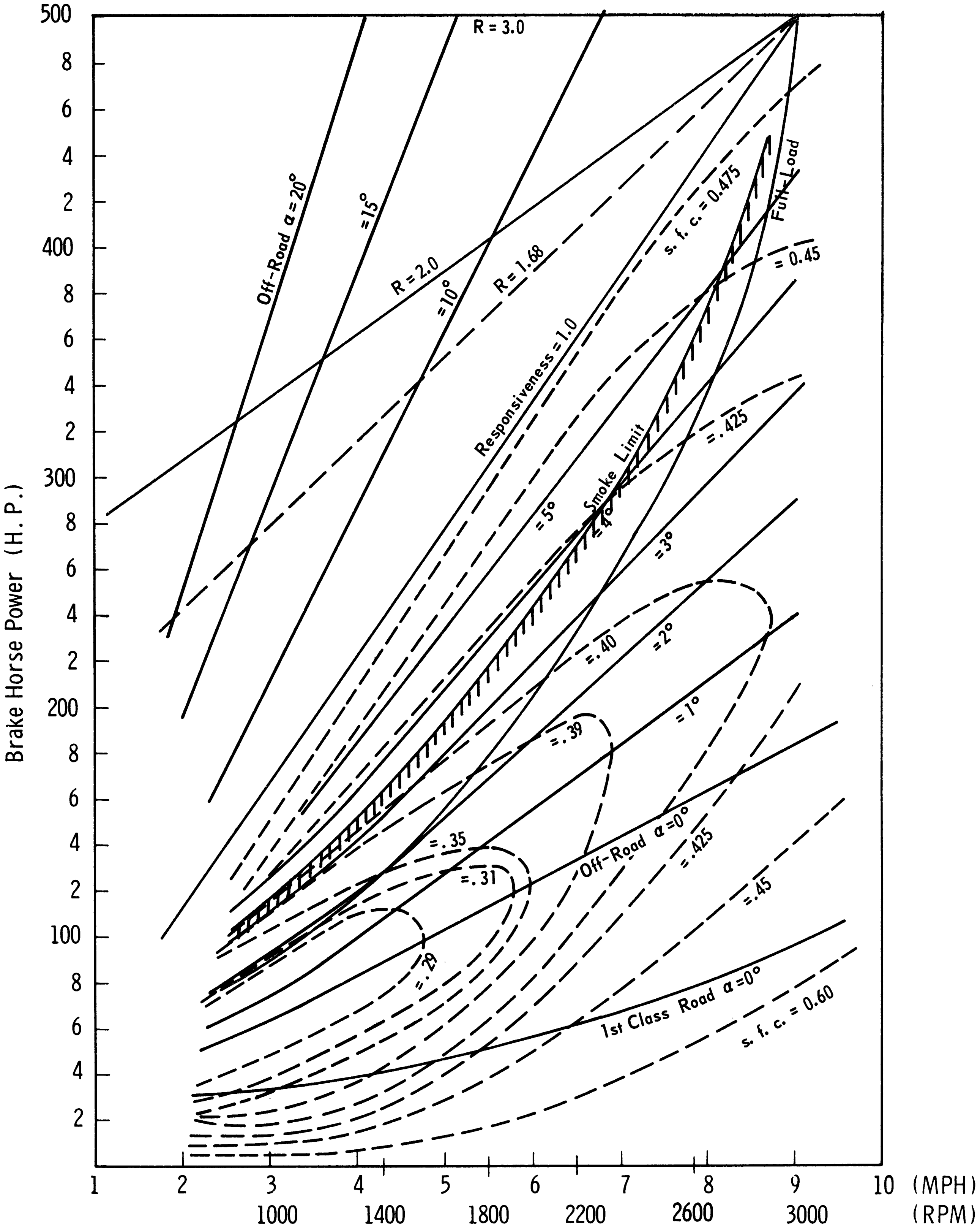

Fig. 11. Second gear lockup operation, 2-9 mph.

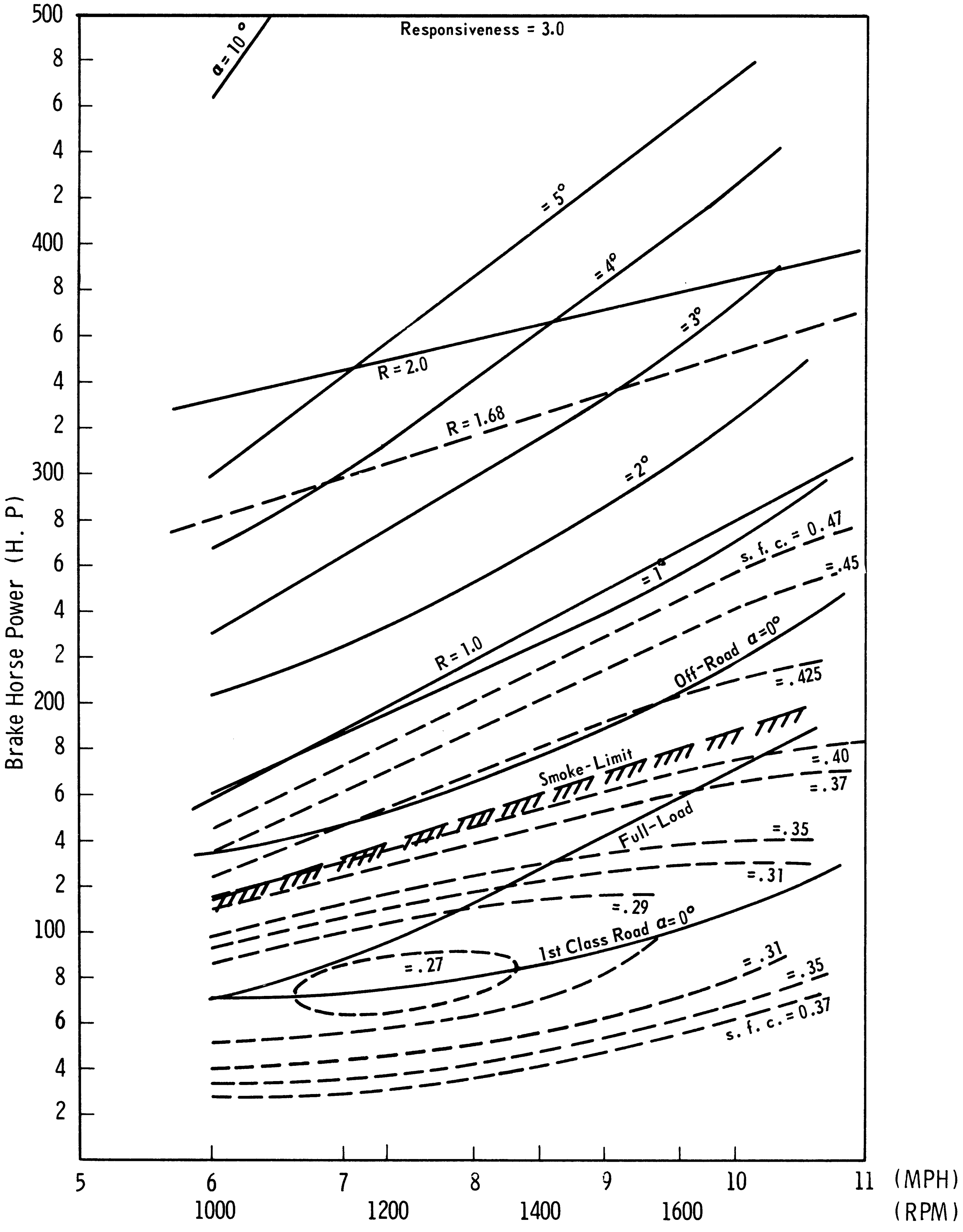

Fig. 12. Third gear lockup operation, 6-10 mph.

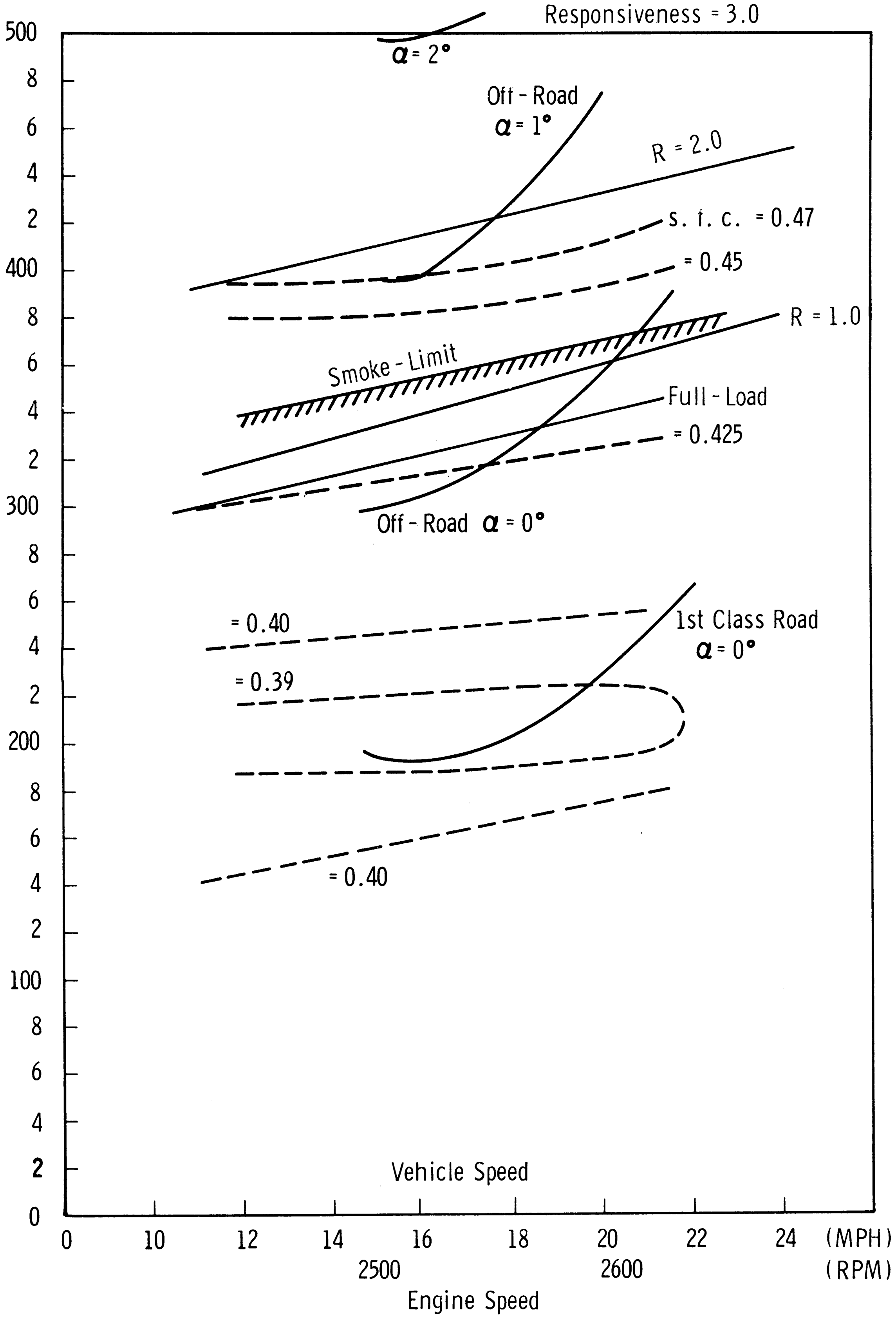

Fig. 13. Fourth gear torque-converter operation, 15-20 mph.

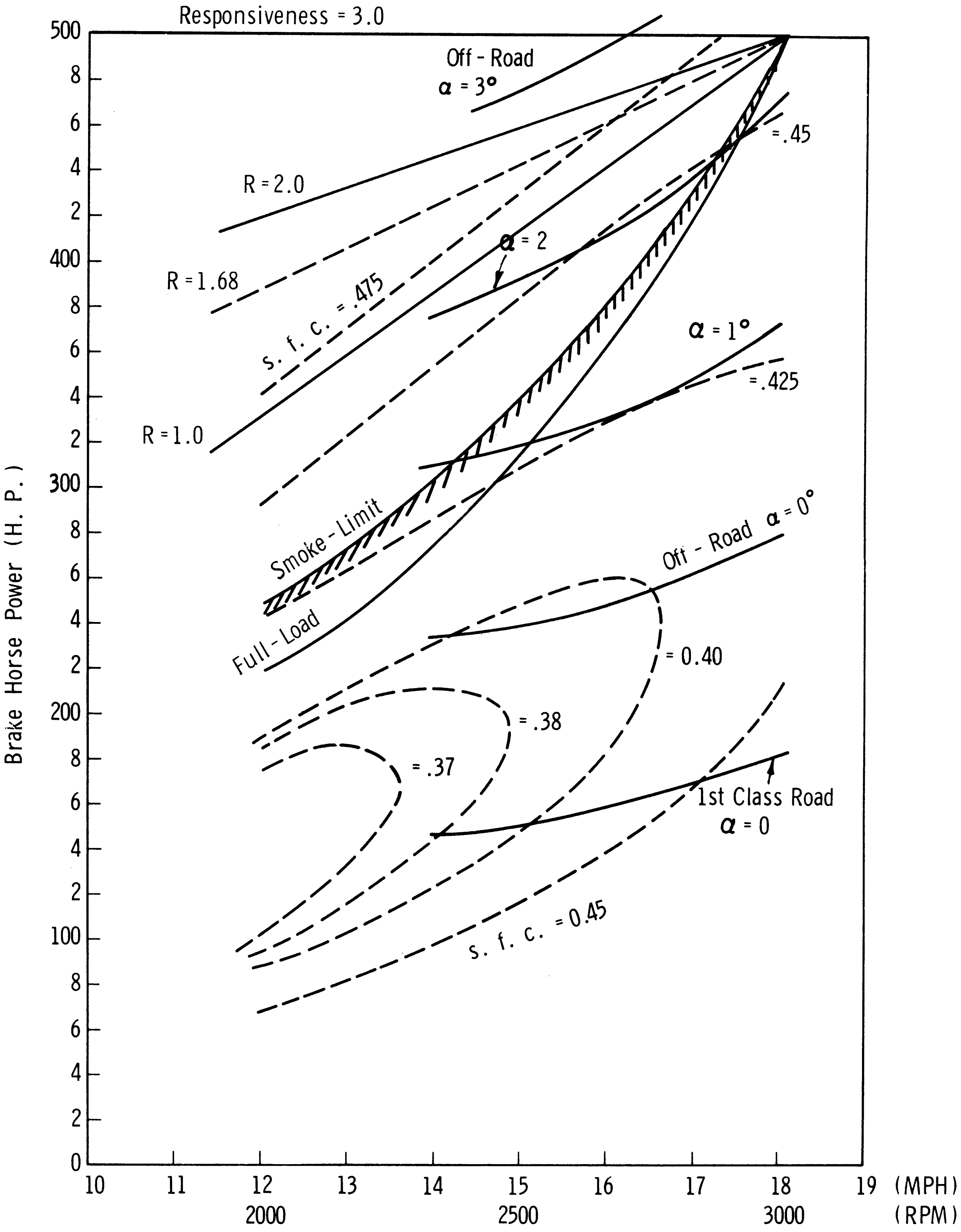

Fig. 14. Third gear lockup operation, 15-18 mph.

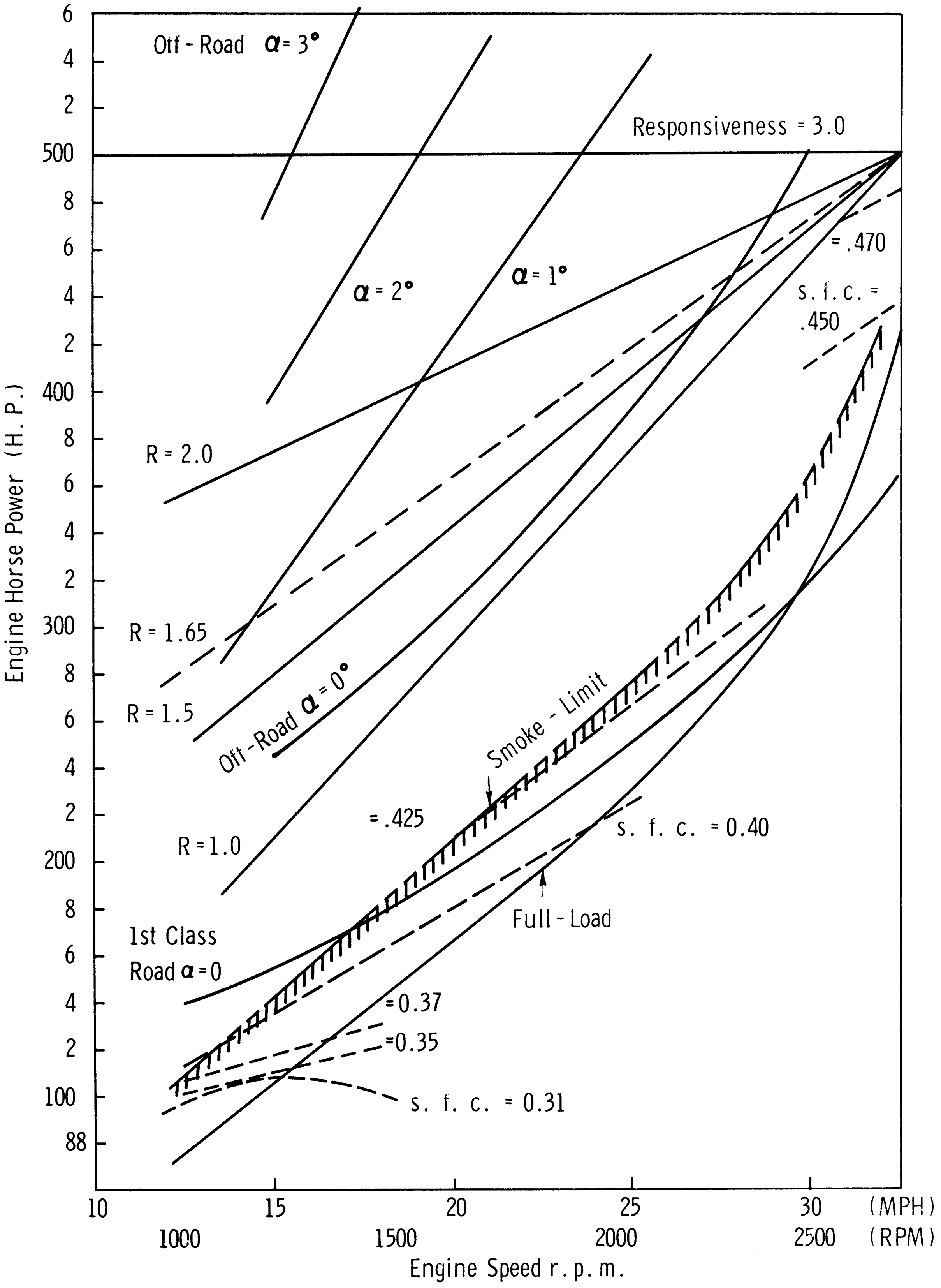

Fig. 15. Fourth gear lockup operation, 15-36 mph.

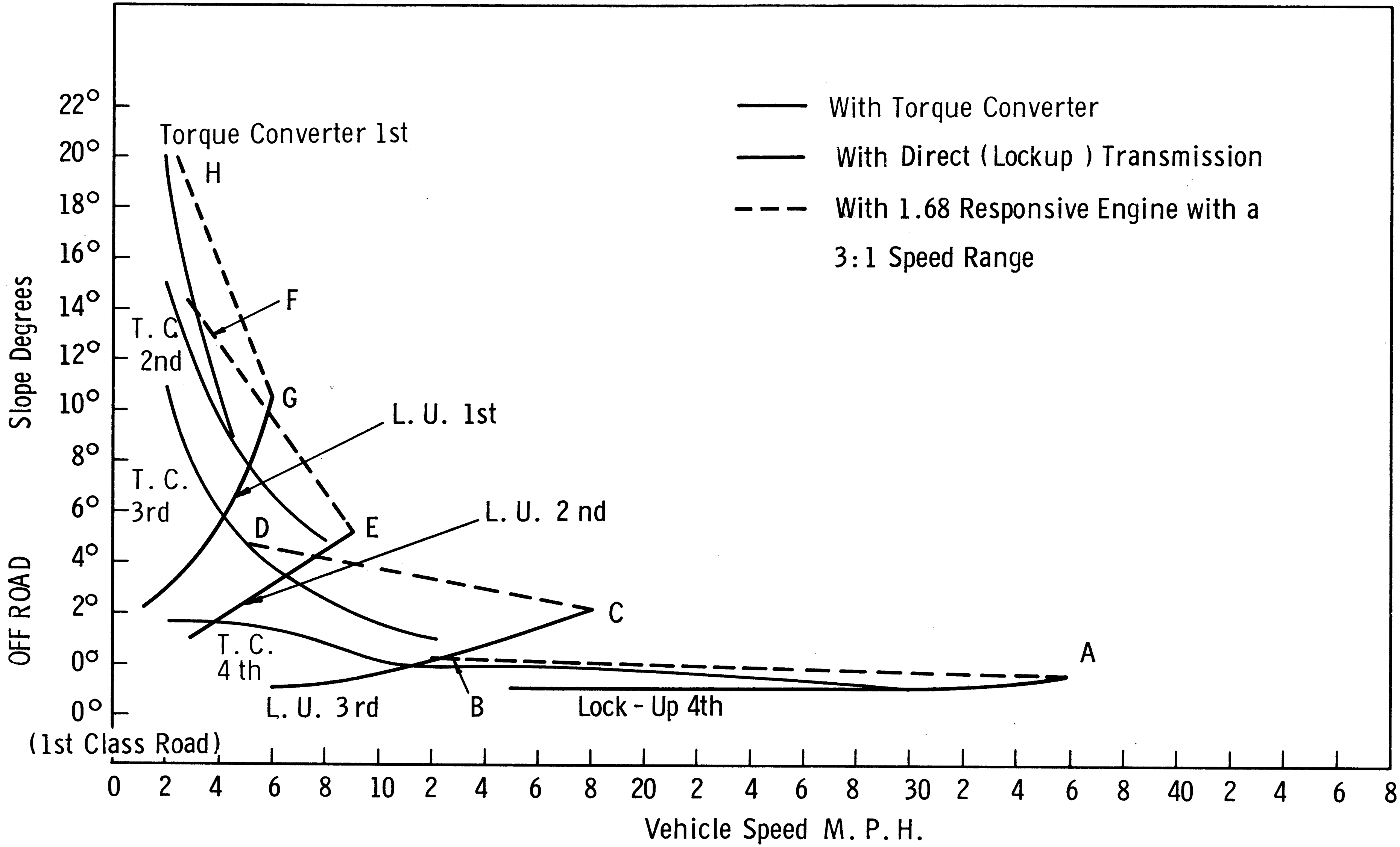

Fig. 16. Possible operating conditions at all speeds in all gears.

TABLE XX

FOURTH GEAR TORQUE-CONVERTER OPERATION, 15-20 MPH

		Miles per Hour						
		15	16	17	18	19	20	30
Engine speed, rpm		2510	2530	2550	2570	2585	2600	-
Transmission efficiency, %		75.0	77.0	77.7	78.5	79.5	79.5	-
				Engine Horsepower				
First Class Road	α = 0°	194.5	191.0	201.7	208.0	217.0	228.0	-
Off the Road	= 0°	306.0	305.0	316.5	327.0	342.0	358.5	-
	= 1°	398.0	394.0	419.0	433.0	450.2	475.5	-
	= 2°	498.5	493.5	525.0	544.0	567.0	597.0	
	= 3°	601.0	588.0	626.0	649.0	-	-	-
	= 4°	-	-	-	-	-	-	-
	= 5°	-	-	-	-	-	-	-
	= 10°	-	-	-	-	-	-	-
	= 15°	-	-	-	-	-	-	-
	= 20°	-	-	-	-	-	-	-

TABLE XXI

THIRD GEAR LOCKUP, 15-18 MPH

		Miles per Hour						
		15	16	17	18	19	20	30
Engine speed, rpm		2510	2670	2820	3000	-	-	-
Transmission efficiency, %		95.0	93.0	91.0	90.5	-	-	-
				Engine Horsepower				
First Class Road	α = 0°	153.8	158.5	172.0	180.0	-	-	-
Off the Road	= 0°	241.8	249.0	270.2	284.0	-	-	-
	= 1°	319.0	327.0	357.5	376.0	-	-	-
	= 2°	394.0	409.0	448.0	473.0	-	-	-
	= 3°	475.0	487.0	534.0	-	-	-	-
	= 4°	539.0	570.0	-	-	-	-	-
	= 5°	-	-	-	-	-	-	-
	= 10°	-	-	-	-	-	-	-
	= 15°	-	-	-	-	-	-	-
	= 20°	-	-	-	-	-	-	-

TABLE XXII

FOURTH GEAR LOCKUP, 15-36 MPH

		Miles per Hour								
		15	16	17	18	19	20	30	33.5	36
Engine speed, rpm		1250	1340	1426	1520	1593	1675	2515	2800	3000
Transmission efficiency, %		94.0	93.0	92.5	92.0	91.5	91.0	88.5	93.0	93.5
		Engine Horsepower								
First Class Road	α = 0°	155.5	158.4	169.2	177.4	188.5	199.6	321.0	345.0	400.0
Off the Road	= 0°	244.0	248.8	265.7	279.2	296.2	313.4	504.0	542.0	-
	= 1°	318.0	326.5	351.5	369.2	391.0	415.5	660.0	-	-
	= 2°	398.0	409.0	440.3	464.2	492.5	522.0	-	-	-
	= 3°	480.0	487.0	514.5	554.0	586.0	623.0	-	-	-
	= 4°	545.0	569.0	614.0	-	-	-	-	-	-
	= 5°	-	-	-	-	-	-	-	-	-
	= 10°	-	-	-	-	-	-	-	-	-
	= 15°	-	-	-	-	-	-	-	-	-
	= 20°	-	-	-	-	-	-	-	-	-

of the minimum degree of responsiveness was then considered. It was finally decided that at no point of possible operation should the responsive engine give less performance than the existing combination of engine and transmission. Secondly, that an engine speed range of 3:1 could eventually be met with some fuel injection and engine developments. The results of these two assumed conditions proved to be that the performance line of the responsive engine, at variable speed, should be approximately tangented to the 4th gear torque-converter condition (see Fig. 16, lines AB), with an engine having the characteristics of AB, in which case the required conditions were more than met at all other states.

With a 3:1 speed ratio, 3000-1000 rpm, the line AB had to provide a BHP of 280 hp at 12 mph, and 500 hp at 36 mph. At 1000 rpm the unit must develop a BMEP of 420 psi, while at 500 hp at 3000 rpm, 250 psi is achieved; that is, a responsiveness of 1.68:1 is required. This latter value for a BMEP (250 psi) of the present normal engine does not impose impossible conditions on existing engines as a continuous full-load engine rating, while the 420 psi has already been demonstrated as being within the realms of possibility in the not too distant future. It follows that a performance line such as AB is capable of being achieved in a multicylinder engine with some more development work. This report is not considering the conditions which would have to be fulfilled to achieve this end.

The line AB of Fig. 16 has been laid down with a transmission efficiency of 90% approximately, i.e., the same average efficiency as the present lockup gear box. It is true that this value could vary somewhat for the various gear ratios to be employed, but for a first approach it is considered sufficiently accurate for the present purpose to assume that the efficiency is constant for all the ratios to be employed. Examination of Fig. 2 shows this to be a reasonable assumption, at least in the lockup case.

Using the corresponding horsepower of line AB, but changing gear ratio in the same steps as the XTG-411-1 transmission, the performance in 3rd, 2nd, and 1st gears is shown by CD, EF, and GH, respectively. It is seen that there is considerable overlap of the speeds from one gear to the next so that the change is not critical at any one speed; in addition, in all ratios, the performance as to climbing ability, acceleration, etc., has been improved over torque-converter or lockup conditions, with the exception of the individual points A, C, E, and G where the same performance was used as the starting point, viz., 500 hp at 3000 rpm.

It follows that it is now possible to examine the overall performance in the following conditions of engine operation:

1. Gear lockup.
2. Torque converter.
3. Combinations of Items 1 and 2.
4. 1.68:1 responsive engine.

The engine for all three conditions will be exactly the same at the full-speed rating, viz., 500 BHP at 3000 rpm, and this rating will not be exceeded at that speed.

V. FUEL FLOW REQUIREMENTS IN LOCKUP

Using the percentage of times listed in Table I for the various speeds and averaging the fuel flow requirement for each condition, Tables XXIII-XXVI can be set up for each gear ratio.

TABLE XXIII

FUEL FLOW—FIRST GEAR LOCKUP

mph	First Class Road, α = 0°			Off the Road, α = 0°		
	BHP	SFC, lb/BHP/hr	Fuel Flow, lb/hr	BHP	SFC, lb/BHP/hr	Fuel Flow, lb/hr
2	22.0	0.40	8.8	44.2	0.32	14.2
3	32.3	0.46	14.9	64.6	0.34	18.6
4	42.5	0.51	21.7	84.5	0.395	33.4
5	52.0	0.56	29.1	104.0	0.45	46.8
6	62.0	0.61	37.9	123.0	0.50	61.5
			112.4			174.5
			Avg 22.5			Avg 34.9

TABLE XXIV

FUEL FLOW—SECOND GEAR LOCKUP

mph	First Class Road, α = 0°			Off the Road, α = 0°		
	BHP	SFC, lb/BHP/hr	Fuel Flow, lb/hr	BHP	SFC, lb/BHP/hr	Fuel Flow, lb/hr
2	← Engine at too low speed →					
3	31.0	0.305	9.45	41.0	0.28	11.5
4	41.0	0.350	14.4	61.0	0.285	17.4
5	50.5	0.40	20.2	81.0	0.30	24.3
6	62.0	0.47	29.1	125.0	0.385	47.3
7	73.0	0.51	37.2	146.0	0.395	57.7
8	83.0	0.55	45.7	169.0	0.410	69.3
9	97.0	0.58	56.3	194.0	0.43	83.4
10	← Engine at too high speed →					
			212.35			310.9
			Avg 30.4			Avg 44.4

TABLE XXV

FUEL FLOW—THIRD GEAR LOCKUP

mph	First Class Road, $\alpha = 0°$			Off the Road, $\alpha = 0°$		
	BHP	SFC, lb/BHP/hr	Fuel Flow, lb/hr	BHP	SFC, lb/BHP/hr	Fuel Flow, lb/hr
15	155	0.38	58.8	240	0.40	96.0
16	158	0.44	69.5	250	0.395	98.9
17	170	0.45	76.6	270	0.415	112.0
18	185	0.46	94.5	285	0.435	124.0
			Engine overspeeds above 18 mph			
			299.4			430.9
			Avg 74.8			Avg 107.8

TABLE XXVI

FUEL FLOW—FOURTH GEAR LOCKUP

mph	First Class Road, $\alpha = 0°$			Off the Road, $\alpha = 0°$		
	BHP	SFC, lb/BHP/hr	Fuel Flow, lb/hr	BHP	SFC, lb/BHP/hr	Fuel Flow, lb/hr
15	155	0.41	63.5	Insufficient horsepower available		
16	158	0.41	64.8			
17	169	0.41	69.3			
18	177	0.415	73.6			
19	189	0.415	78.5			
20	200	0.415	83.0			
30	321	0.425	136.4			
			469.1			
			Avg 67.1			

VI. FUEL FLOW IN TORQUE-CONVERTER OPERATION

Similar data for the condition of torque-converter operation are given in Tables XXVII-XXX. It will be noted that there are serious limitations to the vehicle speed when employing the converter if the maximum allowable engine speed is not to be exceeded when in certain gears. However, from Fig. 16 it can be seen that there is still a complete overlap of the converter operation from about 2 mph up to 30 mph despite this restriction. A speed lower than 2 mph would also be possible at some reduced engine output.

TABLE XXVII

FUEL FLOW—FIRST GEAR TORQUE CONVERTER

mph	First Class Road, $\alpha = 0°$			Off the Road, $\alpha = 0°$		
	BHP	SFC, lb/BHP/hr	Fuel Flow, lb/hr	BHP	SFC, lb/BHP/hr	Fuel Flow, lb/hr
2	25.9	0.95	24.6	51.7	0.59	30.5
3	37.2	0.83	30.9	74.3	0.54	40.2
4	49.3	0.75	37.0	98.6	0.52	51.3
			Engine overspeeds above 4 mph			
			92.5			122.0
			Avg 30.8			Avg 40.7

TABLE XXVIII

FUEL FLOW—SECOND GEAR TORQUE CONVERTER

mph	First Class Road, $\alpha = 0°$			Off the Road, $\alpha = 0°$		
	BHP	SFC, lb/BHP/hr	Fuel Flow, lb/hr	BHP	SFC, lb/BHP/hr	Fuel Flow, lb/hr
2	34.2	0.80	27.4	68.2	0.56	38.2
3	40.0	0.75	30.0	79.6	0.53	42.2
4	50.0	0.65	32.5	100.0	0.50	50.0
5	61.2	0.59	36.1	122.5	0.47	57.5
6	74.3	0.57	42.7	146.5	0.45	65.9
7	89.6	0.56	50.1	179.0	0.44	78.9
			Engine overspeeds above 7 mph			
			218.8			332.7
			Avg 36.5			Avg 55.5

TABLE XXIX

FUEL FLOW—THIRD GEAR TORQUE CONVERTER

mph	First Class Road, $\alpha = 0^\circ$			Off the Road, $\alpha = 0^\circ$		
	BHP	SFC, lb/BHP/hr	Fuel Flow, lb/hr	BHP	SFC, lb/BHP/hr	Fuel Flow, lb/hr
2	52.2	0.60	31.6	104.2	0.47	48.9
3	60.2	0.56	33.7	120.3	0.44	53.0
4	67.6	0.54	36.5	134.6	0.42	56.6
5	74.2	0.52	38.6	148.5	0.40	59.4
6	83.5	0.50	41.8	166.6	0.392	65.4
7	92.9	0.48	44.6	185.5	0.387	71.8
8	101.4	0.47	47.6	206.0	0.384	79.2
9	114.6	0.46	52.7	229.2	0.391	89.6
10	132.5	0.45	59.6	265.0	0.410	108.7
			386.7			533.6
		Avg	43.0		Avg	59.3

TABLE XXX

FUEL FLOW—FOURTH GEAR TORQUE CONVERTER

mph	First Class Road, $\alpha = 0^\circ$			Off the Road, $\alpha = 0^\circ$		
	BHP	SFC, lb/BHP/hr	Fuel Flow, lb/hr	BHP	SFC, lb/BHP/hr	Fuel Flow, lb/hr
2	114.0	0.45	51.2	228.0	0.39	89.0
3	123.0	0.44	54.2	246.0	0.40	98.5
4	118.0	0.45	53.0	234.0	0.395	92.6
5	117.0	0.45	52.6	235.0	0.395	93.0
6	123.0	0.44	54.2	245.3	0.402	98.8
7	132.0	0.425	56.1	263.0	0.408	107.5
8	139.5	0.420	58.6	283.5	0.412	117.0
9	151.0	0.40	60.5	302.0	0.423	128.0
10	167.0	0.39	65.2	335.0	0.435	145.8
			505.6			970.2
Avg for low-speed operation			56.2		Avg	107.8
15	194.5	0.385	74.8	306.0	0.423	129.5
16	191.0	0.390	74.5	305.0	0.423	128.8
17	201.7	0.385	77.6	317.0	0.425	134.7
18	208.0	0.380	79.1	327.0	0.430	140.8
19	217.0	0.387	84.0	342.0	0.435	149.0
20	228.0	0.392	89.5	358.5	0.438	157.2
			479.5			840.0
Avg for high-speed operation			79.9		Avg	140.0

VII. THE BATTLEFIELD DAY FUEL NEEDS

It is now possible to calculate the fuel requirements for the standard Battlefield Day (BFD) when employing a conventional turbocharged compression ignition engine of 500 BHP at 3000 rpm in a 43-ton tank. This condition roughly represents existing conditions and gives a reference point for all comparisons. It is proposed to obtain two values: (1) operating in the most favorable gear ratio for any speed in lockup, and (2) operating at all times in torque-converter condition only.

A. BFD LOCKUP

Since under this condition no responsiveness is to be employed, the conditions to be met as far as hours of operation at various loads are those for a conventional engine, shown in Table I. When these times are combined with the fuel consumptions, as shown in Tables XXIII-XXVII for off-the-road operation, the data of Table XXXI result.

In order to approximate to existing conditions as closely as possible, the speed range of present engines is taken at 2:1, i.e., 3000-1500 rpm. Due to this limitation, the 40% time at 2-10 mph must be divided in some ratio between 1st and 2nd gears. In Table XXXI, 10% of operating time was assigned to 1st gear at 2-5 mph, and 30% in 2nd gear at 5-10 mph; the appropriate fuel flows for these two ratios were averaged from the tables.

It is true that operation in lockup only would place severe restrictions on the vehicle, it does however represent one minimum set of conditions.

TABLE XXXI

BATTLEFIELD DAY WITH ENGINE IN LOCKUP

mph	% Time	Hours	Gear	Fuel Flow Average, lb/hr	Total Fuel, lb
2-5	40.0	2.4	1st	28.3	68.0
5-10	40.0	7.2	2nd	56.5	406.8
15-19	20.0	4.8	3rd	107.8	517.0
Idle	40.0	9.6		5.0	48.0
				Lb of fuel/BFD of 24 hr =	1039.8

B. BFD TORQUE CONVERTER

Here, again, the conventional engine with the torque-converter side of the transmission only will be employed, using its most economical gear ratio for each set of speeds.

It will be seen that the 40% time for the 2-10 mph condition has been divided into 10% at 2-5 mph, 10% at 4-6 mph, and 20% at 7-10 mph, in the different gears indicated. This results in the lowest total fuel consumption when in converter operation, but does involve more gear changing. If the whole 2-10 mph schedule were carried out for the same length of time at the various speeds in 3rd gear, which could be done within the limits set down, the fuel for this 9.6 hr would be 686.5 lb in place of 642.7 lb, making the total requirements at 1405.5 lb; thus, the proposal of Table XXXII results in a saving of approximately 44 lb of fuel.

TABLE XXXII

BATTLEFIELD DAY WITH TORQUE CONVERTER

mph	% Time	Hours	Gear	Fuel Flow Average, lb/hr	Total Fuel, lb
2-3	10.0	2.4	1st	35.4	85.0
4-6	10.0	2.4	2nd	57.8	138.7
7-10	20.0	4.8	3rd	87.3	419.0
15-20	20.0	4.8	4th	140.0	671.0
Idle	40.0	9.6		5.0	48.0
				Lb of fuel/BFD of 24 hr =	1361.7

C. COMBINATIONS OF LOCKUP AND TORQUE CONVERTER

Assuming that the use of the torque converter is most necessary when the going is bad for, say, 50% of the time in the 2-6 mph range, while lockup is satisfactory for the rest of the operation except for about 50% of the time in 4th gear, then, with these assumptions, the BFD fuel needs become as shown in Table XXXIII.

TABLE XXXIII

BATTLEFIELD DAY COMBINATION OF TORQUE CONVERTER AND LOCKUP

mph	% Time	Hours	Gear	Fuel Flow Average, lb/hr	Total Fuel, lb
2-3	5.0	1.2	1st T.C.	35.4	42.5
2-3	5.0	1.2	1st L.U.	16.8	20.2
4-6	5.0	1.2	2nd T.C.	57.8	69.4
4-6	5.0	1.2	2nd L.U.	26.0	31.4
7-9	20.0	4.8	2nd L.U.	70.2	337.0
15-20	10.0	2.4	4th T.C.	140.0	335.5
15-20	10.0	2.4	4th L.U.	107.8	258.5
Idle	40.0	9.6		5.0	48.0
				Lb of fuel/BFD of 24 hr =	1142.5

D. RESPONSIVE ENGINE PERFORMANCE WITH STALL

The schedule proposed for the responsive engine, shown in Table I, can be divided in various ways. It is, however, understood that the responsive engine eliminates the need for a torque converter; thus lockup and responsiveness are the two factors involved.

It will be assumed at this stage that responsiveness can be achieved at will by speeding up the turbocompressor to the desired speed to secure the manifold pressure required for the load condition existing. The problems involved in this requirement will be examined later. At all other times the engine will operate as a conventional one, and the data of Tables XVII-XIX, also XXI-XXVI, apply. The best overall performance will, of course, be obtained when the track slip is maintained at a minimum. Assume the slip at the equivalent of 2 mph when the vehicle is stalled by an obstacle; under these conditions the maximum responsive horsepower available at 1000 rpm can be applied, and this condition can exist for a total of 5% of the 24 hr day, as given in the table. At all other times the engine can behave as a normally turbocharged engine in the selected lockup gear.

With the above assumptions the fuel requirements for the 20, 35, and 40% periods do not change, only the responsive condition will alter. Taking the calculations of Table VIII, Ref. 1, at the 3000 rpm and plotting SFC vs. hp, the calculation errors are meaned out, and at 500 hp at 3000 rpm a specific fuel consumption of 0.475 lb/BHP/hr is obtained; this includes cooling fan, etc. The BMEP at this load and speed is 250 psi; thus, with 1.68:1 responsiveness the mean pressure at 1000 rpm will be 420 psi, a value which is within the limits of some of the present research engines; the BHP will become 280 at 1000 rpm. Assuming that 25% of the heat of combustion has to be dissipated to the cooling system, then about 125 hp equivalent of heat is capable of being dissipated at 3000 rpm. Assume that, due to the increased densities when acting responsively, the heat disposal at 1000 rpm responsive is 30%, or 84 hp, to the coolant. True, the cooling fan slows down as well as the engine, but it seems fairly reasonable that less cooling will be required than at the full 500-hp load. When the short period during which responsiveness is employed is taken into account, cooling fan losses of about 50% of those of full load will be assumed. The frictional losses will also reduce, with the result that friction will be assumed at 25 hp and fan losses at 30 hp; hence, an IHP (indicated horsepower) of 335 will be involved with an indicated MEP of about 500 psi, requiring a manifold pressure of 137" Hg at F/A of 0.0475, or a charger with a ratio of 4.57:1. Figure 2, Ref. 2, gives the corresponding ideal SFC at 0.291 lb/IHP/hr; assume this is rounded off to a practical value of 0.33 lb/IHP/hr; then the fuel flow for this ideal condition becomes 111.0 lb/hr. It is unlikely that any injection system will be equally efficient over a speed range of 3000-1000 rpm; thus the calculations will be based upon a SFC of 0.36 lb/IHP/hr or 121.5 lb/hr, equivalent to 0.433 lb/BHP/hr at the 1000 rpm. At first sight this value seems low compared with that at the 500 hp and 3000 rpm, viz., 0.475 lb, but it must be remembered that the frictional and cooling fan losses have been reduced by about 78 hp, resulting from the reduced speed; any reduction in losses improves the SFC at rapid rate.

The manner in which the horsepower varies with speed during responsive operation could vary greatly and would depend upon the vehicle and terrain being traversed. For the sake of this analysis it will be assumed that the BHP varies in a straight-line relationship from the 500 hp at 3000 rpm to 280 hp at 1000 rpm, similarly the SFC will also be of the straight-line variety. In this case the data of Table XXXIV will present the maximum allowable performance at all speeds when operating responsively.

TABLE XXXIV

MAXIMUM RESPONSIVE HORSEPOWER AT VARIOUS ENGINE SPEEDS

rpm	BHP	SFC	Fuel/hr
3000	500	0.475	237.5
2500	425	0.465	197.1
2000	390	0.454	177.7
1500	336	0.448	150.5
1000	280	0.433	121.5

It is now possible to plot on Fig. 16 the responsive engine performance lines such as AB for 4th gear, CD for 3rd, EF for 2nd, and GH for 1st gear operation.

From the data of the tables already developed it is now possible to formulate Table XXXV for the responsive condition. It is, of course, conceivable that many responsive conditions of one sort or another could be met at all sorts of speeds; to estimate these would require much time, so for a first approach to the subject it will be assumed that formidable obstacles are encountered which will bring the vehicle almost to a standstill, followed by the responsive climb out to be effected at a speed of 1000 rpm and full 280 hp, and that such maneuvers occur for a total of 1.2 hr out of the BFD. Table XXXV gives the fuel demands under such conditions.

With the aid of the data provided above many other combinations of normal and responsive conditions as well as vehicle terrain, could be examined. To do this in a correct manner would require some record of vehicle operation over a typical terrain involving all of the obstacle crossings, slopes, mud, etc., likely to be encountered. If such a program were contemplated it would be advisable to place all the data upon a computer, since by slide-rule methods the above calculations have involved a tremendous time, far more than was originally contemplated.

TABLE XXXV

BATTLEFIELD DAY WITH RESPONSIVE ENGINE

mph	% Time	Hours	Gear	Fuel Flow Average, lb/hr	Total Fuel, lb
2-10	35.0	8.4	2nd L.U.	44.4	373.3
15-19	20.0	4.8	3rd L.U.	107.8	517.0
Responsive	5.0	1.2	1st L.U.	121.5	145.8*
Idle	40.0	9.6		5.0	48.0
				Lb of fuel/BFD of 24 hr =	1084.1

*Allowance has yet to be made for any additional fuel to produce this responsiveness if required (see Turbocharger Requirements).

E. TORQUE CONVERTER WITH STALL

The calculations for the BFD with torque converter did not include any obstacle-crossing involving stall as is the case with the responsive engine.

To have a true comparison, torque-converter conditions will now be examined with the schedule of Table I, including the 5% stall.

It follows that the conditions of Table XXXII will exist for all but 1.2 hr of the total. Stall conditions generally exist in rough terrain when speeds are slow; it could be assumed that the 1.2 hr of stall will be subtracted from the 2.4 hr at the 2-3 mph conditions of Table XXXII and replaced by 1.2 hr of stall with the torque converter in operation, applying maximum torque to the sprocket shaft. This perhaps is not a fair comparison since for stall the responsive engine was delivering only 280 BHP to the transmission with an engine speed of 1000 rpm; the 280 hp was all applied to the transmission effectively. For a fair comparison the torque converter will be assumed to be applying 280 hp at its output end at as near the 1000 rpm as possible; then the engine input to meet this condition must be calculated. Using Fig. 2 plus the fact that a 2-mph slip is to be used as for Item 4, page 42, then for 1000-rpm engine speed in 1st gear the transmission output speed is approximately 190 rpm when acting responsively. It follows that with the torque converter we still need 190-rpm output speed of the transmission to achieve the same slip; thus, in 1st gear converter the engine speed must be 2500 rpm, for which Fig. 5 gives an efficiency of 72.5%. It follows that the engine output to the converter has to be 524 hp if 280 is to be the output of the torque converter. This is in excess of the engine capabilities; at 2500 rpm a maximum of about 350 hp can be achieved under the smoke limiting conditions. It follows that the existing engine plus torque converter falls far short of the responsive engine under the assumed conditions.

The 5% of stall operation will thus be assumed to occur with the engine at 350 hp and 2500 rpm when the SFC is 0.46 lb/BHP/hr approximately or 161.5 lb/hr (Ref. 1). It is true that if the slip were increased a greater horsepower would be available, but the fuel flow would be still further increased. The assumption made above is believed to give a reasonable comparison with the data of Item 4, page 42. The data of Table XXXVI can now be obtained.

It is seen that a 5% stall condition with torque-converter operation adds about 150 lb of fuel/day over and above that of Item 2, page 42.

The final comparison thus becomes:

BFD with responsive engine: 1084.1 fuel lb
BFD with converter: 1513.0 fuel lb.

Each of these two conditions has the same time of stall operations under the same degree of slip.

TABLE XXXVI

BATTLEFIELD DAY WITH TORQUE-CONVERTER STALL

mph	% Time	Hours	Gear	Fuel Flow Average, lb/hr	Total Fuel, lb
Stall	5.0	1.2	1st	161.5	193.8
2-3	5.0	1.2	1st	35.4	42.5
4-6	10.0	2.4	2nd	57.8	138.7
7-10	20.0	4.8	3rd	87.3	419.0
15-20	20.0	4.8	4th	140.0	671.0
Idle	40.0	9.6		5.0	48.0
				Lb of fuel/BFD of 24 hr =	1513.0

VIII. TURBOCHARGER REQUIREMENTS

The responsive engine must be capable of providing turbocharger operation at ratios of 2.6:1 and 4.57:1 together with any ratio in between if at all possible. The object of this section is to examine the possibilities of providing such flexibility in the simplest manner.

It must be admitted that the 2.6:1 condition for 500 hp at 3000 rpm can be provided without any difficulty since it is already being done. The problem now becomes: what range of speed, air flow, etc., can be expected from such equipment without additional complication?

One of the most important factors in compressor design is the air flow, which together with the pressure ratio is mainly responsible for surge. The problem will be approached in the first case by obtaining the air flow requirements.

In Table VIII, Ref. 1, p. 36, the air trapped in the cylinder for the 3000 rpm condition with 2.6:1 ratio is given as 1.197 lb/sec or 1.3 lb/sec with 8-1/2% blow-through. The same engine displacement is now to be supplied at 4.57:1 ratio. It will be assumed, in this first approach, that after-cooling to 200°F is still possible; thus, the air flow at 1000 rpm is given by

$$\text{Cylinder air charge at 1000 rpm} = 1.197 \times \frac{4.57}{2.6} \times \frac{1000}{3000}$$

$$= 0.703 \text{ lb/sec.}$$

The slow speed will probably allow some additional blow-through of the engine during valve overlap; assume this to be 12%. Then

$$\text{Air flow from charger at 1000 rpm} = 0.79 \text{ lb/sec}$$

$$\text{Ratio of } \frac{\text{air flow at 1000 rpm}}{\text{air flow at 3000 rpm}} = 0.61 \text{ .}$$

This, it is believed, is not an impossible condition to be fulfilled, but would probably involve variable turbine geometry.

It is now proposed to examine the conditions in detail. Using the chart of Fig. 8, Ref. 2, together with exhaust temperatures from typical engines operating under the 250 psi BMEP (such as CAE 1100) and 350 psi (Caterpillar research engine), we find exhaust temperatures of about 1350°F for the first condition and a similar one for the second if the engine speed is high. The data of Fig. 7, Ref. 2, indicates an increased exhaust gas temperature with engine speed reduction for the same MEP but at an increased F/A ratio. In the case under examination, the conditions are an increasing MEP as speed reduces, obtained at a constant F/A ratio approximately, but increased air density. Taking all the conditions into consideration it would be anticipated that some factors such as reduced speed, increased percentage of cooling losses, etc., will reduce gas temperature while others such as reduced expansion ratio will increase it. Where these balance out would be difficult to determine.

Since the F/A remains constant, the change of temperature will be small. Let it be assumed that for the 4.57:1 charger condition the exhaust gas temperature will be 1450°F. It is now possible to examine the balance between turbine work available and the input compressor work; the supply and demand is as shown in Table XXXVII.

TABLE XXXVII

COMPRESSOR AND TURBINE WORK

	Compressor		Turbine	
Pressure ratio of compression or expansion	2.6:1	4.57:1	2.21:1	3.88:1
Ambient pressure at inlet, psi	14.7	14.7	32.6	57.2
Ambient temperature at inlet, °F	85	85	1350	1450
Isentropic work of compression or expansion, Btu/lb of flow	41.4	71.9	71.0	121.0
Air or gas flow, lb/sec	1.3	0.79	1.36	0.827
Isentropic work of unit, Btu	53.8	56.4	96.6	99.8
Work of compressor at 78% efficiency	68.8	72.0	--	--
Require efficiency of turbine, %	--	--	71.6	72.2

In constructing the table a pressure drop between manifolds of 15% was allowed, and an efficiency of 78% was assumed for the compression process; then the minimum turbine efficiency was established to provide the necessary work to drive the compressor as a turbocharger. It is seen that efficiencies of 71.6% and 72.2% are involved, values that can be met easily in modern designs, in fact can be exceeded readily.

It follows that, given a suitable centripital design of turbine capable of providing the two flow areas required at the nozzle exit, the exhaust gas available at 1000 rpm will provide the necessary power for compression to 4.57:1, while at the 3000 rpm similar conditions will exist for the 2.6:1 power requirements.

It must be admitted that a ratio of 4.57:1 in one stage of compression is at the limit, perhaps a little above, and will require careful design and high operating speed. However, there should be more than sufficient power for the purpose. At the 2.6:1 ratio there is no question of satisfactory performance; it is in use today.

The range of air flow requirements is such that a vaneless compressor would be capable of providing the two flows at some small drop in efficiency. Since there is an excess of power in the turbine this drop could be tolerated. The detailed final design would have to be made to see if all other required conditions can be met. This is not necessary at this time since it can be concluded that the responsive conditions for 3000 and 1000 rpm can be met by straight turbocharging. There is always the possibility of burning a small quantity of fuel in the excess oxygen of the exhaust gases for some increase in power to the turbine if it proved to be necessary for the emergency condition at 1000 rpm, at, of course, a small penalty in additional fuel.

The solution of the problem of achieving a 1.68:1 responsiveness is thus not too difficult; it is mainly one of designing a turbocharger that would automatically increase in speed under the action of an emergency control applying additional back pressure to the engine by reducing the turbine nozzle outlet area. For general operation it would function at as present, or perhaps on some modified schedule that would keep the manifold pressure at a point giving best economy as far as possible for each operating speed. When stalling conditions are reached, the control would reduce the turbo-nozzle area. This would produce an increased back pressure in the exhaust and thus greater turbine speed, which in turn produces greater manifold pressure followed by increasing engine output, producing the responsive conditions.

The data of Table XXXVII indicate that there is ample power available in the exhaust gases, since turbines of 84 to 86% could readily be designed; thus, there would be power for accelerating the turbo under the action of a suitable control whose duty would be to prevent runaway under normal conditions plus a controlled speed increase when desired.

If an engine of these characteristics is of interest for the purpose involved, the next step appears to be a detailed examination of the turbocharger and the controls that will be desired to fulfill the requirements.

IX. CONCLUSIONS

As a result of this analysis it can be concluded that:

1. An engine of 1.68:1 responsiveness can be designed at the present time without exceeding, by any appreciable amount, mean effective pressure already developed under R and D contracts.

2. To effect this, the work of various contractors would have to be brought together into one engine concept.

3. Such an engine and plain gear box would be the equivalent of the presently examined engine, converter, and transmission components under all conditions of operation in 4th gear, and would exceed present performance under all vehicle speeds in all other gear ratios when operating in a gradually responsive manner over a speed range of 3000-1000 rpm, reaching 1.68:1 responsiveness at the 1000 rpm.

4. Under the above conditions the fuel demands per BFD with responsiveness would be 1084 lb approximately; while with combined torque-converter and lockup operation the requirements are 1143 lb, with lockup only 1039 lb, with converter operation only 1362 lb, and with converter operation with stall 1513 lb/24 hr BFD.

5. To effect this performance characteristic, a new design of turbocharger would be necessary with variable nozzles plus an exhaust manifold control of the variable by-pass type to obtain the desired speed of rotation from the turbo.

6. In order to have a complete prespective of the situation, a further analysis should be made to see what could be achieved, what difficulties encountered, what vehicle performance, etc., would result if, in place of responsiveness, the power plant would operate at the high BMEP, now used only at 1000 rpm, over the whole speed range of the engine.

7. If the speed range employed in these calculations is to be employed in a practical engine application, it is suspected that a fuel injection system capable of such a wide range of speed and metering capabilities must be developed.

8. An analysis should also be made of the engine, transmission, and vehicle dynamics to ascertain what, if any, abnormal stresses would result, or at what speed vehicle bucking would develop which might limit the possible range of responsiveness that can be employed to something less than the 3:1 speed range.

9. Examination of charts and tables reveals that an engine without torque converter but with a responsiveness of only 1.0 down to 1/3 speed would go a long way to achieve desirable characteristics.

X. REFERENCES

1. Vincent, E. T. and Tokuda, N., Engine Performance With Directly Driven Superchargers, ORA Report 05847-1-T, The University of Michigan, Sept. 1963.

2. Vincent, E. T. and Lipson, C., Flexible Versus Responsive Engines, Part I. ORA Report 04612-3-F, The University of Michigan, August 1962.