Motor Transport Fuel Consumption Rates and Travel Time

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Fuel consumption and travel time measurements are a prime consideration in the economical design of highways and contribute a substantial monetary value in benefit-cost analysis. Only limited up-to-date on-the-road data are available, not only for passenger cars but also mainly for various sizes of commercial vehicles. The purpose of this report is to record the procedure and findings of an extensive survey during the summer months of 1959 in which fuel consumption and travel time were measured on nearly every possible classification of truck and trailer combinations, as well as on urban and intercity buses. Both gasoline- and diesel-powered vehicles were tested under varying conditions of grade, surface speed, weight, stopping and slowing.

One of the primary uses of the data will be to provide a comprehension of the differential fuel and travel time benefits associated with each classification of the heavier vehicles operating in greater numbers each year on the highways. Combining the results of this study with a similar investigation (1) of single-unit trucks and passenger cars will complete the range of vehicle types.

The data presented in the report should be highly beneficial to the economical planning and design of highways as well as to assignment of cost responsibility. Comparisons and analyses are possible for fuel and time savings by improvement of roadway surfacing, removal or reduction of stops, elimination of congestion and slowdowns, reduction of grade, shortening of grades, or control of operating speed.

Preliminary analysis of the pretesting data obtained on each vehicle and correlated with the actual data recorded during the road testing indicates a potential method of predicting the operating characteristics under any conditions. Verification of this method would eliminate the need for such a detailed study as this in the future, assuming no radical changes in the means of motor transportation.

●DURING the summer of 1958 the Civil and Mechanical Engineering Departments of the University of Washington entered into a research contract with the Bureau of Public Roads for the specific purpose of measuring the actual fuel consumption and travel time of commercial vehicles on routine routes in Western Washington. Test sections were established to correlate fuel consumption with traffic conditions. This study was one of four performed throughout the nation, with the observed data presented to the Bureau for analysis and correlation (2). However, only the University of Washington study included fuel measurements on diesel-powered vehicles. A diesel-engine fuel metering device was developed by Professors Firey and Meador of the Mechanical Engineering Department (3); with minor perfections, it was possible to make accurate measurements for the conditions of the research performed during the summer months of 1959.

A supplemental research project was performed in the winter of 1958-9 for the Washington State Highway Department and the Bureau of Public Roads to relate winter fuel consumption rates to the summer data collected (4).

The research reported herein was conducted for the Bureau of Public Roads and Washington State Highway Commission. The study required leasing of 17 separate truck, trailer or bus units, which represented 12 different vehicles or combinations for the testing purpose. It was necessary to employ nine drivers and nine observers to operate two 10-hr shifts per day to collect the required data in the time provided. In addition, six faculty personnel were utilized to perform supervisory, survey and instrumentation functions.

It was a definite asset to the study to secure engineering students, not only to record the data, but also to operate the test trucks and buses.

RESEARCH STUDY PROCEDURE

Test Vehicle Characteristics

The research contract specified the testing of five gasoline-powered truck or tractor-and-trailer combinations, one gasoline bus, four diesel-powered truck or tractor-and-trailer combinations, and two diesel buses. Descriptions of the test units are presented in Figure 1. Additional information on each vehicle is given in Table 1.

It will be noted that all trailer units used for this study were of the tanker type.

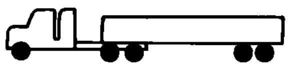
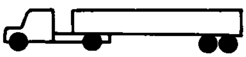
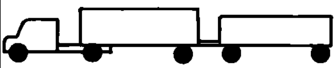
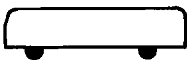
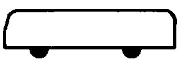
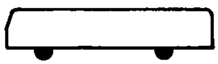
TEST VEHICLE DESCRIPTIONS					
TEST UNIT	AXLE CLASS.	GASOLINE	TEST UNIT	AXLE CLASS.	DIESEL
1-A	3-S2		5-A	3-S2	
2-B	2-S2		3-B	2-S2	
2-C-D	2-S1-2		3-C-D	2-S1-2	
10	2-2		8	3-2	
7-C	2-S1		9	2-Bus (Rural)	
6	2-Bus (Urban)		4	2-Bus (Urban)	

Figure 1.

TABLE 1

TEST VEHICLE DESCRIPTIVE DATA

1. Test unit no.	1-A	2-B	2-C-D	3-B	3-C-D	4	6	9	5-A	7-C	8	10
2. Axle classification of combination	3-S2	2-S2	2S1-2	2-S2	2-S1-2	2-Bus Urban	2-Bus Urban	2-Bus Rural	3-S2	2-S1	3-2	2-2
3. Power unit vehicle	Tractor	Tractor	Tractor	Tractor	Tractor	Bus	Bus	Bus	Tractor	Tractor	Truck	Truck
a. Year of manufacture	1955	1950	1950	1959	1959	1955E	1947	1948	1957	1958	1950	1958
b. Body type (none on tractors)											Tanker	Tanker
c. Frontal area of power unit												
d. (1) Wheelbase axle 1 to axle 2 (ft)	15.7	13.8	13.8	10.7	10.7	23.5	18.0	21.8	16.9	13.0	16.1	14.6
(2) Wheelbase axle 2 to axle 3 (ft)	4.0										4.4	
e. (1) Engine, fuel	Gasoline	Gasoline	Gasoline	Diesel	Diesel	Diesel	Gasoline	Diesel	Diesel	Gasoline	Diesel	Gasoline
(2) Engine, no. of cylinders	6	6	6	6	6	6	6	6	6	6	6	8
(3) Engine, displacement, in.[3]	501	503	503	672	672	425.6	404	425.31	743	331	426	332
(4) Engine, mfgrs. net HP at RPM	184 at 2,600	185 at 2,600	185 at 2,600	205 at 2,100	205 at 2,100	167 at 2,000	180 at 2,800	208 at 2,100	220 at 2,100	122 at 2,800	208 at 2,100	187 at 3,600
f. Rear axle gear ratio	6.69	7.05	7.05	5.30	5.30		$6\frac{1}{8}$	$4\frac{1}{11}$	$6\frac{1}{8}$	U8.28 0 5.99	$5\frac{2}{3}$	U9.77 0 7.17
g. (1) Transmission ratio, main 1st	8.08	7.33	7.33	7.53	7.53	Torque Converter	Torque Converter	3.81	5.19	7.08	5.19	7.58
(2) Transmission ratio, main 2nd	4.67	4.67	4.67	4.32	4.32			2.50	2.88	3.83	2.88	4.38
(3) Transmission ratio, main 3rd	2.62	3.06	3.06	2.60	2.60			1.50	1.72	2.03	1.72	2.40
(4) Transmission ratio, main 4th	1.38	1.72	1.72	1.62	1.62				1.00	1.31	1.00	1.48
(5) Transmission ratio, main 5th	1.00	1.00	1.00	1.00	1.00					1.00		1.00
(6) Transmission ratio, aux. 1st	1.29	1.24	1.24	1.18	1.18				1.29		1.29	
(7) Transmission ratio, aux. 2nd	1.00	1.00	1.00	1.00	1.00				1.00		1.00	
(8) Transmission ratio, aux. 3rd	0.84	0.88	0.88	0.85	0.85				0.84		0.84	
h. Tire size, power unit	10x20	10.00x20	10.00x20	10x20	10x20	11x20	F10x22 R 9x20	11x19	10x22	9x20	11x24.5	10x20
4. a. First trailer is (semi or full)	Semi	Semi	Semi	Semi	Semi				Semi	Semi	Full	Full
b. Trailer, body type	Tanker	Tanker	Tanker	Tanker	Tanker				Tanker	Tanker	Tanker	Tanker
c. Trailer, frontal area												
d. (1) Trailer, wheelbase, kingpin to axle (ft)	25	19	18	20	18				23	19		
(2) Trailer, wheelbase, axle 1 to axle 2 (ft)	4.0	4.0		4.0					4.0		17.8	15.1
e. (1) Second trailer is (converter-gear semi or full)			Full		Full							
(2) Trailer, body type			Tanker		Tanker							
(3) Trailer, frontal area												
(4) Trailer, wheelbase, axle 1 to axle 2 (ft)			17.65		17.65							
f. (1) Combination, over-all length, (bumper to bumper) (ft)	53.3	45.4	62.95	41.2	60.0	39.7	32.8	34.5	52.9	36.4	60.0	51.5
(2) Gross weight, empty (lb)	26,180	24,430	26,990	24,760	27,320	20,510	15,590		28,350	21,580	31,016	22,350
(3) Gross weight, 70% of max GVW (lb)	49,980	42,526	49,930	41,700	50,010				46,600	28,730	53,704	38,600
(4) Gross weight, full load (lb)	64,650	57,246	72,500	57,800	71,540	27,780	21,350	28,450	66,300	41,490	75,550	58,120

These tankers were selected to minimize the effect of wind resistance as well as for ease of loading with water.

In procurement of the vehicles an attempt was made to select not only a representative vehicle for each classification but also a late model, if possible. The latter was not always the case, due either to the scarcity of the vehicle or the high demand for commercial service. Each vehicle was subjected to preliminary tests, as discussed in a subsequent section.

Road Test Section Characteristics

To obtain the necessary test data on fuel consumption and travel time, it was required to select roadway test sections with a high type surfacing on a range of grades, as well as a level gravel section.

Figure 2 shows the location of the test sections in the vicinity of Olympia, Wash. Table 2 gives a summary description of the test sections.

Considerable reconnaissance was required to obtain the various types of test sections necessary. Segments of US 99 south of Olympia were most nearly ideal, not only because of their location on a freeway with relatively low traffic volume and adequate turn-around facilities but also because of the proximity of the steeper grade sections and the gravel road.

Research Test Measurements

The basic data recorded by the observer were as follows:

1. Test unit number.
2. Loading condition.
3. Test section.
4. Indicated speed.
5. Driver.
6. Direction.
7. Date.
8. Time of day.
9. Road condition.
10. Operating gear.
11. Tachometer reading.
12. Fuel temperature.
13. Initial fuel reading.
14. Final fuel reading.
15. Fuel used.
16. Elapsed time.

Vehicles were operated on the paved level roadway of section 1 at three loading conditions (empty, maximum legal load, and approximately 70 percent of legal load). The only exception to these loadings was in the case of the buses, which were loaded to the normal load factor as supplied by the transit company. For each loading condition the vehicles were operated at speeds of 15, 25, 35, 45, and 55 mph, or the top speed if less than 55 mph.

The test unit made at least three round-trips at each speed. It was the opinion of the research team that in some cases three round-trips were not an adequate sample; therefore, when the fuel consumption and travel time results were compared and reasonable agreement was not obtained (± 5 percent), additional observations were made.

The operating conditions on the level gravel section 6 were similar to level section 1, except the higher speed operation could not be obtained with safety.

On the grade sections 2, 3, 4, 5, and 7 the procedure differed only in the test speed. The first observations were made at the maximum constant speed the vehicle could maintain on the grade. Two lower speed runs were then made using lower gear settings

A comparison of the data obtained on the constant-speed runs on section 1 with the observations on the gravel section 6 will reflect the effect of roadway surfacing on fuel consumption and travel time.

Relating the data on the grade sections (2, 3, 4, 5, 7) with the standard section 1 will reveal the effect of grade.

To measure the additional fuel and time required to make a stop from the various test speeds, continuous cycles of stopping and accelerating to test speed were performe on section 1, with time measurements recorded at the end of a deceleration and acceler tion, and any lost time in starting from the stopped position. Fuel measurement was taken for the total length of section 1 for the various stop-and-go cycles. From these

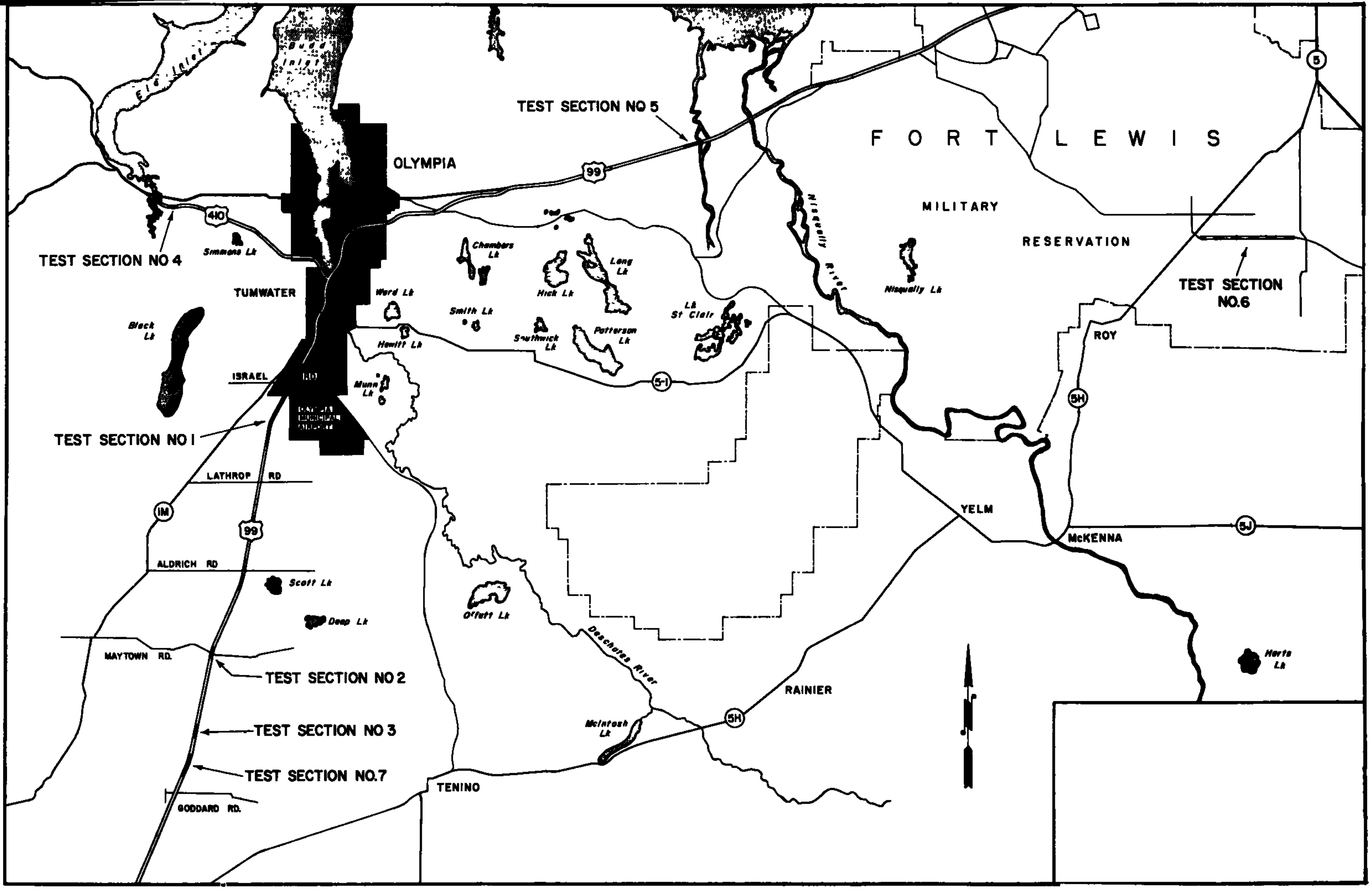

OLYMPIA
TUMWATER
FORT LEWIS
MILITARY
RESERVATION
TEST SECTION NO 1
TEST SECTION NO 2
TEST SECTION NO 3
TEST SECTION NO 4
TEST SECTION NO 5
TEST SECTION NO.6
TEST SECTION NO.7
ISRAEL RD
LATHROP RD
ALDRICH RD
MAYTOWN RD.
GODDARD RD.
YELM
McKENNA
ROY
RAINIER
TENINO
Nisqually River
Deschutes River
Eld Inlet
Budd Inlet
Black Lk
Simmons Lk
Chambers Lk
Ward Lk
Hewitt Lk
Smith Lk
Hick Lk
Long Lk
Southwick Lk
Patterson Lk
Lk St Clair
Munn Lk
Nisqually Lk
Scott Lk
Deep Lk
Offutt Lk
McIntosh Lk
Harts Lk
99
410
5
5-I
5H
5J
IM

Figure 2.

TABLE 2

SUMMARY OF TEST ROADWAY CHARACTERISTICS

Test Section	Surface Type	Ave. Grade (%)	Horiz. Curve Δ	Horiz. Curve D	Lanes (no.)	Lane Width (ft)	Highway Type	Section Length[1] (ft) N	Section Length[1] (ft) S
1	Asph. conc.	0.09	$18^{\circ}30'$	1°	4	12	Freeway	10,718	10,676
2	Asph. conc.	2.79	0	0	4	12	Freeway	1,246	1,246
3	Asph. conc.	1.53	0	0	4	12	Freeway	1,520	1,536
4	Asph. conc.	4.0	0	0	4	12	Freeway	1,040	1,040
5	Cem. conc.	5.96	0	0	4	11	4' painted centerline	2,022	2,022
6	Gravel	0.34	Slight		2	12	Loose gravel	10,998±	10,998±
7	Asph. conc.	0.68	$9^{\circ}52'$	1°	4	12	Freeway	2,714	2,719

[1]Length of test section varied with speed and load conditions due to limited approach length.

data it is possible to evaluate the effect of control devices or congestion causing a vehicle to come to a stop.

A similar series of tests was performed simulating congested conditions which would require the vehicle to slow an increment of 10 mph and also 15 mph below the test speeds.

Analysis of fuel consumption used during a stopping cycle would not be complete without measuring the fuel used while the vehicle is stopped. Table 3 gives idle fuel consumption rates for all of the vehicles tested. In general, the amount of fuel used was extremely small and tests were continued for periods as long as 30 min. The method of analysis and the results are presented in a later section.

TABLE 3

IDLE FUEL CONSUMPTION RATES

Power Unit	Fuel Flow (rpm)	Fuel Flow (gal/min)
1	650	0.0148
2	650	0.0131
3	600	0.00742
4	[1]	0.00750
5	700	0.00488
6	[1]	0.0121
7	600	0.01030
8	300	0.00762
9	[1]	0.00780
10	750	0.01500

[1]No tachometer.

VEHICLE INSTRUMENTATION, PRETESTING AND ANALYSIS

Vehicle Instrumentation

Instrumentation was chiefly concerned with measurement of fuel quantity and fuel temperature during each specified road test. Fuel quantity was determined by use of either a calibrated burette arrangement or a Petrometa fuel meter. In each case the quantity could be measured to within ± 5 cc accuracy. Fuel temperature was read from a thermometer fitted into the fuel supply line.

Burette Arrangement. Figure 3 shows schematically the fuel measuring device as used in this study. One 500-cc and two 2,000-cc graduated burettes, with valves, fuel pump, thermometer, and suitable piping, were fitted on a plywood base in the cab of the test vehicle. An observer in the test vehicle manually controlled the valves to permit use of fuel only from the burettes during traverse of a test section. Figure 4 shows typical meter board installations for bus and truck tractor.

Petrometa Fuel Meter. A mechanical-electrical fuel measuring instrument known as the MGA Petrometa Fuel Meter[1] was used extensively on one test vehicle and to a limited extent on two other vehicles. Calibration of this instrument was difficult, as th

[1]Manufactured by M.G.A. Industries, Ltd., Loughton, Essex, England.

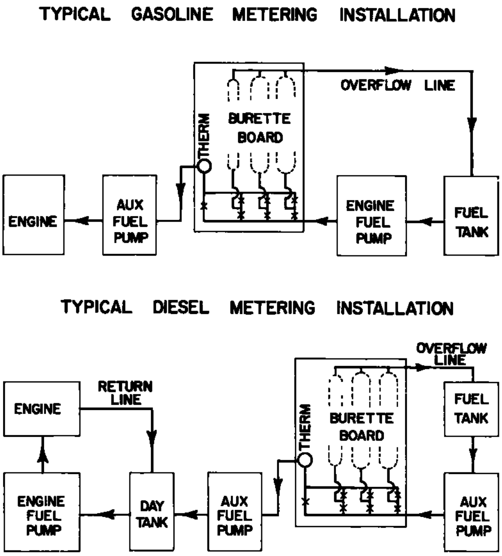


Figure 3.

calibration factor varied for different flow rates, and also appeared to be sensitive to fuel pump pressure and battery voltage. Use of the meter greatly speeded data taking; but further use of the instrument was prevented by the difficulty in calibration of the meter for the great variety of flow rates encountered.

Day Tank. Diesel engines having a recirculating fuel system required an addition of a day tank to the fuel measuring equipment. Figure 3 also shows schematically the day tank arrangement and its location in the diesel fuel measuring system. Figure 5 shows the actual day tank mounted behind the tractor cab.

Fuel is returned from the injector system to the day tank rather than to the fuel tank through the normal return. A float valve maintained a constant level in the day tank by admitting fuel from the burette arrangement to replace fuel used by the engine.

Vehicle Pretesting

Prior to test running, each vehicle was pretested to ascertain whether the engine and running gear were in proper condition. The vehicle rolling resistance, engine friction horsepower, engine thermal efficiency, wide-open throttle power output, and

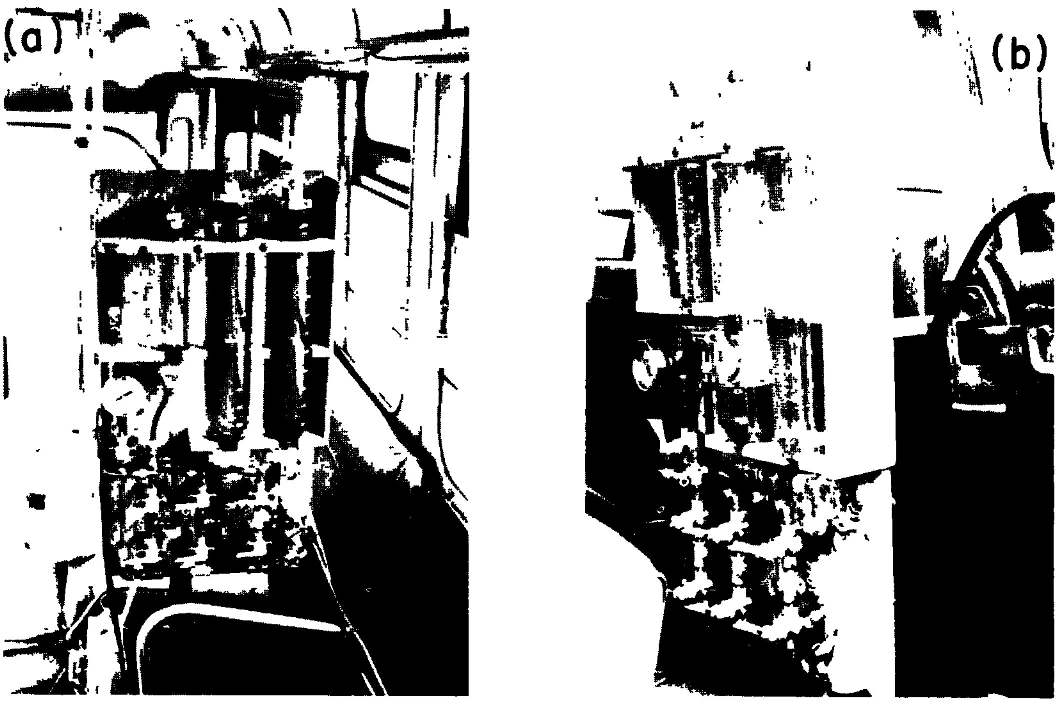


Figure 4. Burette installation in (a) bus and (b) tractor.

air-fuel ratio were measured by road test. If the measured values lay within reasonable limits the vehicle was considered in proper condition for test running.

The pretest measurements and calculations are explained in succeeding sections wherein the following abbreviated nomenclature is used:

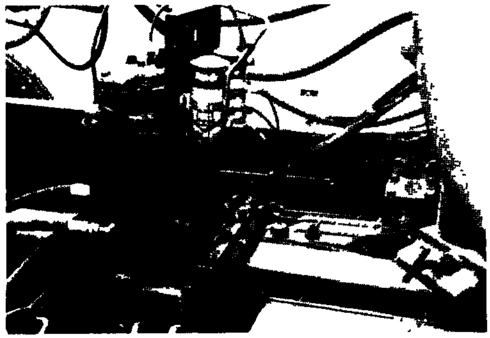


Figure 5. Day tank installation in diesel unit.

- RHP = Road horsepower, the power required to overcome gear and bearing friction in the drive train, plus tire hysteresis, plus tire and road surface slippage, plus road surface deflection, plus air resistance;
- PHP = Potential horsepower, the power required to increase vehicle potential energy when climbing a grade (negative on a downgrade);
- AHP = Acceleration horsepower, the power required to increase vehicle kinetic energy when accelerating (negative when decelerating);
- FHP = Friction horsepower, the power required to overcome internal friction of the engine;
- IHP = Indicated horsepower, the power developed by the combustion of fuel in the engine combustion chamber and delivered to the engine pistons;
- BHP = Brake horsepower, the power delivered by the engine to the clutch (BHP = IHP - FHP);
- HPB = Power to braking, the power required to overcome the friction of the vehicle brakes when applied;
- GVW = Gross vehicle weight, in lb;
- KE = Vehicle kinetic energy, in ft-lb;
- N_E = Engine rpm;
- mph = Vehicle miles per hour;
- t = Time, in min;
- n_i = Indicated thermal efficiency of the engine;
- n_b = Brake thermal efficiency of the engine;
- w_f = Fuel flow rate, in lb per hr;
- gph = Fuel flow rate, in gal per hr;
- G = Total fuel used, in gal;
- HHV = Fuel higher heating value, in Btu per lb;
- D = Fuel density, in lb per gal;
- T = Number of tires on the vehicle;
- K = Ratio FHP/N_E^2; and
- B = Ratio FHP/N_E.

Rolling Resistance Test. Vehicle rolling resistance was measured as the road horsepower, RHP, above 20 mph. This test consisted of bringing the vehicle up to a selected speed, disengaging the clutch, and recording the time required to slow down to each 5-mph speed. In this experiment the initial kinetic energy of the vehicle is utilized to propel the vehicle over the road; hence, the rate of loss of vehicle kinetic energy equals the RHP.

$$RHP = \frac{-1}{550} \frac{d(KE)}{dt} \qquad (1)$$

Vehicle KE consists of two portions—the translational KE due to vehicle speed, and the rotational KE due to wheel and axle spin. Rotational KE was estimated from the known wheel dimensions and materials, the axles and drive train being presumed equivalent to one wheel and tire. After introducing the KE equations and suitable constants

$$RHP = \frac{GVW}{8,210}\left(\frac{mph}{60}\right)\left(\frac{-d\ mph}{dt}\right)\left(1 + 152\ \frac{T+1}{GVW}\right) \qquad (2)$$

Values of $\frac{-d(mph)}{dt}$ were measured graphically from a plot of mph vs t obtained from the coasting test, such as shown in Figure 6. All such plots for the trucks tested showed two straight-line segments with a change of slope occurring between 18 and 24 mph. RHP is thus a linear function of mph, but the ratio of RHP to mph is higher above 20 mph.

The rolling resistance tests were run in both directions of test section 1 and the results averaged to compensate for any grade or wind effects.

It was the original plan to compare the measured RHP of a vehicle with the RHP calculated by the SAE method as described in SAE publication TR-82, "Truck Ability Prediction Procedure." If the measured RHP was no more than 10 percent greater than the calculated RHP the vehicle was to be considered satisfactory in rolling resistance for the test running. This plan proved unfeasible, however, because in every case the measured RHP was found to be far lower than the RHP calculated by the SAE method. Furthermore, measured RHP varied linearly with speed, whereas the SAE method predicts RHP to vary non-linearly with speed. The source of these discrepancies could not be clearly determined from these experiments. In SAE publication TR-82 it is explained that the procedure is based on experiments with trucks of less than 30,000-lb GVW and may not be applicable to the heavier vehicles used in these tests. The measured RHP is considered reasonably correct, inasmuch as the vehicle pretest results, which included the RHP, fairly accurately predicted vehicle performance during test running, as discussed subsequently.

The acceptability of a vehicle in respect to rolling resistance could only be based on a comparison of its RHP with that of other vehicles tested. Hence, the RHP standard was necessarily developed as the testing progressed. Measured values of the ratio

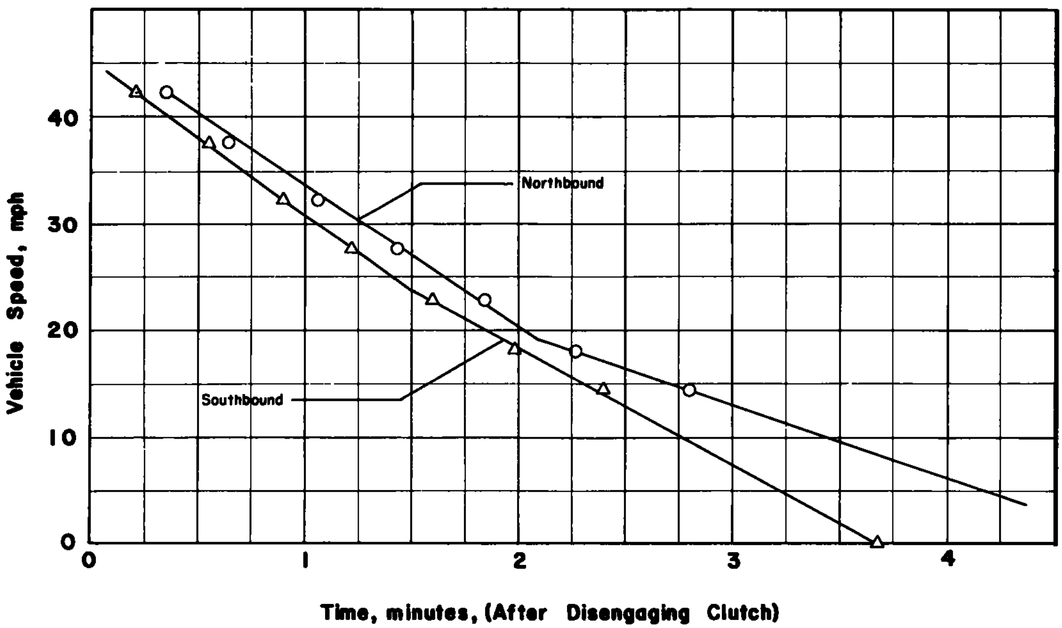


Figure 6. Typical rolling resistance test data, vehicle 1-A, out of gear, GVW=48,985 lb.

RHP/mph were found to be a linear function of GVW, as shown in Figure 7. The averag of these results is expressed by

$$\text{RHP} = \frac{\text{GVW}}{55,600}(\text{mph}) + 0.52\ (\text{mph}) \tag{3}$$

which appears to be adequate over the following range of vehicle conditions:

1. GVW between 20,000 and 75,000 lb.
2. Speeds between 20 and 50 mph.
3. Number of tires between 6 and 18.
4. Tire pressure of 80 psig.

If the RHP of a vehicle was no more than 10 percent greater than this average curve, the vehicle was considered acceptable.

The linear relation between RHP, GVW and mph suggests that air resistance is perhaps relatively small and that tire losses are the major rolling resistance of heavy vehicles within the range of speeds tested.

Engine Friction Horsepower Test. Engine FHP was measured as the difference between RHP and the rolling resistance power measured with the clutch engaged and the ignition or fuel cut off at wide-open throttle. The procedure is identical with that used to measure RHP, except that the initial vehicle KE is utilized to propel the vehicle over the road and also to overcome internal friction of the engine.

Engine FHP is used principally in pushing the piston rings up and down in the cylinde This friction is viscous, hence FHP varies approximately as the square of engine rpm, or

$$\text{FHP} = K\,N_E^2 \tag{4}$$

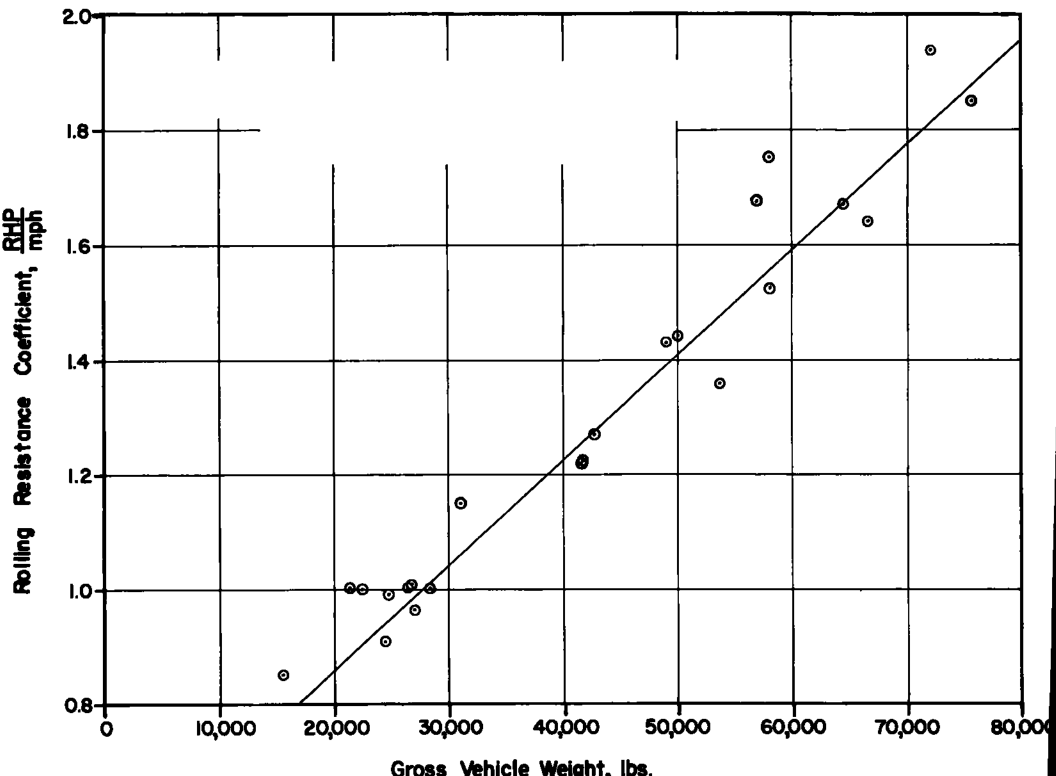


Figure 7. Coefficient of rolling resistance as a function of GVW.

Unfortunately, the test procedure used was not precise enough to permit an accurate determination of K, because FHP was measured as the small difference of two large measured values which varied almost linearly in mph, hence with N_E. Thus, the measured FHP is here expressed approximately as a linear function of N_E, or

$$FHP = B\,N_E \tag{5}$$

This relation is necessarily approximate and useable only within the engine speed range where measured. For large trucks no serious error is involved, because the engines are normally operated within a narrow range of speeds.

A summary of the measured B values is presented in Table 4.

TABLE 4

MEASURED VALUES OF $B = FHP/N_E$

Power Unit No.	Used in Veh. Comb.	B	Engine Displacement (cu in.)	Engine Type
1	1-A	0.0105	501	Gasoline
2	2-B	0.0125	503	Gasoline
3	3-C-D	0.0246	672	Diesel
5	5-A	0.0148	672	Diesel
7	7-C	0.0094	331	Gasoline
8	8	0.0453	426	Diesel[1]
10	10	0.0123	332	Gasoline

[1]Two-stroke.

Engine FHP was not used directly as a criterion of vehicle acceptability, inasmuch as it varies widely with engine design and the number and type of auxiliaries being driven by the engine. The FHP was needed, however, for the calculation of engine thermal efficiency.

Engine Thermal Efficiency Test. Engine thermal efficiency is the ratio of power output to rate of supply of fuel heating value, both quantities being expressed in similar units; that is,

$$n = \frac{(HP)\,(2,545)}{w_f\,(HHV)} \tag{6a}$$

or in more convenient units,

$$n = \frac{HP}{gph}\;\frac{2,545}{D(HHV)} \tag{6b}$$

Two values of n can be calculated for an engine; brake thermal efficiency, n_b, when BHP is used, and indicated thermal efficiency, n_i, when IHP is used. Because of engine characteristics it is frequently most convenient to use n_i for gasoline engines and n_b for diesel engines. Gasoline engines in proper condition have an approximately constant value of n_i between 0.20 and 0.25 over a wide range of operating conditions. Diesel engines in proper condition have roughly constant values of n_b between 0.15 and 0.20 over a fairly wide range of operating conditions.

Calculations of n were made only for the level road, steady-speed tests. The engine BHP or IHP was calculated from the measured RHP and FHP.

$$BHP = RHP \tag{7}$$

$$IHP = RHP + FHP \tag{8}$$

The fuel flow rate, in gph, was taken directly from the steady-speed test data.

If the average engine thermal efficiency was greater than the previously stated minima, the vehicle was considered satisfactory in efficiency for test purposes. The measured values of n are summarized in Table 5.

TABLE 5

ENGINE THERMAL EFFICIENCY DATA

Power Unit No.	Used in Vehicle Comb.	Gasoline-Powered Vehicles Indicated Thermal Effic., n_i			Diesel-Powered Vehicles Brake Thermal Effic., n_b		
		Max.	Min.	Avg.	Max.	Min.	Avg.
1	1-A	0.230	0.193	0.210	-	-	-
2	2-B	0.276	0.205	0.247	-	-	-
7	7-C	0.254	0.204	0.233	-	-	-
10	10	0.293	0.204	0.261	-	-	-
3	3-C-D	-	-	-	0.220	0.153	0.191
5	5-A	-	-	-	0.194	0.175	0.185
8	8	-	-	-	0.193	0.127	0.162

Wide-Open Throttle Power Test. Engine power output at wide-open throttle (WOT) was measured by an acceleration test and the results were compared with the manufacturer's rated power of the engine. If the measured power output equalled or exceeded 75 percent of the rated power output, the vehicle was considered satisfactory in power output for testing.

In the acceleration test the vehicle is accelerated through a measured speed interval at wide-open throttle and time intervals and speeds are recorded. Under these conditions

$$IHP_{WOT} = FHP + RHP + AHP \tag{9}$$

FHP and RHP are calculated from the measured values and AHP is calculated as the rate of increase of vehicle KE; that is,

$$AHP = \frac{GVW}{8,210}(mph)\left(\frac{d(mph)}{dt}\right)\left(1 + 152\,\frac{T+1}{GVW}\right) \tag{10}$$

The calculation procedure is entirely similar to that used in the rolling resistance test.

The manufacturer's rated power is the maximum power output the engine is considered capable of delivering at a certain rpm without auxiliaries such as a fan, generator, or air compressor. In the acceleration test it is not possible to measure the corresponding quantity because the axuiliaries are being driven and their power requirement is measured as a part of the engine friction horsepower. Instead the BHP_{WOT} was estimated as 90 percent of the IHP_{WOT}.

The results of the WOT tests are summarized in Table 6.

Operating Air-Fuel Ratio Test. The operating air-fuel ratio of the gasoline-powered vehicles was measured with an air-flow ratio meter with the vehicle operating at steady-spe[ed] conditions. The meter used was of the thermal conductivity cell type. The operating air-fuel ratio was considered acceptable if it fell within the range of 12 to 14 lb of air per lb of fuel.

No attempt was made to measure the operating air-fuel ratio of the diesel-powered vehicles, because this is known to vary widely with engine design and load.

Analysis of Vehicle Pretest Results

The pretest results provide not only a check on the mechanical condition of the vehicle but also a means of calculating both the results of the test and the probable performance of the vehicle in normal commercial service. Agreement between calculated

TABLE 6

WIDE-OPEN THROTTLE POWER OUTPUT

Power Unit No.	Used in Veh. Comb.	Measured IHP_{WOT}	BHP_{WOT} Est.[1]	BHP_{WOT} Manuf. Rated	Ratio, Est./Rated
1	1-A	170 at 2,600 rpm	153	184 at 2,600 rpm	0.830
2	2-B	158 at 2,600 rpm	143	185 at 2,600 rpm	0.770
3	3-C-D	180 at 2,100 rpm	162	205 at 2,100 rpm	0.795
5	5-A	210 at 2,100 rpm	189	220 at 2,100 rpm	0.860
8	8	248 at 2,100 rpm	223	208 at 2,100 rpm	1.070
10	10	188 at 3,400 rpm	170	196 at 3,600 rpm	0.865

[1]Estimated as 0.90 IHP_{WOT}.

and measured test results demonstrates the internal consistency of the data and the essential correctness of the pretest results. A means of calculating vehicle performance in normal commercial service is part of what is needed to determine both the most economic method of operating vehicles over existing highways and the most economic design of a highway for motor transport use.

Only the calculation of some of the results of the test and the comparison with the measured values is discussed here, inasmuch as the test vehicles were not operated in normal commercial service. Unfortunately, the time available permitted calculation of only a portion of the test results. The general method of calculation is described and the available results are presented and compared with the measured values. A reasonable agreement was found.

Method of Calculating Test Results on Grades. At steady speed on a grade the engine IHP is fully absorbed by the FHP, RHP and PHP; that is,

$$IHP = FHP + RHP + PHP \qquad (11)$$

FHP and RHP are calculated from the measured pretest results. For the steeper grades and higher loads RHP below 20 mph must be used if vehicle speed does not exceed 20 mph. The PHP is calculated as the rate of increase of vehicle potential energy, or

$$PHP = \frac{1}{550}\frac{d(PE)}{dt} = \frac{GVW}{37,500}(\%\ grade)(mph) \qquad (12)$$

The required IHP is then calculated for several speeds and grades and the results are plotted as in Figure 8. The intersection of the grade line with the IHP_{WOT}, the maximum power output of the engine, determines the maximum vehicle speed on each grade. At speeds below this maximum, power is available for acceleration. At steady speeds below the maximum the driver has a choice between reduced throttle at high N_E or increased throttle at reduced N_E. The driver's choice in this matter will influence the fuel consumption, more economical gpm being obtained at lower values of N_E. For this reason the gpm can be best calculated only at the maximum speed on each grade. For this calculation IHP_{WOT} is calculated at the maximum useable engine rpm. The gpm at maximum speed on grade is then calculated from the previously measured engine thermal efficiency;

$$gpm = \frac{(0.0204)(IHP_{WOT})}{n_i\ (mph)} \qquad (13)$$

The ratio N_E/mph is then calculated and the nearest available gear ratio selected from those available. The results of such a calculation for vehicle 2B are presented in Table 7. The calculated and measured results are seen to agree reasonably well.

Method of Calculating Slow-and-Go Test Results. The slow-and-go test results were calculated by two different methods—the acceleration method and the braking method.

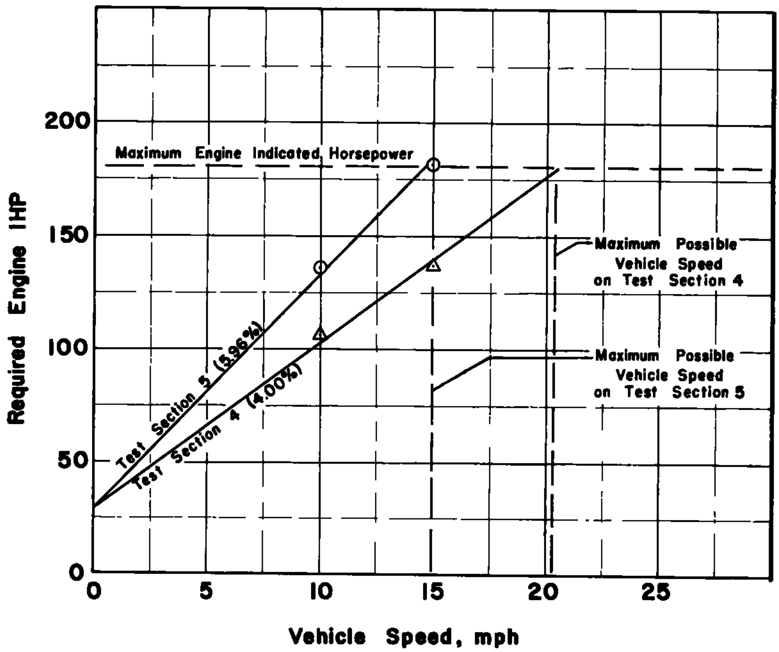


Figure 8. Required engine IHP at various vehicle speeds on two grades, vehicle 2-B, GVW=57,000 lb.

In both methods some of the actual test data are needed, because the driver has too muc choice of running to permit a precalculation of the vehicle cycle.

TABLE 7

CALCULATED AND MEASURED PERFORMANCE OF VEHICLE 2-B ON GRADES

Test Sect. No.	Grade (%)	Calculated Max. Speed (mph)	Calculated Gpm	Calculated Gear Used	Measured Max. Speed (mph)	Measured Gpm	Measured Gear Used
(a) At Full Load, GVW = 57,000 lb							
2	2.78	28	0.60	3/D	29.7	0.54	3/D
4	4.00	21	0.80	4/U	20.8	0.724	4/U
5	5.96	15	1.16	4/D	13.0	1.09	4/D
(b) Vehicle Empty, GVW = 24,430 lb							
4	4.00	43.0	0.385	5/D	40.0	0.353	5/D
5	5.96	31.3	0.525	4/O	28.0	0.51	4/O

(a) Acceleration method. In the acceleration method the actual cycle of operation o the vehicle is followed and the engine is presumed to be at WOT during acceleration and closed throttle during deceleration. The fuel used is calculated for each portion of the cycle, the sum being the total fuel used, G, over the test section. The ratio of G to test section length is then the gpm.

During acceleration Eq. 9 applies, with RHP and FHP calculated from the pretest results. AHP is calculated as the rate of increase of vehicle kinetic energy,

$$AHP = \frac{GVW}{82,100} (mph) \left(\frac{d(mph)}{dt}\right) \left(1 + 152 \frac{T+1}{GVW}\right) \tag{14}$$

The value of $\frac{d(mph)}{dt}$ is obtained from the actual test data, wherein the time to accelerate through a selected speed interval is recorded. The fuel flow rate, in gph, and the fuel used during acceleration are then calculated from the measured engine thermal efficiency, n_i; that is,

$$gph = \frac{(0.0204)\ (IHP)}{n_i} \tag{15}$$

$$G_a = \text{gallons used} = gph \left(\frac{t_a}{60}\right) \tag{16}$$

in which t_a is the average time of acceleration.

Dueing deceleration the engine is presumed to be at closed throttle. The closed-throttle fuel flow can be approximated as equal to the measured idle fuel flow rate. A somewhat more accurate value of closed-throttle flow is obtained from the downhill runs on steep grades. It matters little which method is used, as the total fuel used during deceleration is a very small portion of the total; that is,

$$G_d = gph\left(\frac{t_d}{60}\right) \tag{17}$$

in which t_d is the average time of deceleration.

The total fuel used over the test section is then the sum of the fuel used over each portion:

$$G = a\ G_a + d\ G_d \tag{18}$$

in which

a = number of accelerations in the test section; and
d = number of decelerations in the test section.

Then

$$\text{Avg. gph} = \frac{(G)\ (60)}{(a\ t_a + d\ t_d)} \tag{19}$$

$$\text{Avg. gpm} = \frac{\text{Avg. gph}}{\text{Avg. mph}}\,. \tag{20}$$

(b) Braking method. In the braking method the vehicle operation during slow-and-go is presumed equivalent to steady-speed operation at the average mph with the brakes dragging.

$$\text{Equiv. IHP} = RHP + FHP + HPB' \tag{21}$$

The equivalent power dissipated at the brakes, HPB', is calculated as if the power dissipated at the brakes during deceleration, HPB, were uniformly distributed over the entire running time; that is,

$$HPB' = HPB\left(\frac{t_d}{t_a + t_d}\right) \tag{22}$$

During deceleration power is delivered to the vehicle by the engine and by the rate of loss of vehicle kinetic energy, whereas power is dissipated at the brakes and in overcoming FHP and RHP.

$$IHP - AHP = RHP + FHP + HPB_d \tag{23a}$$

or

$$HPB_d = IHP - AHP - RHP - FHP \tag{23b}$$

in which IHP is the engine indicated power at idle, RHP and FHP are calculated as before, and AHP is calculated from the rate of loss of vehicle KE. The gpm is then calculated from the known engine thermal efficiency.

The results of these calculations for vehicle 2-B are presented in Table 8, together with the measured test results. With the exception of the 35-25-35-mph cycle with vehicle empty, the calculated and measured results are in reasonably good agreement.

TABLE 8

CALCULATED AND MEASURED PERFORMANCE OF VEHICLE 2-B DURING SLOW-AND-GO TESTS

Slow-And-Go Cycle (mph)	Fuel Consumption (gpm)		
	Calculated		
	Accel. Method	Braking Method	Measured
(a) At Full Load, GVW = 57,000 lb			
45-30-45	0.347	0.338	0.312
35-25-35	0.425	0.379	0.386
(b) Vehicle Empty, GVW = 24,430 lb			
45-30-45	0.338	0.316	0.298
35-25-35	0.30	0.277	0.346

Summary of Analysis of Pretest Results

Calculations of the foregoing type were carried out for several, but not all, of the test vehicles. The results are summarized in Figures 9 and 10. As shown in Figure 9, a consistent correlation was obtained between measured and calculated fuel consumption on grades, but the measured gpm was about 15 percent less than the calculated gpm. The exact cause of this discrepancy is not known. One possible explanation is that the lubricating oil on the cylinder wall is hotter and less viscous during the wide-open throttle tests on grades than during the non-firing friction horsepower tests on level road. Hence, engine FHP on grades may be less than the measured value, resulting in better gpm than calculated. This may also explain in part the consistent observation by truckers that their gpm in summer are always better than in winter. During summer oil temperatures are higher than in winter and the consequent reduction in FHP results in better gpm.

The comparison of measured and calculated gpm for the slow-and-go tests (Fig. 10) is reasonably close. However, calculations have been carried out for only a few of the test vehicles.

In general, it appears likely that with certain improvements the vehicle pretest method described herein could be utilized to accurately predict the travel time and fuel consumption of a truck on an existing or planned highway. The improvements would consist largely of better instruments for speed and time measurements, a truly level test course, and measurement of engine lubricating oil temperatures under various operating conditions. Tests wherein pretest measurements of improved accuracy were compared with normally loaded vehicles running over various existing highways could demonstrate whether the method is reliable.

ANALYSIS AND RESULTS

Data Processing

Upon completion of the first series of test units, it became apparent that the field data for the complete study would fill 36 loose-leaf notebooks. Because of the volume of material involved, it was decided to process the data by the use of punch card equipment. This made it possible not only to tabulate any number of copies of the field data but also to perform preliminary summary calculations for analysis purposes by

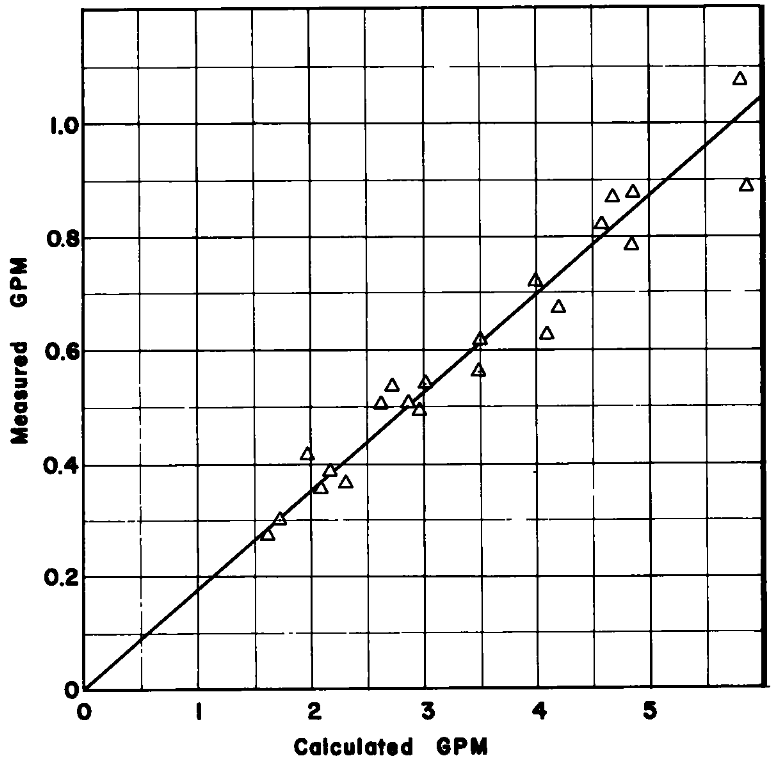


Figure 9. Comparison of measured fuel consumption to fuel consumption calculated from vehicle pretest results; uphill on grade 4 (4.00 percent) and grade 5 (5.96 percent; vehicles 1-A, 2-B, 3-C-D, 5-A and 10 at empty and full loads.

use of the electronic computer. Many additional calculations were required and use was also made of a smaller computer.

From the time and fuel measurements it was necessary to perform a few calculations to present the data in a usable and standardized form. All such calculations, programed on the computer, consisted of the following for all tests except the varying speed events:

1. Temperature correction of fuel used. All fuel was corrected to 68°F, with coefficients of expansion of 6.0×10^{-4} for gasoline, 4.4×10^{-4} for diesel fuel, and 5.3×10^{-4} for automotive diesel fuel.
2. Conversion of measured volume (cc) to gallons ($X2.642 \times 10^{-4}$).
3. Conversion to gallons per mile for each direction of test run. This was necessary because most test sections were longer in one direction than the other due to curvature or operational limitations.
4. Conversion of recorded time to traverse the test section to a uniform speed for each run.
5. Averaging of both fuel and speed by using the summation of fuel or time and the distance traveled (weighted if more observations were made in one direction than the other). This latter calculation was necessary since the level test section 1 was not on an absolutely flat grade.
6. Allowance of tabulation space for calculations of fuel consumption in gallons per minute, miles per gallon, and ton-miles per gallon, for possible future analysis.

Table A-1 (see Appendix) represents a typical tabulation of the constant-speed test field data transferred from punch cards, as well as the results of the programed calculations. A general equation is given at the bottom of the table for calculating the fuel consumption in gallons per mile.

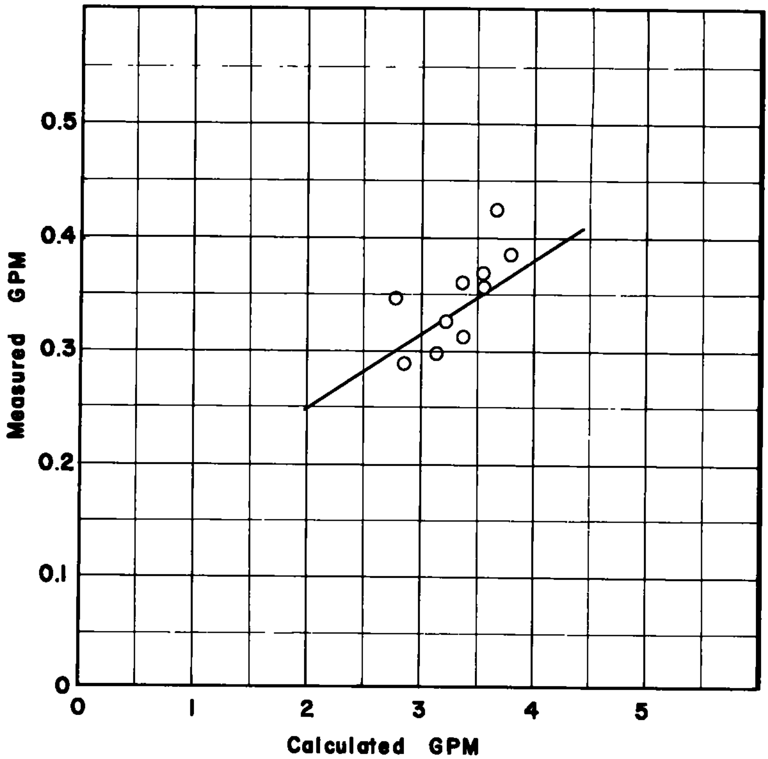


Figure 10. Comparison of measured fuel comsumption with fuel consumption calculated from vehicle pretest results (acceleration method); slowdown cycle tests on level road; vehicles 1-A and 2-B at all tested loads.

For analysis of the 15- and 10-mph slowdown and the stop test events the field data were reproduced from punch cards. Table A-2 is a sample of these input data. The output data from the computer are given in Table A-3, which gives calculated values of time to decelerate and accelerate per test cycle, as well as fuel in gallons per cycle and time in minutes per cycle. The other values in the tabulations were programed by reducing the constant-speed operation at the end of test section 1 to distance and fuel used for a complete number of cycles performed in the test section, and reducing to gallons per cycle event and distance. With the distance determined per cycle, a constant-speed fuel consumption could be determined from constant-speed tests. The fuel saved would be the difference between the fuel used per cycle and the fuel required to traverse the cycle distance at the upper limit of the speed cycle.

Table A-4 represents a sample tabulation of the fuel and time saved per cycle by use of a simplified method using a smaller computer. The latter method was resorted to due to necessary adjustments in the field data and the non-availability for re-analysis of the larger electronic computer originally utilized. The programing calculation is given at the bottom of the table.

Presentation of Data

The fuel consumption in adjusted gallons per mile has been plotted against the corresponding corrected actual test speed for all test events except the slowdown and stop tests. In the latter case the fuel use in gallons per cycle was correlated with the upper limit of the speed change cycle. Likewise, the time per cycle was matched with the upper speed. Time measurements for constant-speed operation were not further analyzed because time is a reciprocal function of speed.

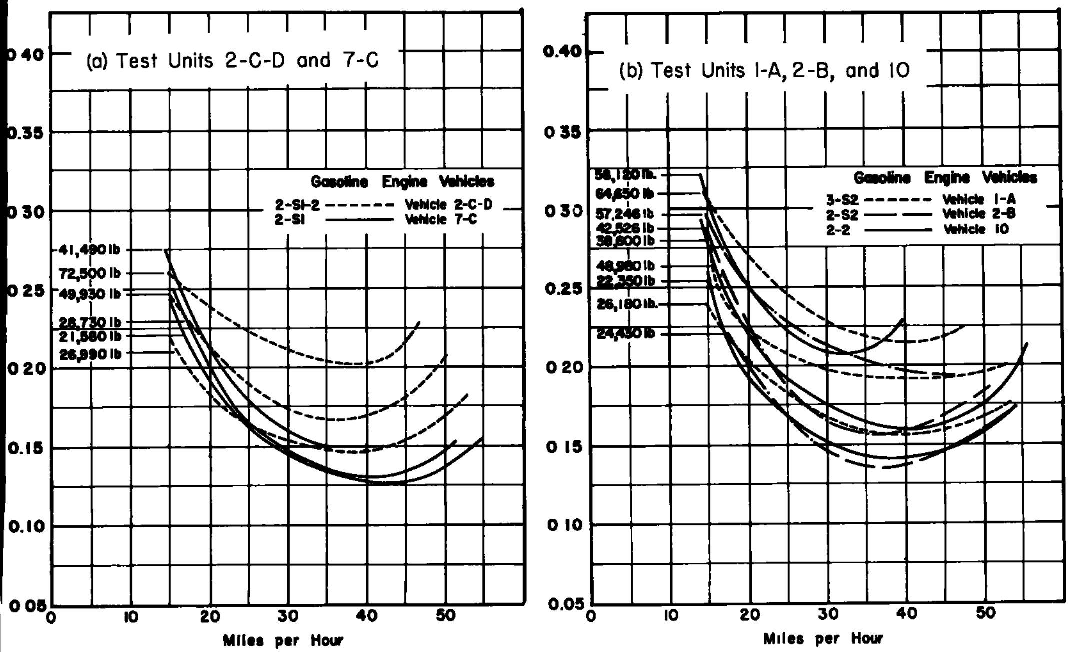


Figure 11. Fuel consumption for varying loads, gasoline-powered vehicles, level paved section 1.

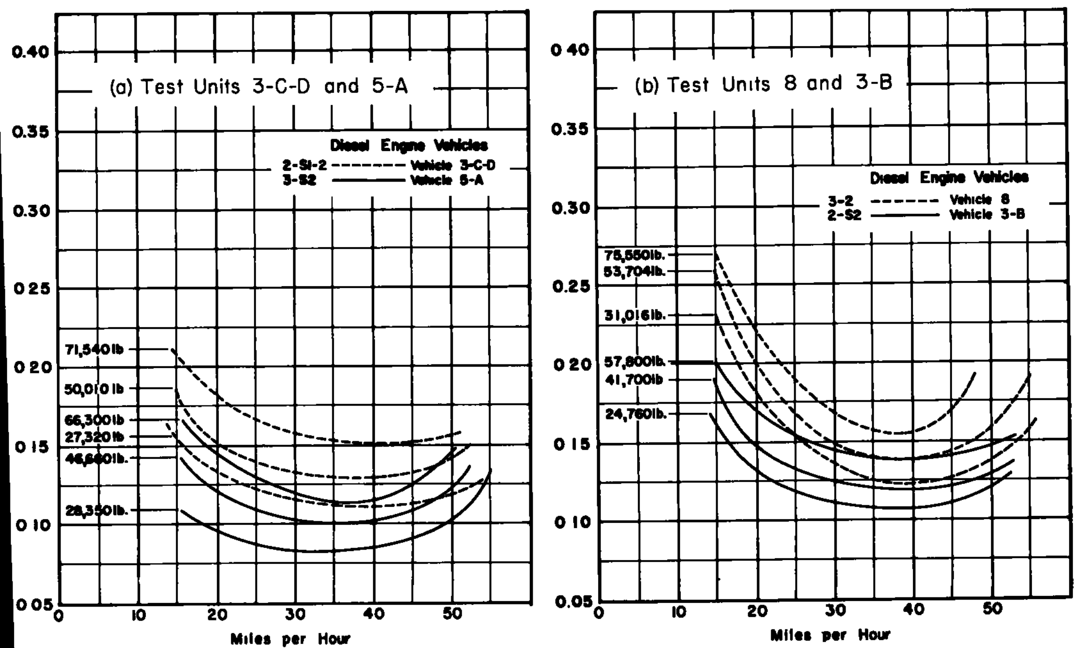


Figure 12. Fuel consumption for varying loads, diesel-powered vehicles, level paved section 1.

Constant-Speed Fuel Consumption for Varying Loads on Level Paved Section

The test event of constant-speed fuel consumption for varying loads on level paved section can be considered the standard of comparison for fuel savings by surface type, stop or slowdown elimination, or even grade elimination.

Combination on one chart of the results of all twelve vehicles tested was not practical, particularly because each vehicle except the three buses was tested under three loading conditions, requiring 30 separate curves. To best represent the results, the vehicles were combined into two groups for gasoline vehicles and two for diesel, with another for the buses. The fuel consumption for these vehicles operating at constant speed under three loading conditions is shown in Figures 11, 12 and 13, from which some of the following important characteristics and comparisons are apparent:

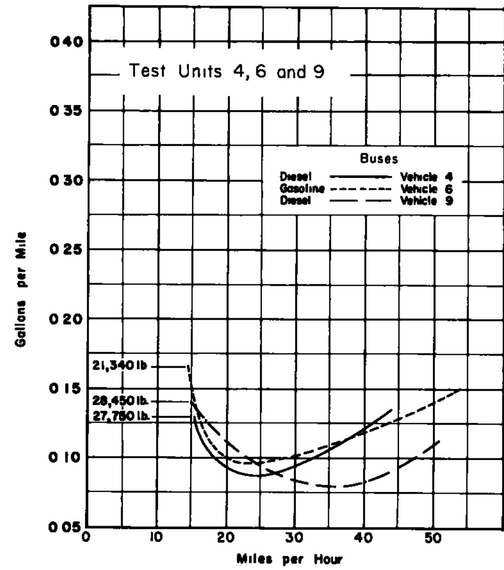


Figure 13. Fuel consumption for buses, level paved section 1.

1. The optimum operating speed for the gasoline-powered vehicles is slightly less than 40 mph with the exception of the under-powered vehicles operating with maximum legal load.
2. The diesel-powered vehicles have a corresponding optimum speed, but the operating range is considerably greater (25 to 45 mph) as indicated by the flatness of the curves.
3. Weight appears to have less effect on the fuel consumption rate of the diesel vehicles. For the gasoline trucks there is a disproportionate increase in fuel consumption with an increase in load to the maximum.
4. The fuel consumption rates for gasoline vehicles at optimum speed with a 70 percent load average 50 percent more than for comparable diesel trucks. At the low-speed range of 20 mph the difference is 60 percent greater.
5. The two urban buses, 4 and 6, have an optimum speed of about 25 mph. These vehicles were equipped with hydromatic transmissions, which shifted at approximately 27 mph. These results reflect the design of the vehicles for urban operation. The crossing of the two curves is the influence of the lower gearing of the diesel vehicle and the corresponding top speed, as well as the difference in loading of the vehicles. The rural diesel bus has the characteristic of other shift-type diesel vehicles tested.

Constant-Speed Fuel Consumption for Varying Loads on Level Gravel Section

It was not the intent of the project to measure the fuel consumption of the test units on a wide variety of surface types. The two surface types may be considered as the two extreme cases. Figures 14, 15 and 16 show the results for the same test vehicles operated on the loose gravel road.

The same general characteristics are indicated for the fuel consumption on both gravel and paved sections; however, the optimum speed is lower for most of the vehicles and the higher speeds increase the fuel consumption more than the lower speeds for the heavier load capacity vehicles.

On the gravel section the gasoline trucks use an average of 47 percent more fuel than their diesel counterparts at part load and optimum speed.

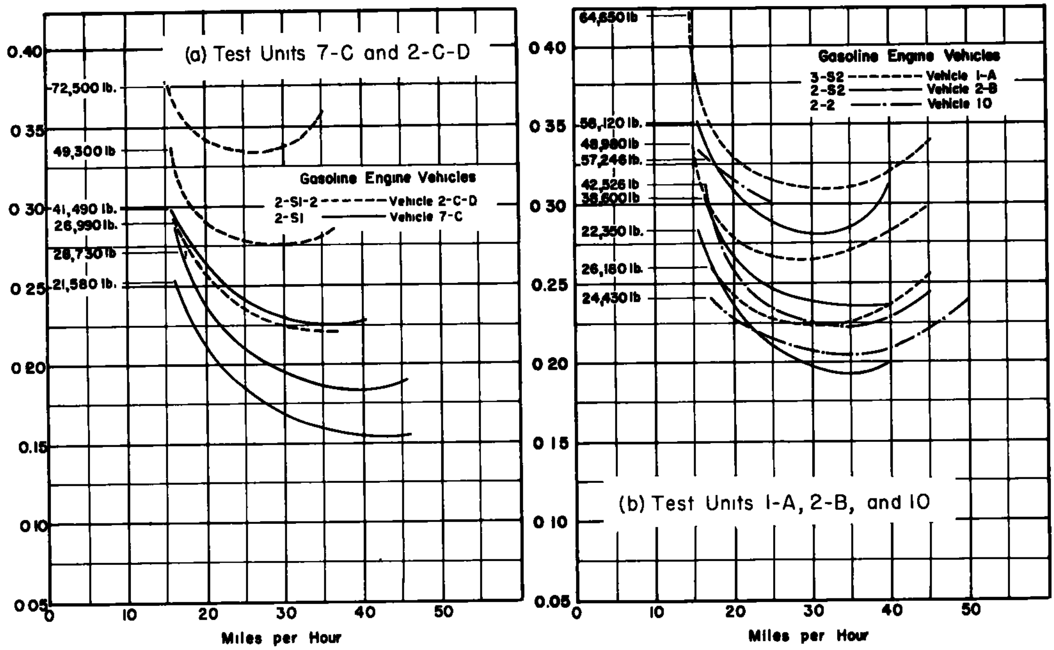


Figure 14. Fuel consumption for varying loads, gasoline-powered vehicles, level gravel section 6.

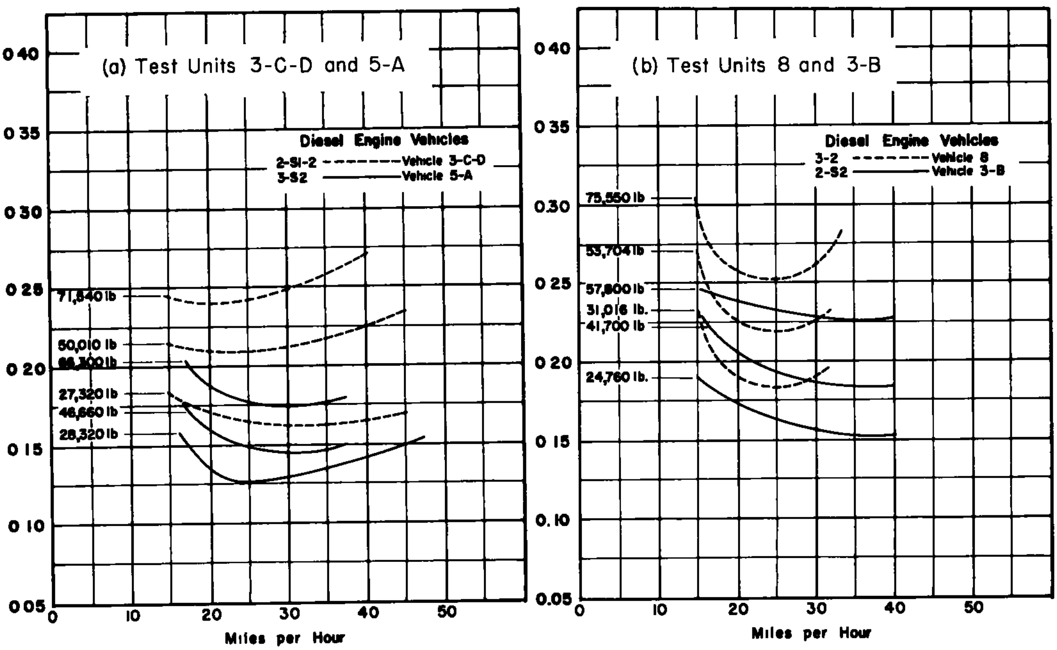


Figure 15. Fuel consumption for varying loads, diesel-powered vehicles, level gravel section 6.

Benefits by Improvement of Surfacing

The difference between the fuel consumption rate on the gravel road and the paved highway at corresponding speeds represents the fuel savings in gallons per mile. This saving is shown in Figures 17, 18, and 19 for all of the vehicles tested. There is remarkable consistency for the curves of any one vehicle, but most of the gasoline trucks have a minimum savings at 20 mph. All vehicles with the exception of the buses show increased fuel savings benefits with increasing speed and/or load.

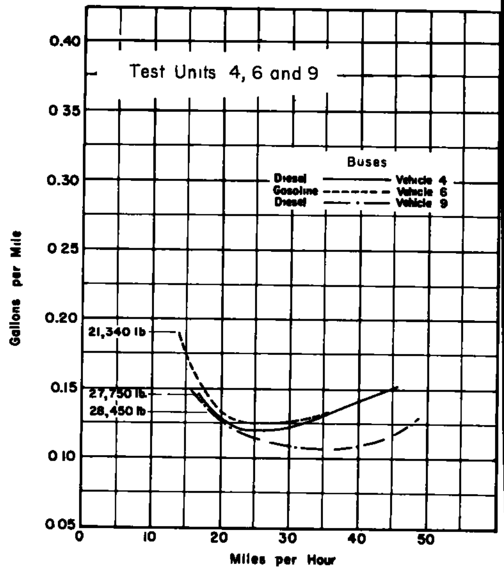


Figure 16. Fuel consumption for buses, level gravel section 6.

The curves for the buses appear to be opposite the others. The maximum savings for the urban buses is at 20 mph, and for the rural bus at 35 mph. Any increase or decrease in speed results in a decrease in savings. This represents less effect of speed and gravel on the fuel consumption rates.

A more complete analysis of the benefits to be realized by surface improvement should take into account the operating speed on each of the surface types. The values presented are for the fuel savings for a vehicle operating at the same speed on the gravel surfaced road as compared to the paved section. In many cases the maximum speed for safe conduct of the tests on the gravel section was 35 mph. Therefore, normal operating speeds of 30 mph for the gravel and 50 mph for the paved surface would be more probable. In none of the cases is it possible to obtain a negative savings because of this speed difference, but certainly

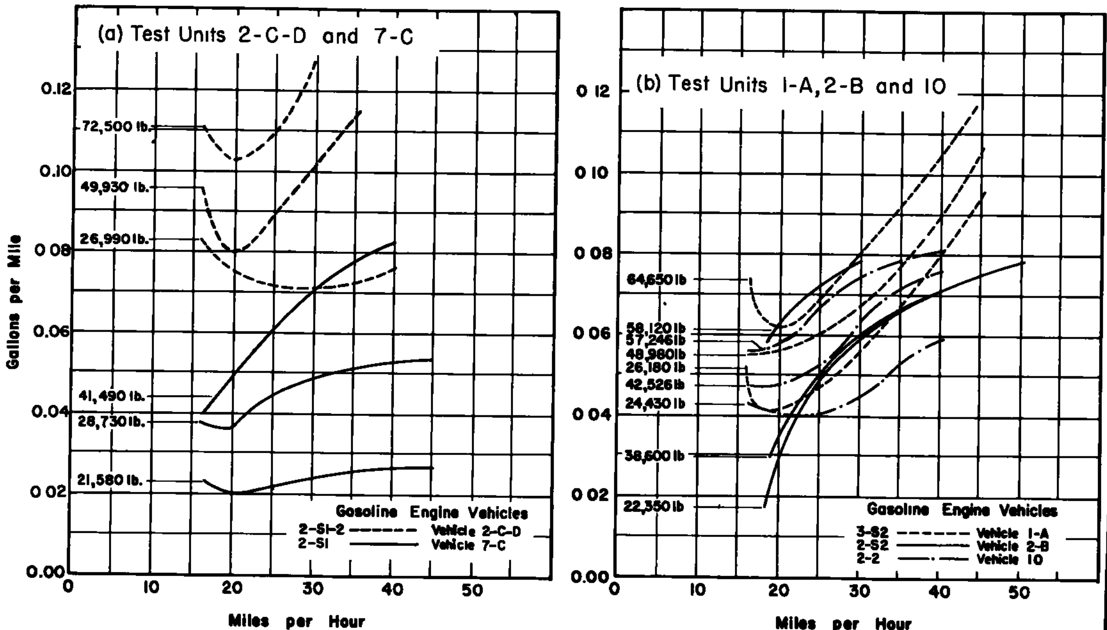


Figure 17. Fuel savings by improvement in surface type, gasoline-powered vehicles.

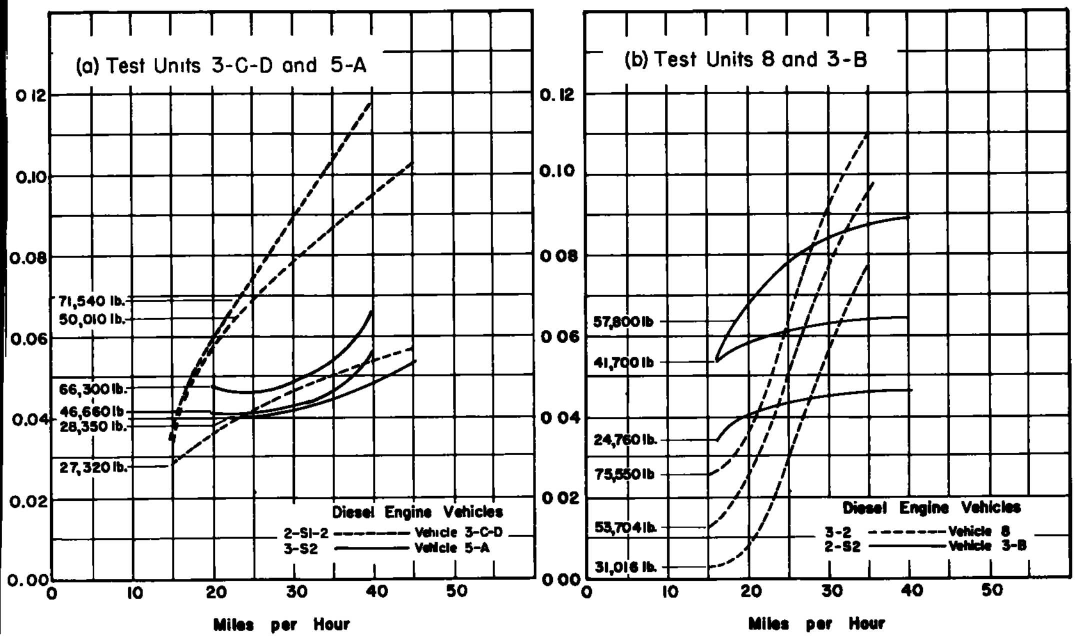


Figure 18. Fuel savings by improvement in surface type, diesel-powered vehicles.

it would reduce the fuel saved values of Figures 17, 18, and 19 for either of the speeds.

Fuel Consumption and Speed on Grades

It is repeated here for emphasis that the test runs on grades were performed at the approach speed that could be maintained on the grade test section, in conformity with the survey specifications. In actual operation the vehicle would approach at a much higher speed than the test speed, particularly for the steeper grades. A limited number of observations were made for the latter condition; they indicate a need for future detailed measurements.

The data presented in this report are indicative of the fuel consumption rates on long grades where the approach fuel consumption is a small percentage of the constant crawl-speed fuel consumption.

A family of curves was prepared for each vehicle operating with the three loading conditions for six different grades, including the level section. Typical results for two comparable gasoline- and diesel-powered vehicles (2-B and 3-B) are shown in Figures 20 and 21, respectively.

Additional curves were interpolated to present grades from 0 to 6 percent. The right end points of the curves have been connected and represent the maximum constant crawl speed for each grade, with the exception of the flatter grades which are dependent on the approach conditions.

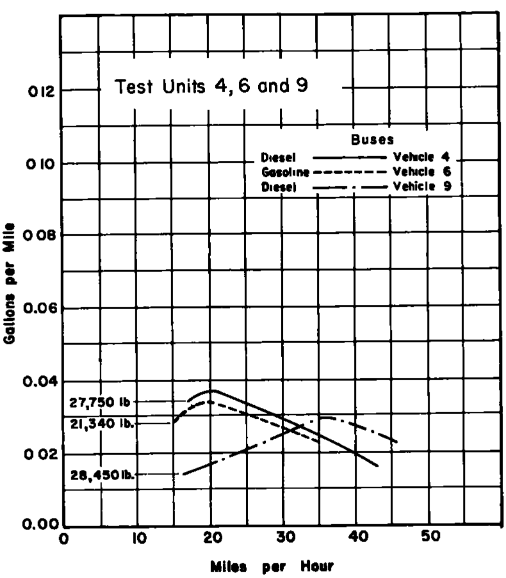


Figure 19. Fuel savings by improvement in surface type, buses.

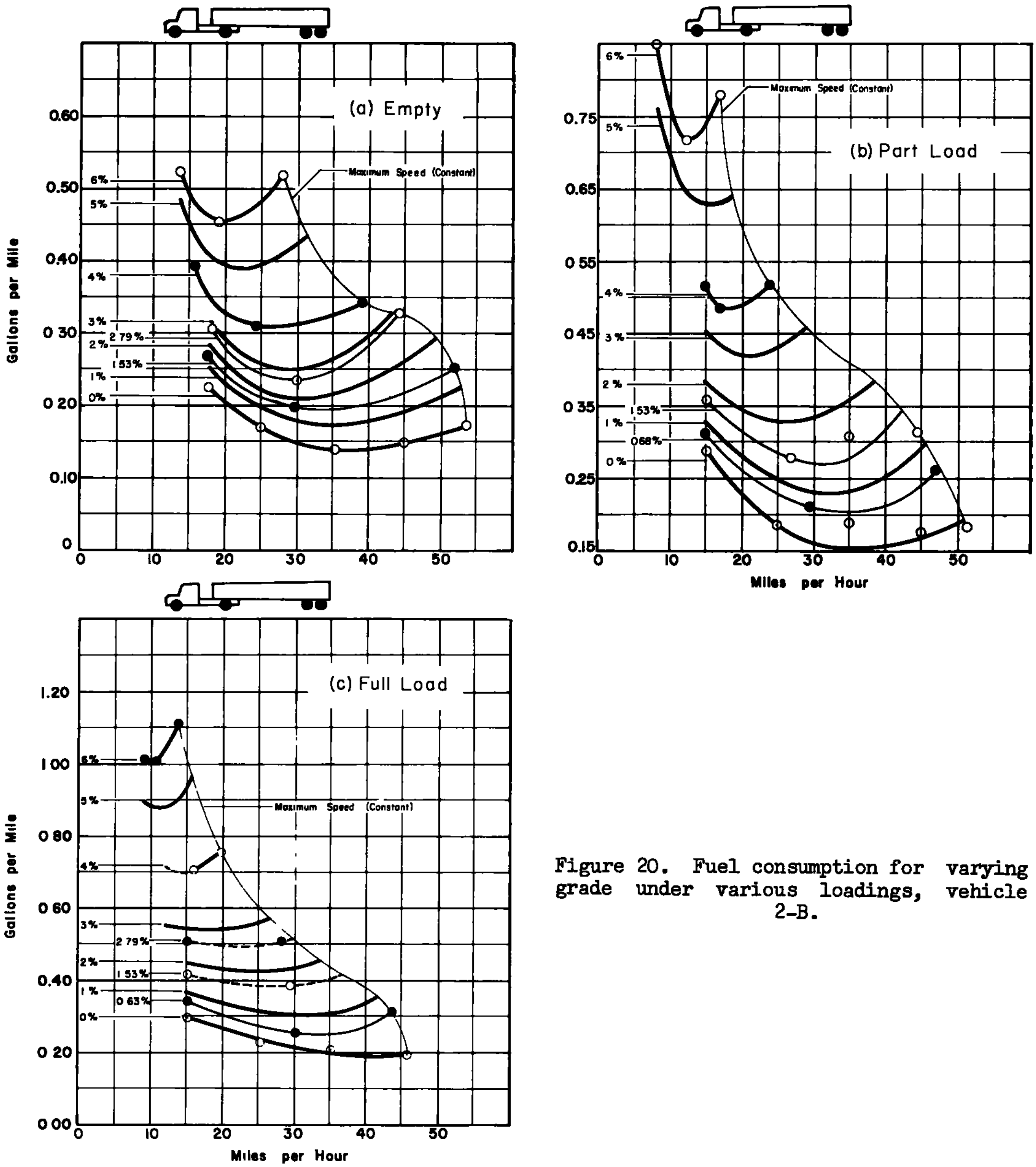


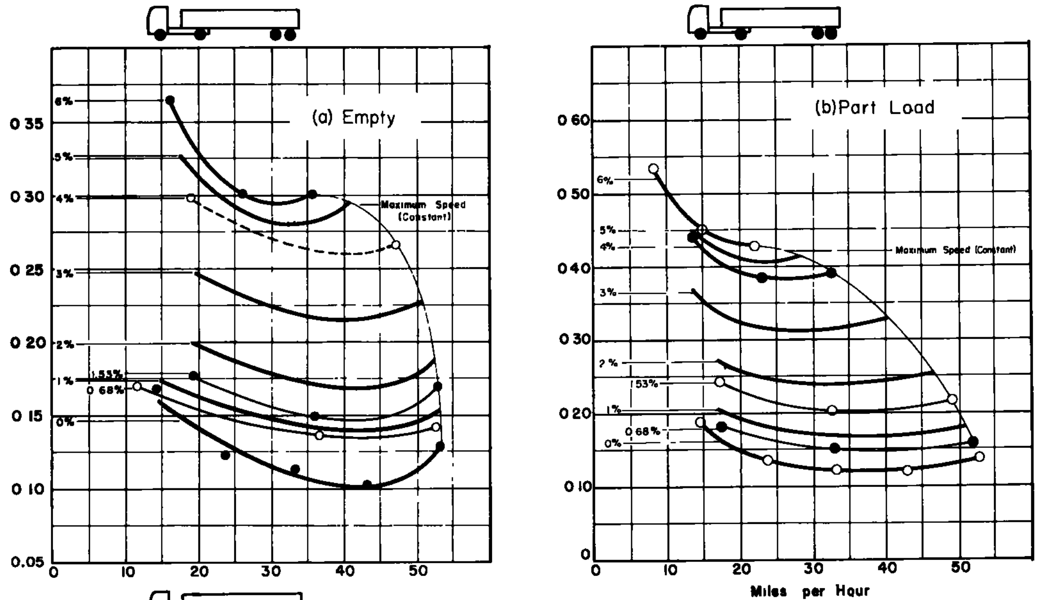
Figure 20. Fuel consumption for varying grade under various loadings, vehicle 2-B.

Some characteristic observations are as follows:

1. Logically, maximum speed is reduced and fuel consumption increased with increasing load conditions. On the 6 percent grade the full-load fuel consumption rate is approximately double the empty-load rate, whereas the speed is about one-half. This is true for either gasoline- or diesel-powered vehicles.

2. For the gasoline vehicle the greatest rate of speed reduction occurs on 3, 2 and 1.5 percent grades for empty, part and full loads, respectively. For the diesel vehicle the corresponding grades are approximately 5, 4 and 2 percent.

3. A review of all the gasoline-powered vehicles indicates a disproportionate increase in fuel consumption above the 3 percent grade, whereas the diesel vehicles display a more uniform rate of increased fuel flow with increased grade.



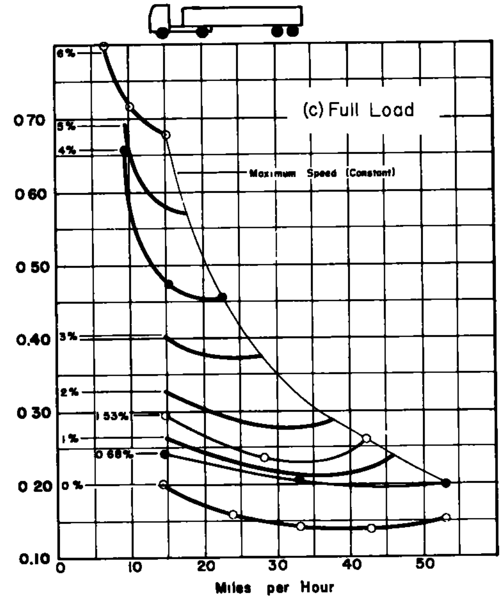


Figure 21. Fuel consumption for varying grade under various loadings, vehicle 3-B.

The maximum crawl speed as a function of grade and weight-to-horsepower ratio is presented in Figure 22 for gasoline units 2-B and 2-C-D and diesel units 3-B and 3-C-D. Data combining other test units are not presented here for a wider range of weight-to-horsepower ratios inasmuch as engine efficiency and other adjustments are necessary for standardization. These curves are not extended for grades less than 1.5 percent because the maximum speed is dependent on the length and grade approach conditions. Detailed analysis is not presented here except to mention the consistency of the shape of the curves and the fact that the curves for the diesel-powered vehicle are generally to the right of those for the gasoline-powered vehicle, representing higher crawl speeds for the diesel unit. Additional refinement of these data is necessary and will be incorporated in future research.

Downhill fuel consumption cannot be analyzed in detail, particularly for the diesel test units, due in part to the low fuel consumption rate and the relatively short test

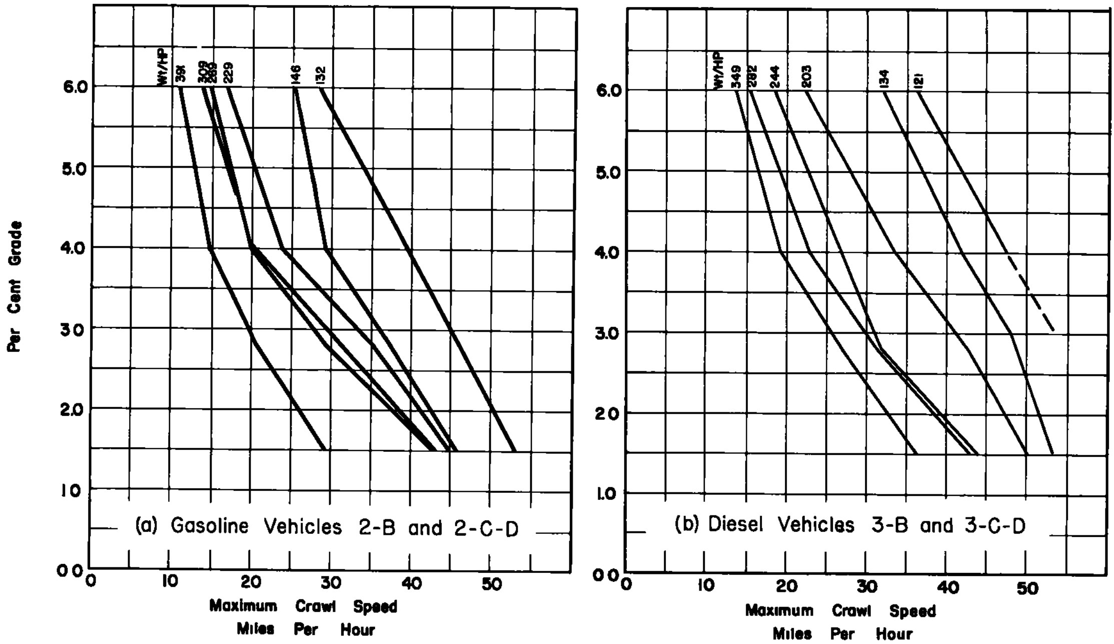


Figure 22. Maximum crawl speed vs grade for weight-to-horsepower ratio.

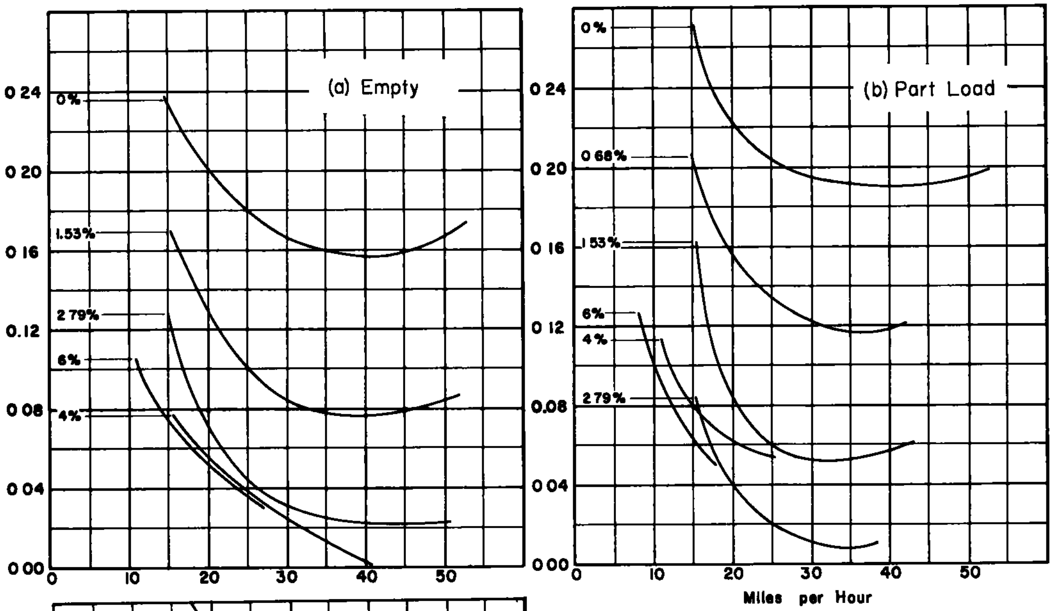
sections. Figure 23 shows the downhill fuel consumption for gasoline-powered vehicle 1-A for empty, part and full load conditions. Other gasoline test units show the same general trend of decreasing fuel consumption with increasing downgrade. The only exception is for the 6 percent grade under increasing load. In the case of part and full load the fuel consumption was greater on the 6 percent grade than on the 4 percent grade. This is rationalized by the drivers in the fact that braking was necessary in addition to engine compression on the 6 percent grade and occasionally on the 4 percent grade.

Figure 24 shows the average fuel consumption rate for the combined uphill and downhill rise and fall operation of this gasoline test unit. Additional study is necessary due to the inherent inaccuracy of the downhill fuel consumption; however, there is an indication of similar fuel consumption rates for grades up to 3 percent. This grade, of course, reduces with increased load. Future research will identify the optimum grade for uphill and downhill operation, with consideration given to the varying speed of operation on the grades instead of the constant speeds as studied here.

Similar curves for diesel vehicles cannot be prepared because the operation of diesel engines is different not only from gasoline engines, but also within the diesel engine types. Most of the new diesel engine models have a fuel shut-off system for downhill operation, in which case the rate of fuel flow approaches idle fuel rate, except when braking is required. Other diesel models operate similar to gasoline engines, except that the fuel rate is lower with a reduced rpm during downhill operation of this type. Longer test sections are necessary to produce valid downhill results.

Benefits by Reduction in Grade

The savings in fuel by reduction of grade can be determined from the curves simply by obtaining the fuel rates for each grade at its corresponding grade speed and multiplying by comparable lengths of grade. The difference would represent the fuel savings, whereas the time savings would be the difference in time required to traverse each grade length at the operating grade speed.



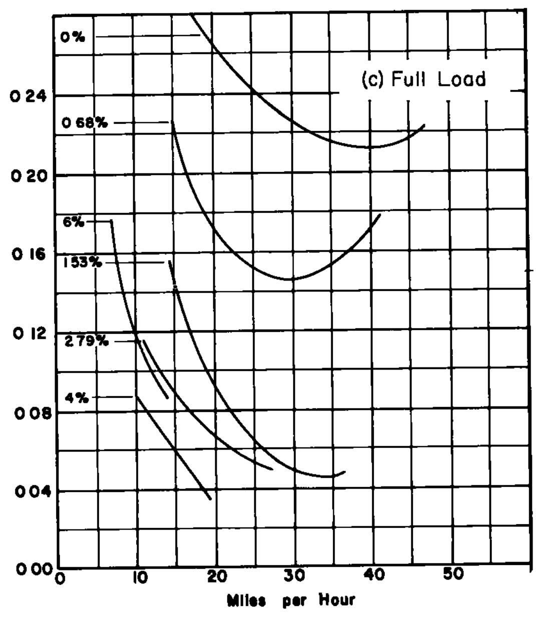


Figure 23. Fuel consumption for varying downhill grade, vehicle 1-A.

Fuel and Time Consumption Resulting from Stops or Slowdowns

The data obtained from the series of tests on fuel and time consumption resulting from stops and slowdowns represent the results of the only event reflecting driver characteristics. Time did not permit development of a device to control the rate of deceleration and many of the data had to be scrutinized for comparable rates between the drivers. The acceleration rate was more uniform and constituted the greatest percentage of the time and fuel consumed for the total cycle, the fuel being less affected than the time by this driver difference in deceleration rates. As mentioned previously, fuel and time savings are basically the difference between fuel and time consumed in performing a stop or slowdown cycle and the fuel and time required to traverse the same distance at a constant speed. Figures 25 and 26 show, respectively, the savings in fuel and time for gasoline-powered vehicle 2-B. Results for diesel vehicle 3-B are shown in Figures 27 and 28. The following are general characteristics for these test events:

1. Fuel savings for the gasoline vehicle increase with greater speed of the event cycle, increased speed change increment, or heavier load.
2. A similar trend is indicated for the diesel unit, only there is a leveling off, or even reduction, in savings at the higher speeds.
3. For any given event or speed the fuel savings for the gasoline vehicle are more than 100 percent greater than for the diesel unit.
4. Comparison of the two vehicles for the time saved by elimination of a stop reveals the same savings for empty load condition, but greater savings realized by the gasoline unit as the maximum load and speed are reached. This reflects the greater ability of the diesel unit to adjust to differential speed conditions, particularly at higher speeds and load conditions.
5. The 15-mph slowdown event shows the time savings to be a minimum at top cycle speeds of 30 to 40 mph. Lower or higher speeds give greater time savings for both vehicles. The gasoline vehicle realizes a greater benefit in all cases and predominantly so at the low and high speeds, where the difference approximates 50 percent.
6. The shorter 10 mph slowdown curves show that the diesel units realize the greater time savings up to speeds of 35 to 45 mph for full and empty load conditions, respectively. Above these speeds the gasoline vehicle again exceeds in time benefit.

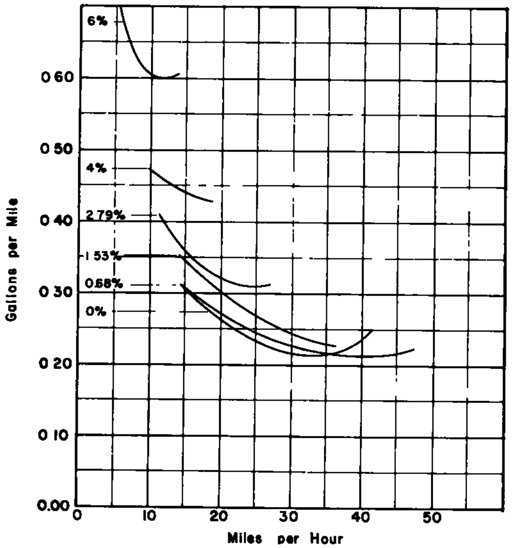


Figure 24. Fuel consumption for varying uphill and downhill grade, vehicle 1-A under full load.

Use of the data presented is illustrated by means of examples in the next section.

EXAMPLES OF FUEL AND TIME SAVING BENEFITS

1. Surface Improvement

A 50-mi level section of gravel roadway with an ADT of 2,500 vehicles per day is to be improved with a high-type surfacing. The average-type vehicle is represented by vehicles 2-B and 3-B with part load condition. Each is determined to be 5 percent of the total.

Find the annual benefits to the trucks:
Number of each truck per year = 2,500 x 0.05 x 365 = 45,625
Safe operating speed on gravel road = 30 mph
Operating speed on paved highway = 40 mph
Gasoline fuel rate on gravel (Fig. 14b) = 0.240 gpm
Gasoline fuel rate on pavement (Fig. 11b) = 0.159 gpm
Gasoline fuel savings per vehicle per mile = 0.081 gpm
Diesel fuel rate on gravel (Fig. 15b) = 0.187 gpm
Diesel fuel rate on pavement (Fig. 12b) = 0.120 gpm
Diesel fuel savings per vehicle per mile = 0.067 gpm
Gasoline price assumed at $0.35 per gallon
Diesel fuel price assumed at $0.20 per gallon
Annual savings to gasoline trucks =
45,625 veh x 50 mi. x 0.081 gpm saved x $0.35/gal = $64,673

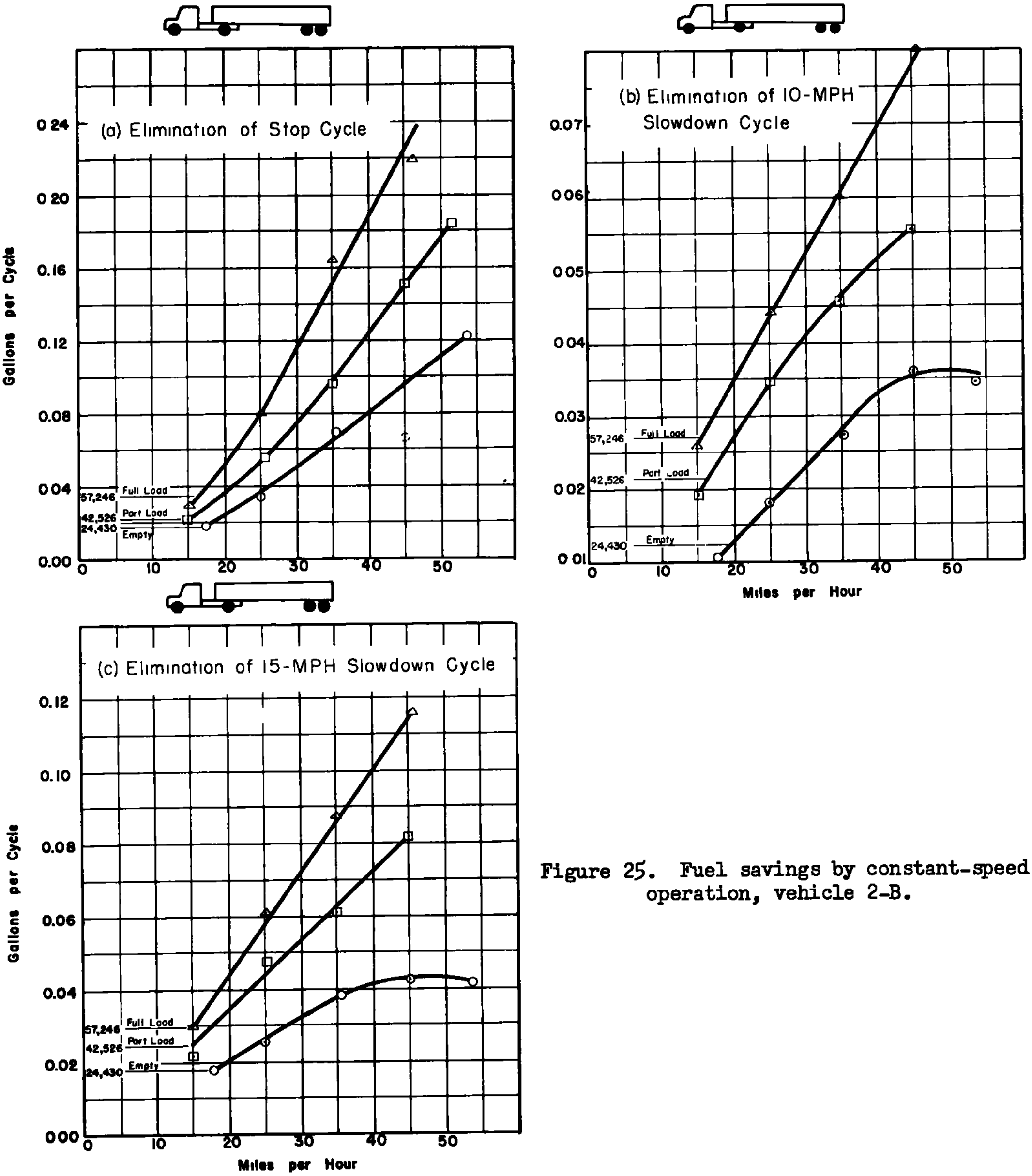


Figure 25. Fuel savings by constant-speed operation, vehicle 2-B.

Annual savings to diesel trucks =

45,625 x 50 x 0.067 gpm saved x $0.20/gal = $30,569

Annual fuel saving benefits of trucks = $95,242

$$\text{Time savings per vehicle} = \left(\frac{50\text{ mi}}{30\text{ mph}} - \frac{50}{40}\right) \times 60 = 25\text{ min}$$

Assuming the driver's time is valued at wages of approximately $0.045 per min, and avoiding a value of the vehicle's time, which is a study in itself,

Annual time saving benefit = 25 x 45,625 x $0.045 x 2 = $102,656

Total annual benefits to these trucks = $197,898

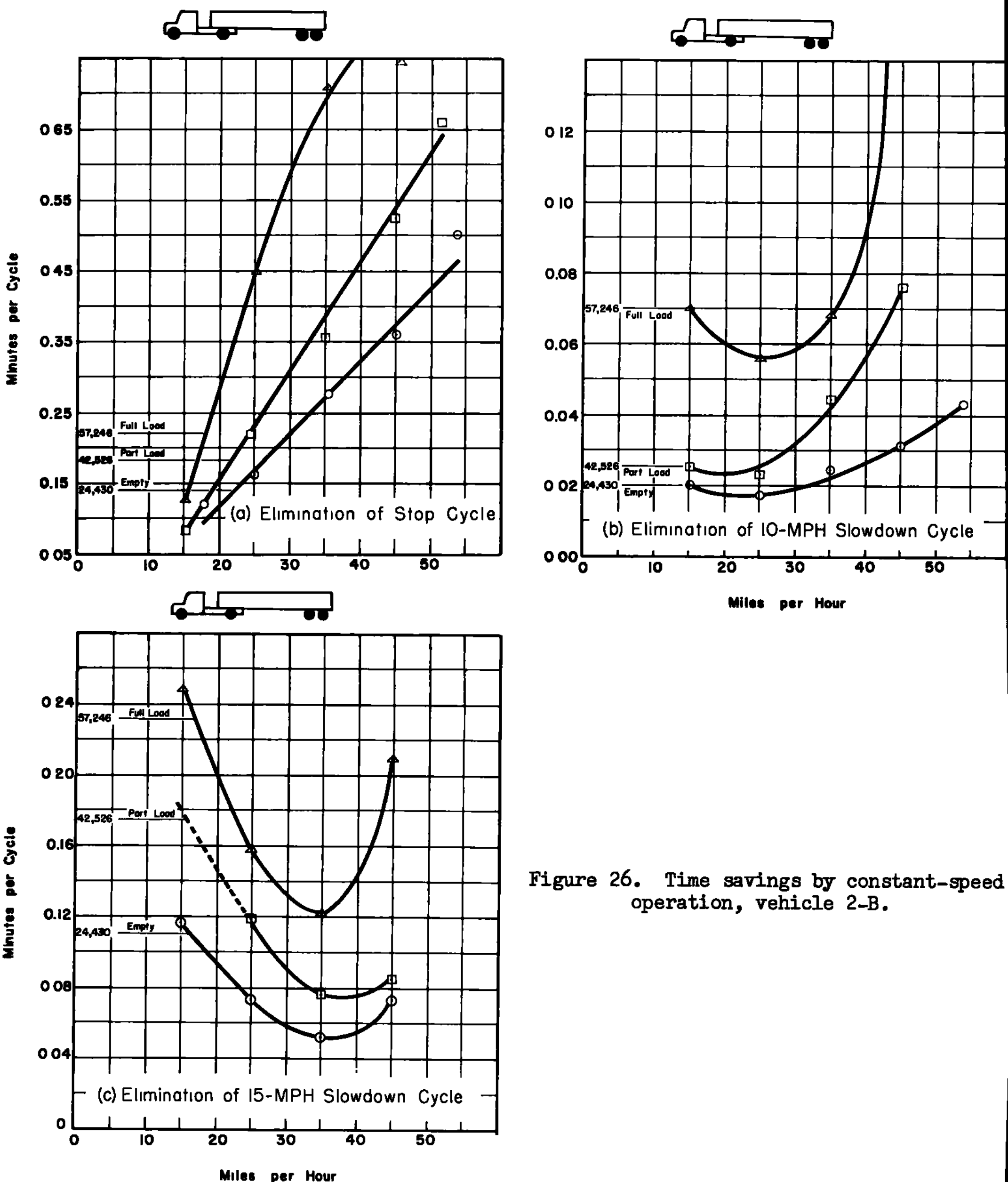
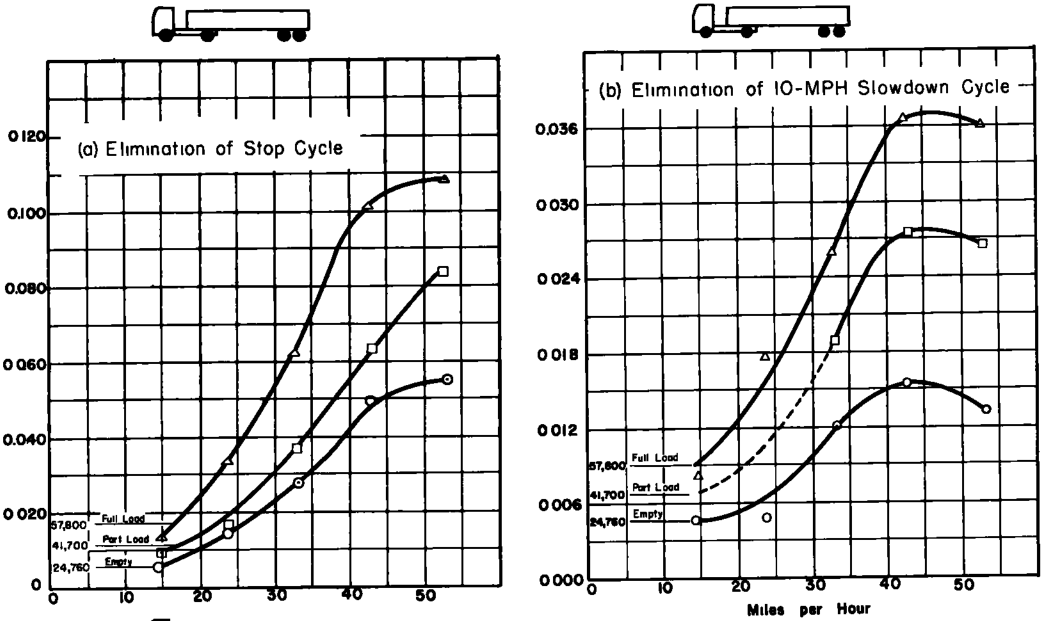


Figure 26. Time savings by constant-speed operation, vehicle 2-B.

2. Elimination of Congestion

A 10-mi congested arterial street serving an industrial area is to be improved by traffic engineering measures of parking restrictions, turn restrictions and a traffic signal system to facilitate movement of the heavier trucks at an average progression speed of 35 mph. The present operation causes twelve 10-mph slowdowns from 30 mph. The average truck is 70 percent loaded and there are 10 percent of the 2-B type and 10 percent of the 3-B type. The ADT is 2,000 vehicles.

Find the annual benefits in fuel and time savings to be realized by these trucks if the traffic control measures eliminate 10 of the slowdowns.



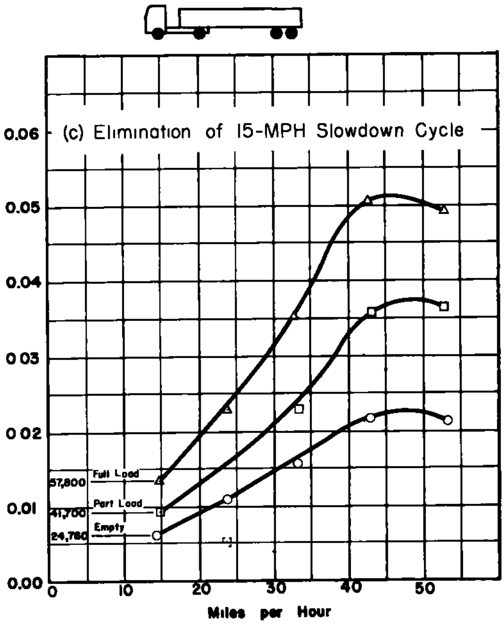


Figure 27. Fuel savings by constant-speed operation, vehicle 3-B.

Gasoline fuel saved per vehicle per cycle (Fig. 25b)	=	0.0415 gal
Gasoline time saved per vehicle per cycle (Fig. 26b)	=	0.032 min
Diesel fuel saved per vehicle per cycle (Fig. 27b)	=	0.016 gal
Diesel time saved per vehicle per cycle (Fig. 28b)	=	0.049 min

Annual gasoline benefits =
2,000 x 0.10 x 365 x 0.0415 x 10 x \$0.35 = \$10,603

Annual diesel benefits =
2,000 x 0.10 x 365 x 0.016 x 10 x \$0.20 = 2,336

Total fuel saving benefits to these trucks = \$12,939

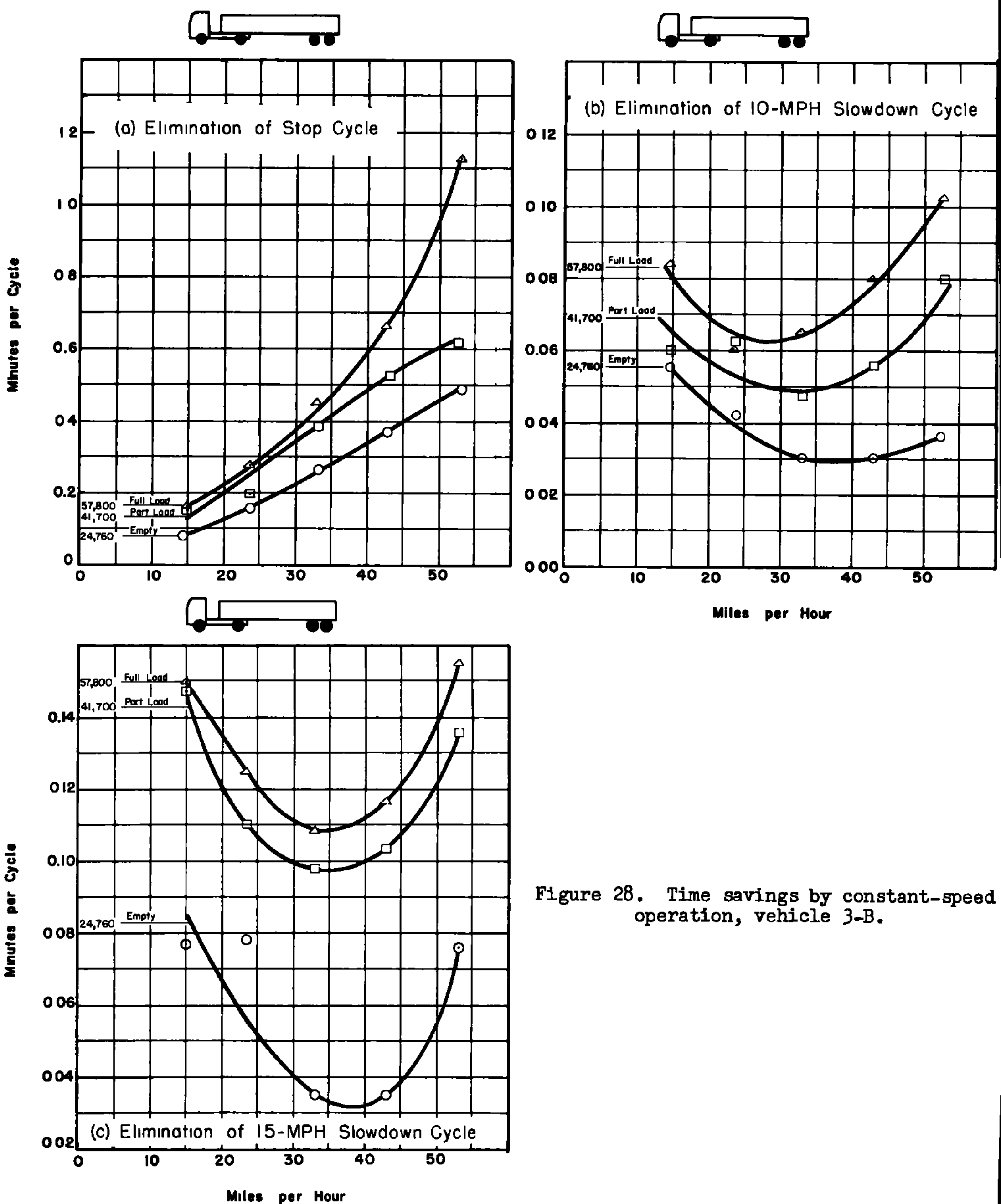


Figure 28. Time savings by constant-speed operation, vehicle 3-B.

Annual time savings, gasoline =		
2,000 x 0.10 x 365 x 0.032 x 10 x $0.045	=	$1,051
Annual time savings, diesel =		
2,000 x 0.10 x 365 x 0.049 x 10 x $0.045	=	$1,610
Total time saving benefit to these trucks	=	$2,661
Total annual benefits to these trucks	=	$15,600

3. Elimination of Stops

Two intersecting major highways are controlled by a traffic signal. Traffic volume counts give an ADT of 8,000 on each road. The following classification count is the same for each arterial:

Vehicle			Traffic Volume	
Class	Type	No.	(%)	(veh/yr)
2-S2	Diesel	3-B	2	58,400
	Gasoline	2-B	2	58,400
3-S2	Diesel	5-A	1.5	43,800
	Gasoline	1-A	1.5	43,800
2-S1-2	Diesel	3-C-D	1	29,200
	Gasoline	2-C-D	1	29,200
Bus	Diesel	4	3	87,600
	Gasoline	6	3	87,600

An intersection delay study shows that 40 percent of the vehicles are required to stop for the signal and are delayed an average of 0.3 min. Speed studies indicate an operating speed of 40 mph on each highway. Loadometer studies show that the vehicles average 70 percent of maximum legal load.

Find the benefits to be derived by these vehicles if the signal is replaced by a grade separation that will not materially change the length of the travel paths and the grades are designed to provide for momentum operation, resulting in no effect on fuel consumption.

The benefits are calculated as follows:

Vehicle		Savings		Idle Fuel Flow	Benefits ($/yr)		
Desig.	(no./yr)	Fuel (gal/veh)	Time (min/veh)	(gpm)	Fuel[1]	Time[2]	Idle[3]
3-B	58,400	0.055	0.48	0.0074	257	505	10
2-B	58,400	0.125	0.47	0.0131	1,020	495	32
5-A	43,800	0.075	0.68	0.0049	262	535	5
1-A	43,800	0.128	0.69	0.0148	782	543	27
3-C-D	29,200	0.078	0.47	0.0074	182	246	5
2-C-D	29,200	0.155	0.69	0.0131	634	362	16
4	87,600	0.041	0.32	0.0075	287	504	16
6	87,600	0.051	0.42	0.0121	625	660	45
Total	-	-	-	-	4,048	3,850	156
Grand Total						$8,054	

[1]Veh/yr x % stopping x fuel savings x fuel cost.
[2]Veh/yr x % stopping x time savings x time cost.
[3]Veh/yr x % stopping x idle time x idle fuel flow x fuel cost.

4. Grade Reduction

The 6 percent grade used in this study is 0.8 mi long and it is planned to replace this steep grade with a 3 percent grade 1.6 mi long.

Compare the cost of operation for each grade using vehicles 2-B and 3-B, part load.

Grade (%)	Veh.	Fuel Used (gal/mi)	Max. Speed (mph)	Tot. Fuel Used (gal)	Time Used (min)
3	2-B	0.46	28	0.736	3.43
	3-B	0.33	40	0.528	2.40
6	2-B	0.78	17	0.624	2.82
	3-B	0.43	22	0.344	2.18

It is evident from this analysis that the steeper grade requires less fuel and time than the longer 3 percent grade. If the downhill characteristics were considered, the savings would be even greater. These results, however, should not be construed as justification for maintaining the steeper 6 percent grade, as other undesirable operati characteristics may prevail. The reduced operating speed on the steep grade may prove to be too great a speed differential from that of lighter and more powerful vehic resulting in a serious accident hazard.

Summary

The examples presented here have purposely been simplified for illustrating a particular type of benefit and it should be realized that most refined benefit-cost analyses will require a combination of the examples presented, requiring numerous calculation It is believed that time and fuel benefits can be reduced to a form for systematic computer analysis.

The examples presented illustrate a definite conclusion that the monetary benefits derived from savings in fuel constitute a major element of the benefits realized by truck transport vehicles. The monetary comparison of power unit types is subject to the cost per gallon of the fuel prevailing in the area of study.

The value of time for various types of vehicles and trip purposes has not been standardized, but to those familiar with benefit analyses it has been apparent that most assignments of value of time for passenger cars has resulted in vehicle operating bene fits insignificant in comparison with time benefits. Such is not the case for the truck transports and any such benefit analyses should properly consider these vehicles even though they may represent only a small percentage of the total traffic volume.

ACKNOWLEDGMENTS

The instrumentation and preliminary testing of the vehicles used in the tests reported here were developed by the junior author.

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3. Anon., "The Trend in Engineering at the University of Washington." 11:1, 19 (Ja 1959).
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Appendix

TABLE A-1

COMPUTER TABULATION OF FIELD DATA AND PRELIMINARY CALCULATION ON FUEL CONSUMPTION RATES AND TRAVEL TIME FOR ALL EVENTS EXCEPT STOP AND SLOW CYCLE

[illegible]	Unit no.	Load	Section no.	Intended Speed	Driver	Run no.	Direction	Date	Time of day	Road cond.	Gear	Tach.	(Tons) Fuel temp.	Init. fuel (Ton mi per gal)	Final fuel	Fuel used	Adj fuel used	Elapsed time	Distance	True speed	Mile/gal	Gal/minute	Gal/mile
	1A	E	1	35	8	1	S	6/25/59	1635	D	5U	2300	90	2395	1090	1305	1288	3.71	2.022	32.70	5.942	0.0917	0.1683
	1A	E	1	35	8	1	N	6/25/59	1715	D	5U	2300	90	2395	1185	1210	1194	3.70	2.030	32.92	6.436	0.0853	0.1554
	1A	E	1	35	8	2	S	6/25/59	1730	D	5U	2300	94	2395	1080	1315	1295	3.72	2.022	32.61	5.910	0.0920	0.1692
	1A	E	1	35	8	2	N	6/25/59	1805	D	5U	2300	90	2395	1180	1215	1199	3.75	2.030	32.48	6.409	0.0845	0.1560
	1A	E	1	35	8	3	S	6/25/59	1825	D	5U	2300	90	2395	1080	1315	1298	3.75	2.022	32.35	5.897	0.0914	0.1696
	1A	E	1	35	8	3	N	6/25/59	1905	D	5U	2300	86	2395	1180	1215	1202	3.75	2.030	32.48	6.393	0.0847	0.1564
[illegible]	1A	E	1	35			N			D	5U		13.240	84.885		3640	3595	11.20	6.089	32.62	6.411	0.0848	0.1560
[illegible]	1A	E	1	35			S			D	5U		13.240	78.320		3935	3881	11.18	6.065	32.55	5.915	0.0917	0.1690
[illegible]	1A	E	1	35			B			D	5U		13.240	81.477		7575	7476	22.38	12.154	32.58	6.154	0.0882	0.1625

Adj. Fuel, cc = (Fuel used, cc) - (68°F - Fuel temp, °F)(Coeff. of expansion, /°F)(Fuel used, cc)

$$\text{gal / mi} = \frac{\text{(Adj fuel, cc)(Conversion factor, gal/cc)}}{\text{(Distance traveled, mi)}}$$

TABLE A-2

COMPUTER TABULATION OF FIELD DATA FOR STOP AND SLOW EVENT.(INPUT)

Unit	Load	High Speed	Low Speed	Driver	Run No.	Direction	Date	Time of Day	Road Condition	Fuel Temp.	Init. Fuel	Final Fuel	Start Decel.	End Decel.	Start Acel.	End Acel.	Start Decel.	End Decel.	Start Acel.	End Acel.	End Run
1A	E	35	00	7	4	S	6/30/59	4075	D	079	4023	1825	.00	.11	.16	.85	.85	.96	1.02	1.68	
													1.68	1.83	1.87	2.48	2.61	2.67	2.67	3.26	
													3.26	3.42	3.48	4.04	4.04	4.17	4.23	4.83	
													4.83	4.96	5.01	5.60	5.60	5.74	5.79	6.44	6.63

TABLE A-3

COMPUTER CALCULATION AND TABULATION OF FUEL, TIME AND DISTANCE FOR STOP AND SLOW EVENTS

Vehicle	Load	High Speed	Low Speed	Driver	Run No.	Direction	Date	Road Condit.	No. Cycles	Decel. Time Per Cycle	Acceleration Time per cycle	Total time Per cycle	Distance per cycle (feet)	Gal. per cycle	Total Decel. Time per Run	Total Acel. Time per Run	Total time Per run	Distance Per run	Fuel Used	Adj. Fuel Used	Miles per gal.	Gal. per Minute	Gal. per Mile
1A	E	35	00	7	04	S	6/30/59	D	8	0.12	0.62	0.81	1266	0.0963	.99	4.95	6.44	1.918	2998	2915	2.491	0.1196	0.4014
1A	E	35	00	7	14	N	6/30/59	D	8	0.14	0.61	0.80	1268	0.0903	1.14	4.84	6.40	1.921	2823	2736	2.658	0.1129	0.3762
1A	E	35	00	7	05	S	6/30/59	D	8	0.13	0.63	0.82	1263	0.0941	1.05	5.04	6.52	1.913	2953	2851	2.540	0.1155	0.3937
1A	E	35	00	7	15	N	6/30/59	D	8	0.15	0.62	0.82	1282	0.0902	1.19	4.97	6.55	1.943	2803	2731	2.693	0.1102	0.3714
1A	E	35	00	7	06	S	6/30/59	D	8	0.13	0.64	0.82	1284	0.0932	1.05	5.11	6.58	1.946	2892	2823	2.609	0.1133	0.3833
1A	E	35	00	7	16	N	6/30/59	D	8	0.14	0.62	0.81	1272	0.0906	1.11	4.96	6.50	1.927	2828	2743	2.659	0.1115	0.3761
1A	E	35	00			A	34.52	D	48	0.14	0.62	0.81	1272	0.0925	6.53	29.87	38.99	11.568		16799	2.607	0.1138	0.3837

Adj. Fuel, cc = (Fuel used, cc) - (68°F - Fuel temp, °F) (Coeff. of expansion, /°F)(Fuel used, cc)

$$\text{gal / cycle} = \frac{\text{(Adj. Fuel, cc)(Conversion factor, gal/cc)} - (t_1 - t_2)\text{(Const. Speed consumption, Gal/min)}}{\text{No. of cycles}}$$

Where: t_1 = Time reading at end of test section, min

t_2 = Time reading at end of acceleration of last cycle, min

TABLE A-4

CALCULATION AND TABULATION OF FUEL AND TIME SAVED PER CYCLE FOR STOP AND SLOW EVENTS

High Speed	Low Speed	Driver	Time/run	Fuel Temp.	Fuel Used	Adj. Fuel Used	No. of S & G Runs	No. of Cycles	No. of Const. Speed Runs	Time Const. Speed Runs	Fuel Used Const. Speed	Fuel Saved per Cycle	Time Saved per Cycle
35	0	7	6.63	79	2998.	2978.							
			6.60	80	2823.	2802.							
			6.70	88	2953.	2917.							
			6.71	79	2803.	2784.							
			6.72	81	2892.	2869.							
			6.69	81	2828.	2805.							
			40.07			17158	6.	48.	6.	22.38	7476	.0532	.36

$$\text{Adj. fuel, cc} = \text{(Fuel used, cc)} - (68^\circ - \text{Fuel temp. }^\circ\text{F})(\text{Coeff. of expansion }/^\circ\text{F})(\text{Fuel used, cc})$$

$$a = \frac{(\text{No. of Runs S \& G})(\text{Adj. Fuel Const. Speed, cc})}{(\text{No. of Runs Const. Speed})}$$

$$b = \frac{(\text{No. of Runs S \& G})(\text{Const. Speed Time, min.})}{(\text{No. of Runs Const. Speed})}$$

$$\text{Fuel Saved/Cycle} = \frac{(\text{Total S \& G Adj. Fuel}) - a \quad (\text{Conversion factor, gal/mi.})}{(\text{Total No. of Cycles})}$$

$$\text{Time Saved/Cycle} = \frac{(\text{Total time S \& G, min.}) - b}{(\text{Total No. of Cycles})}$$

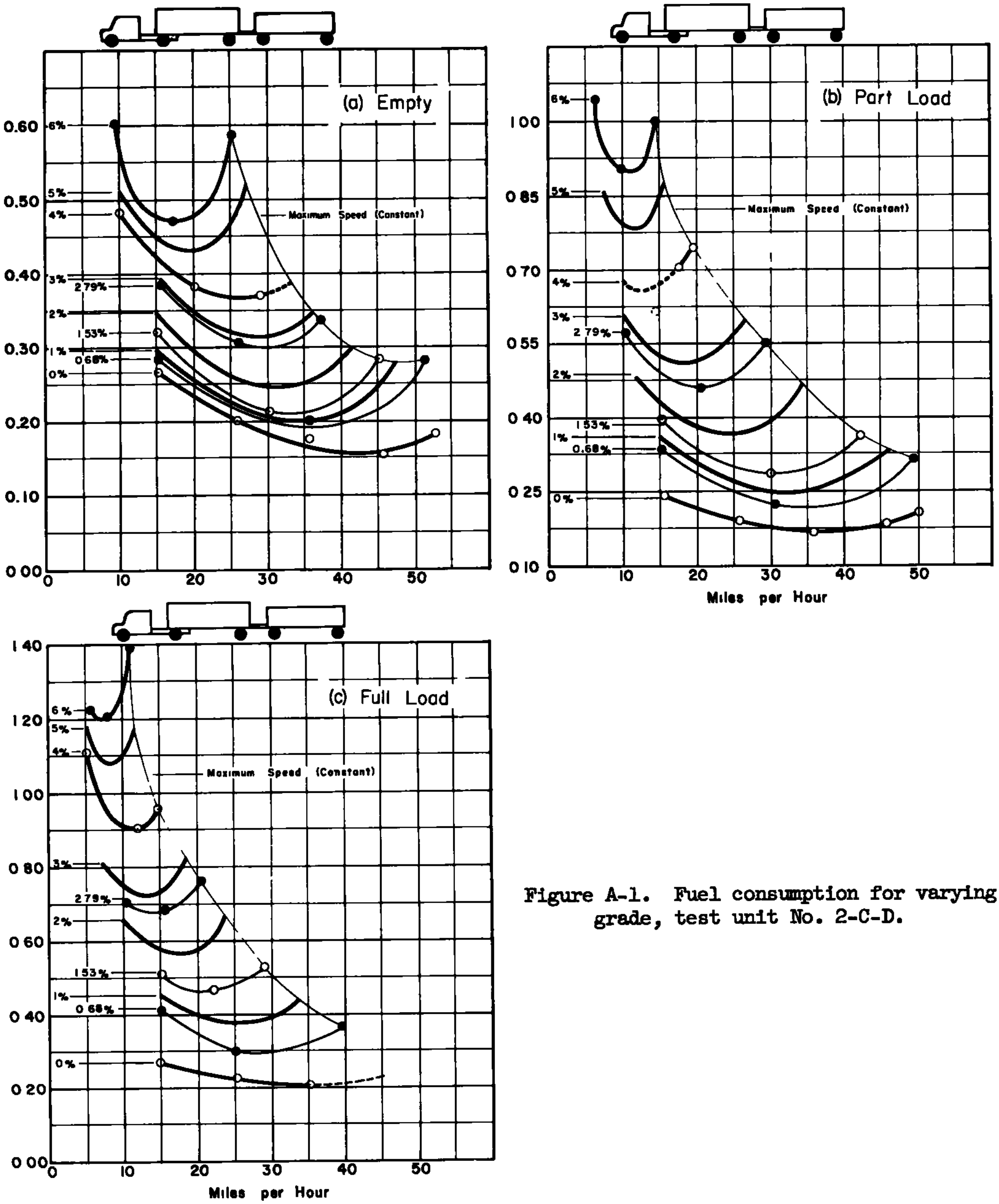


Figure A-1. Fuel consumption for varying grade, test unit No. 2-C-D.

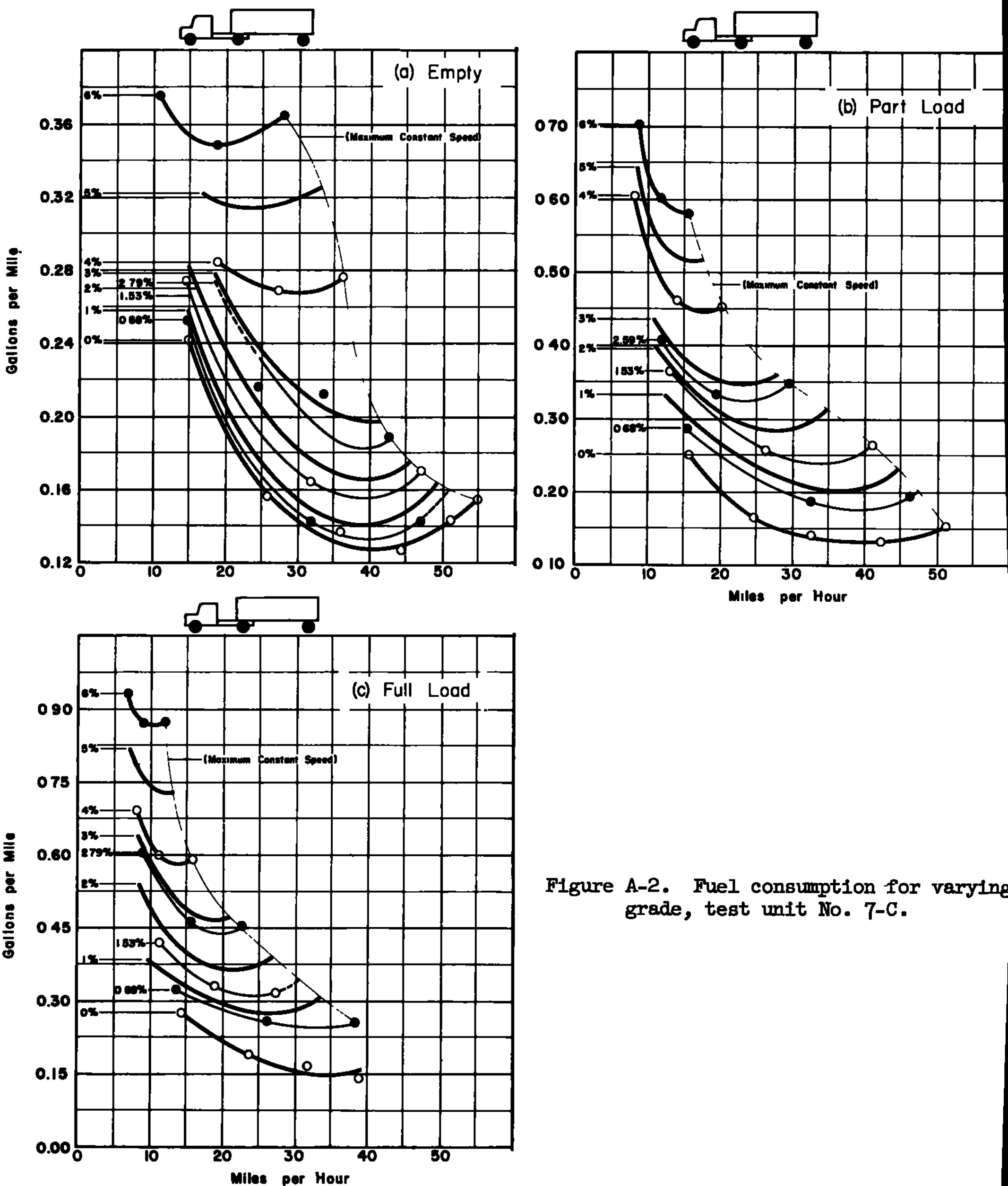


Figure A-2. Fuel consumption for varying grade, test unit No. 7-C.

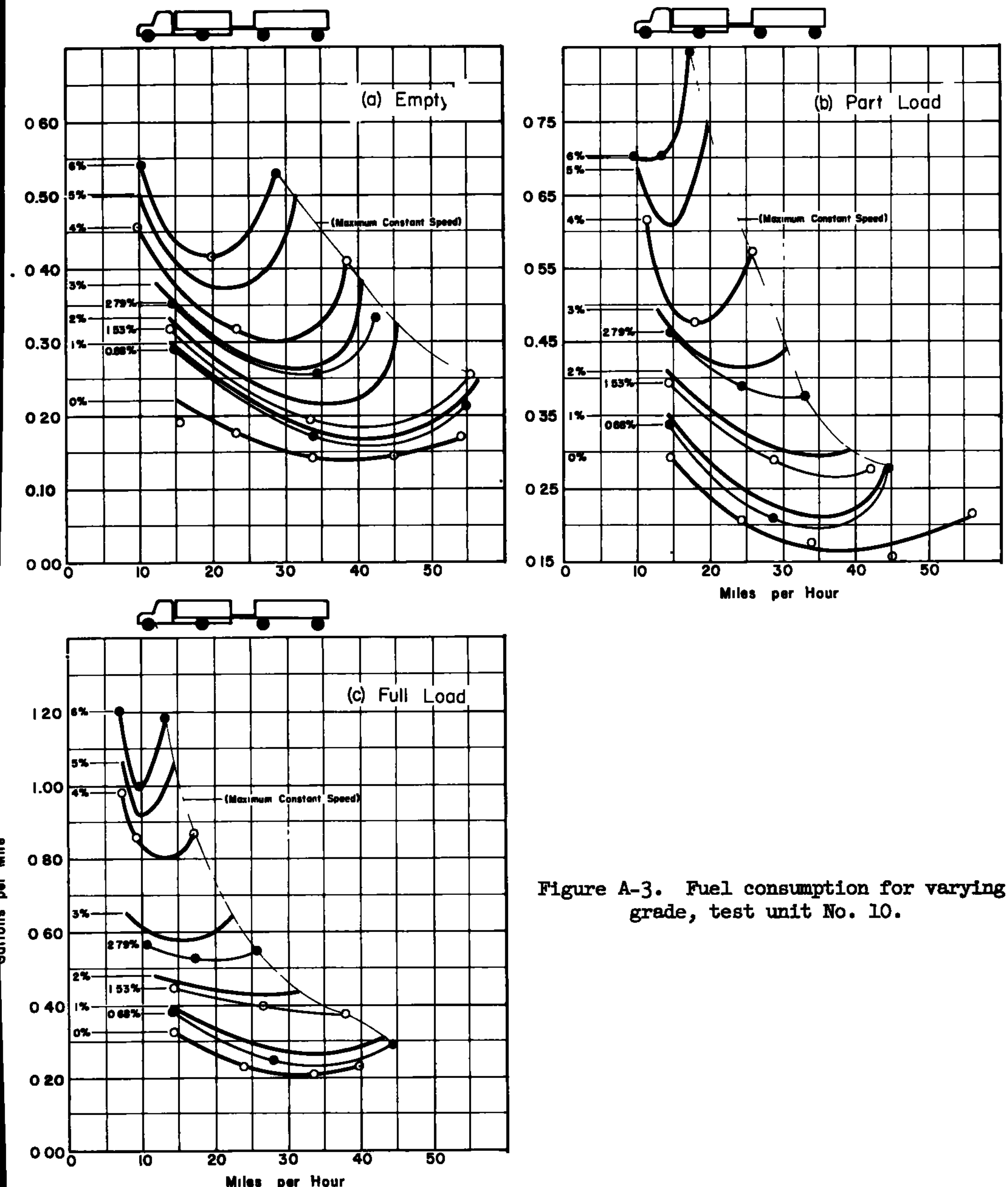


Figure A-3. Fuel consumption for varying grade, test unit No. 10.

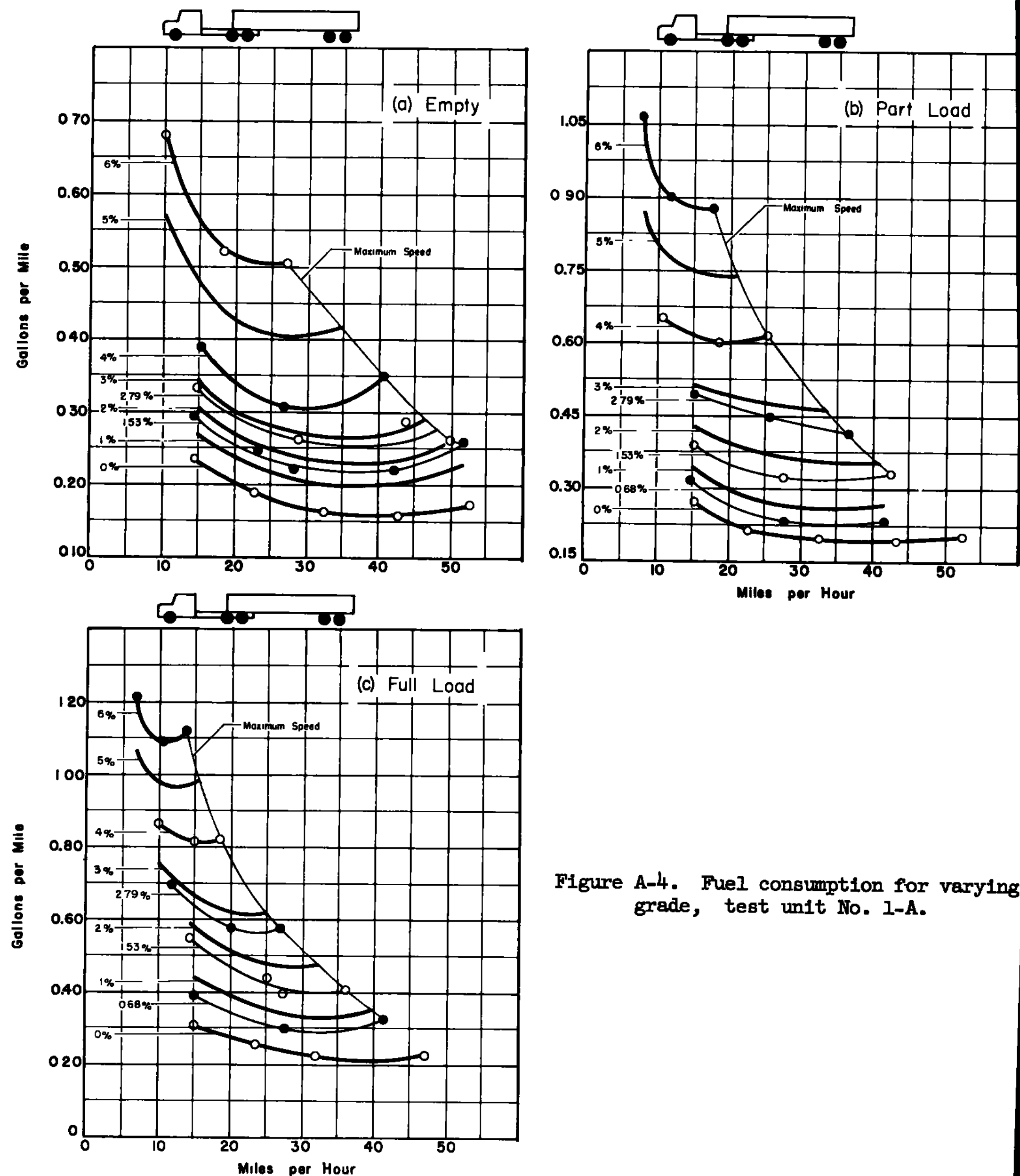
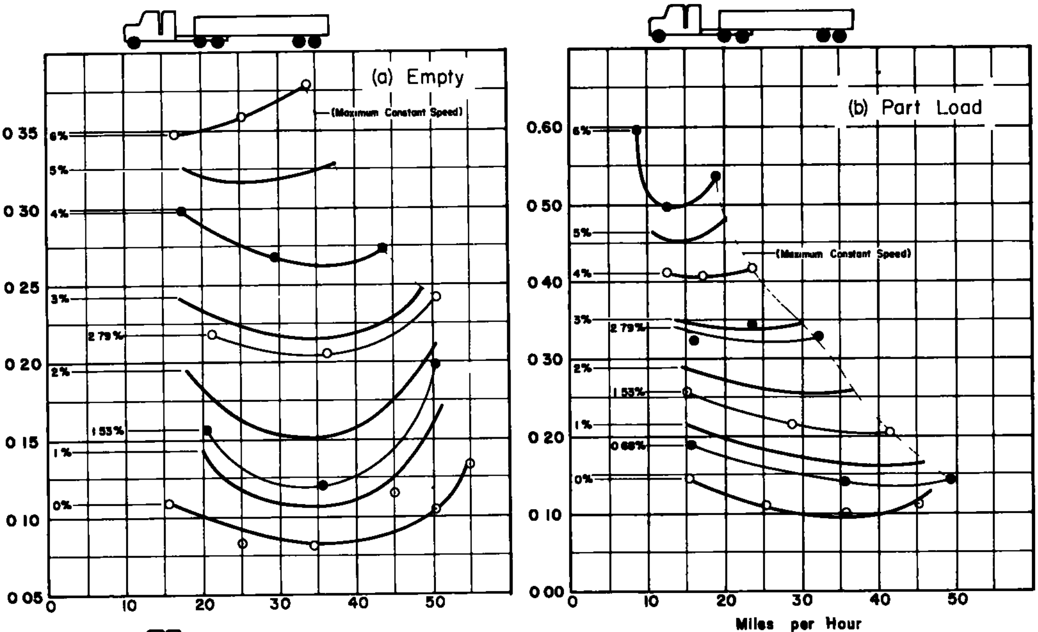


Figure A-4. Fuel consumption for varying grade, test unit No. 1-A.



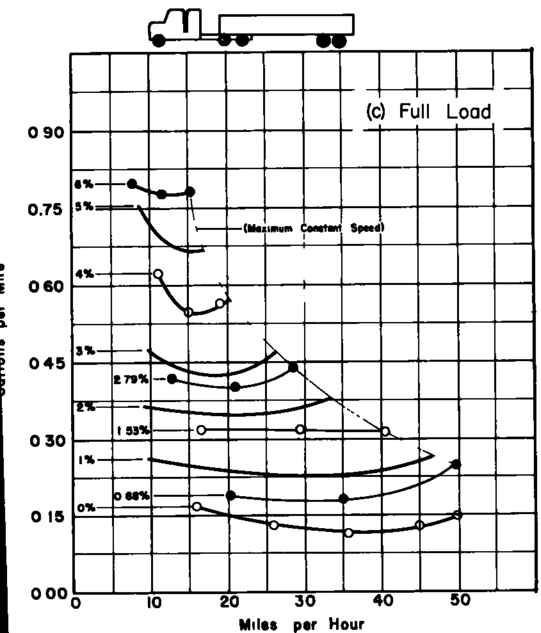


Figure A-5. Fuel consumption for varying grade, test unit No. 5-A.

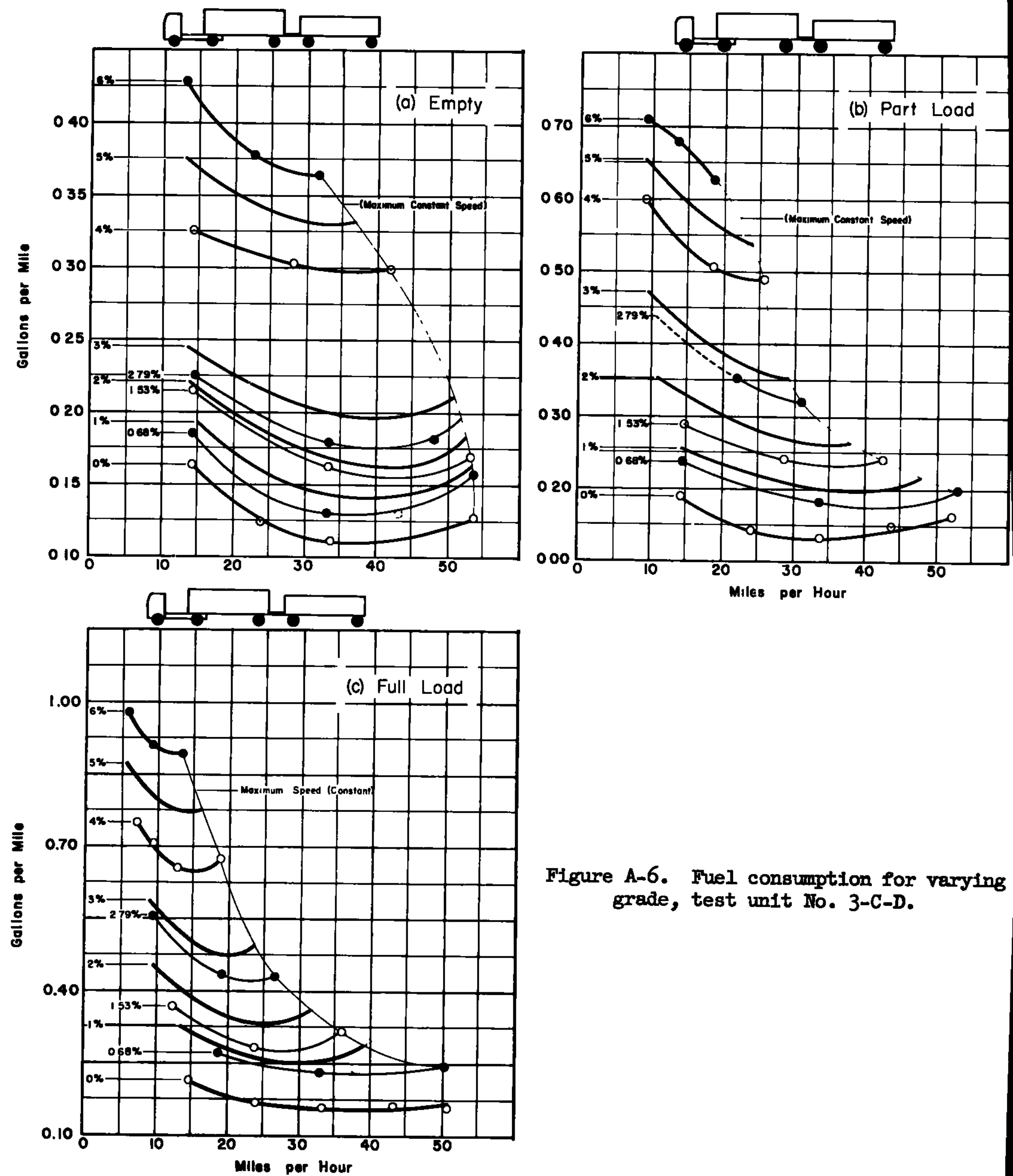


Figure A-6. Fuel consumption for varying grade, test unit No. 3-C-D.

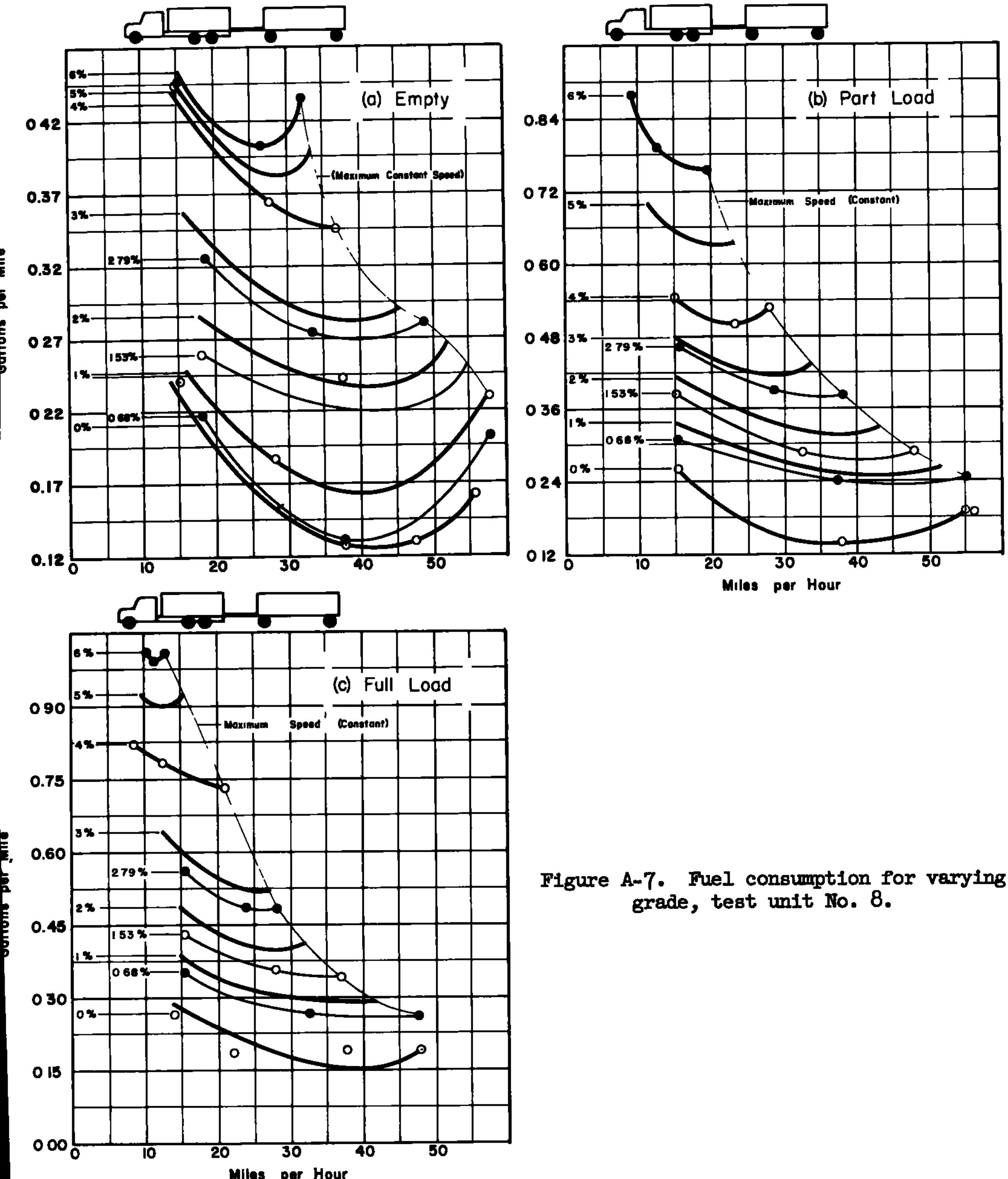


Figure A-7. Fuel consumption for varying grade, test unit No. 8.

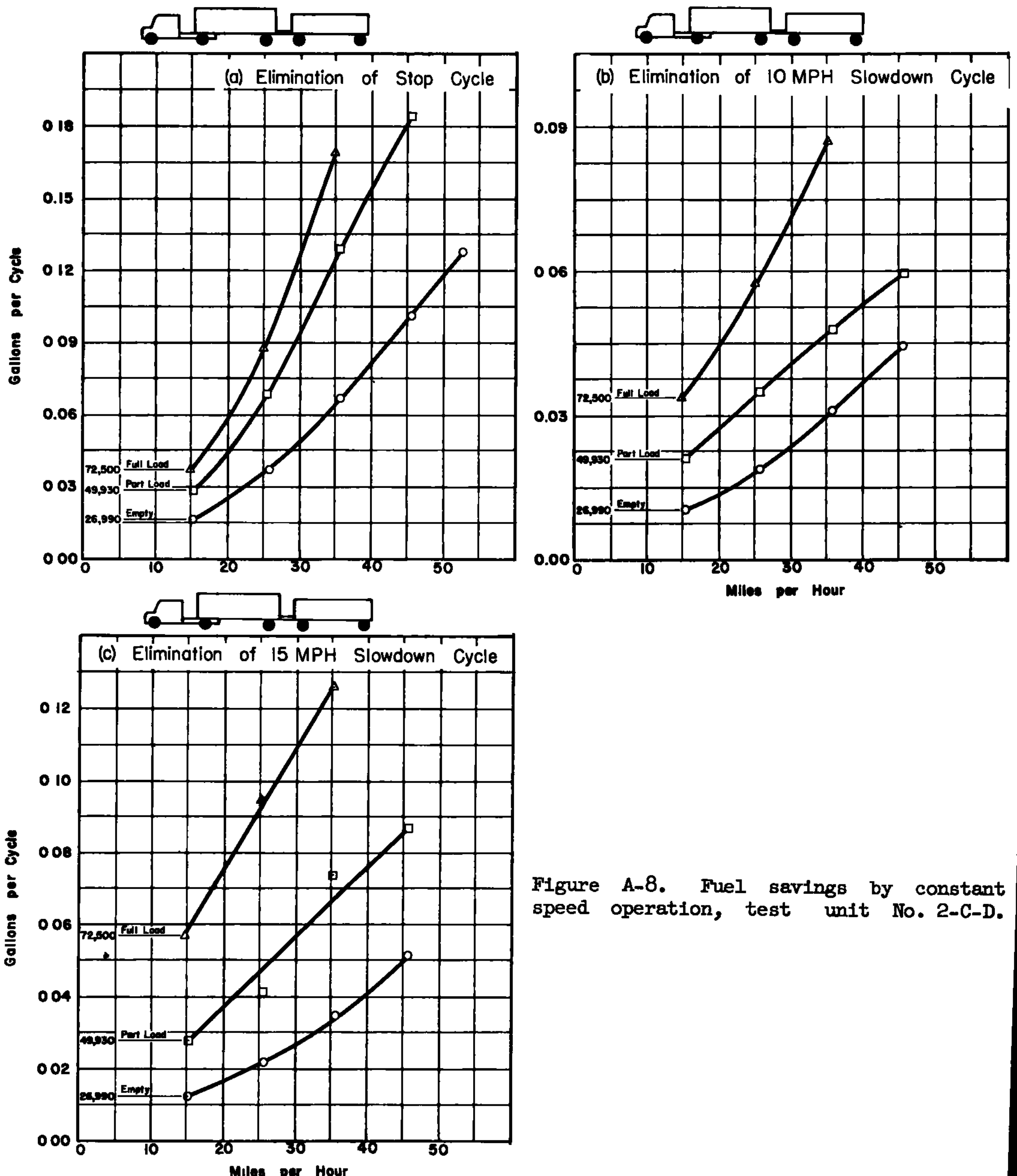
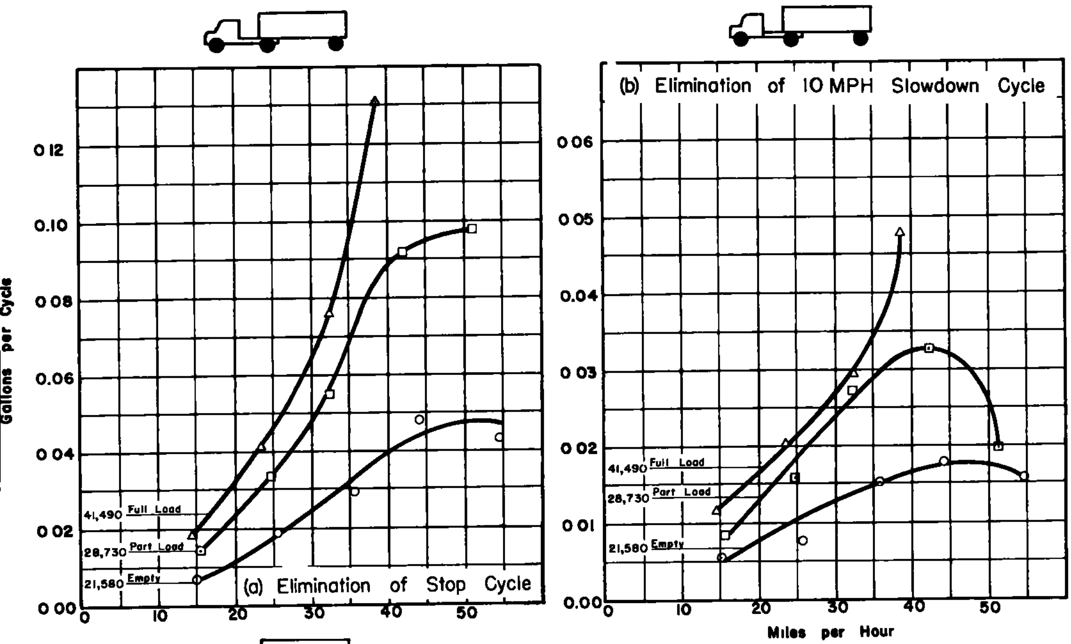


Figure A-8. Fuel savings by constant speed operation, test unit No. 2-C-D.



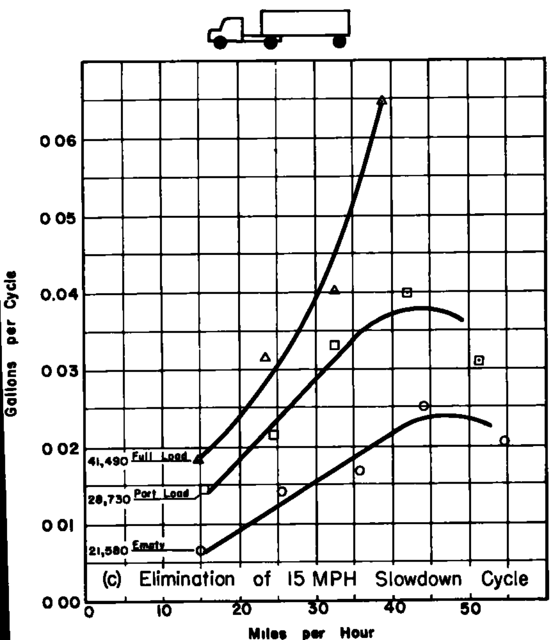


Figure A-9. Fuel savings by constant speed operation, test unit No. 7-C.

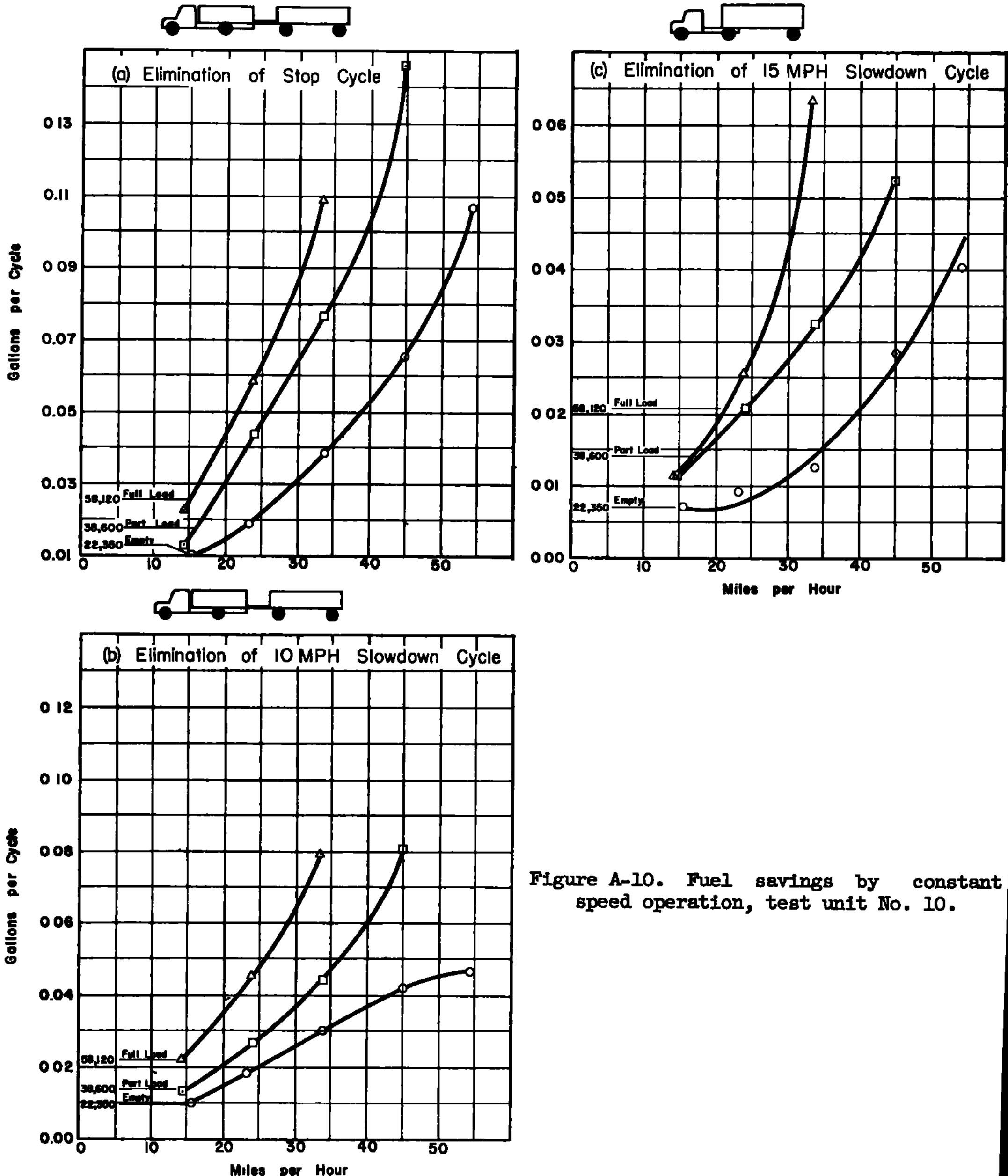


Figure A-10. Fuel savings by constant speed operation, test unit No. 10.

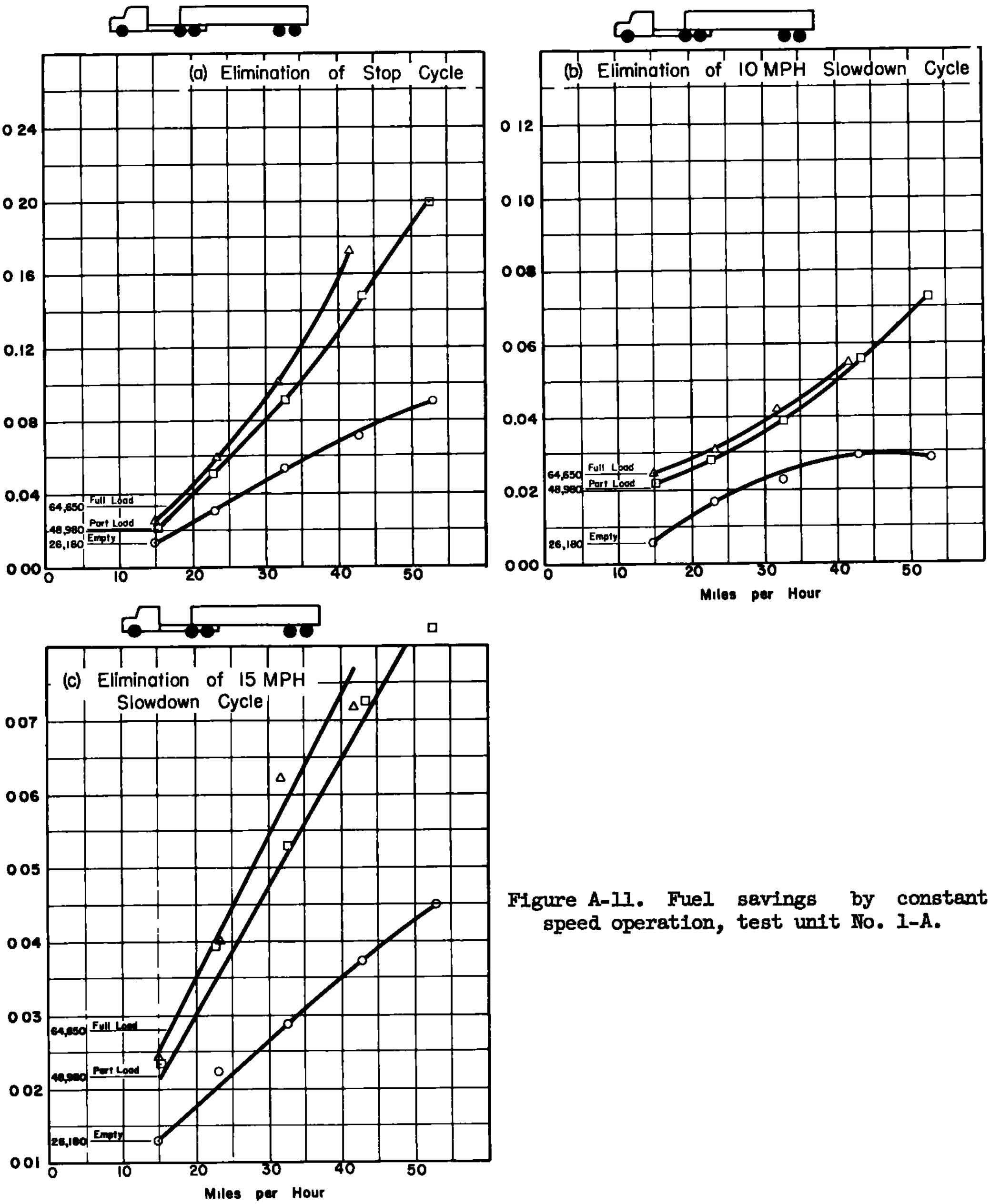


Figure A-11. Fuel savings by constant speed operation, test unit No. 1-A.

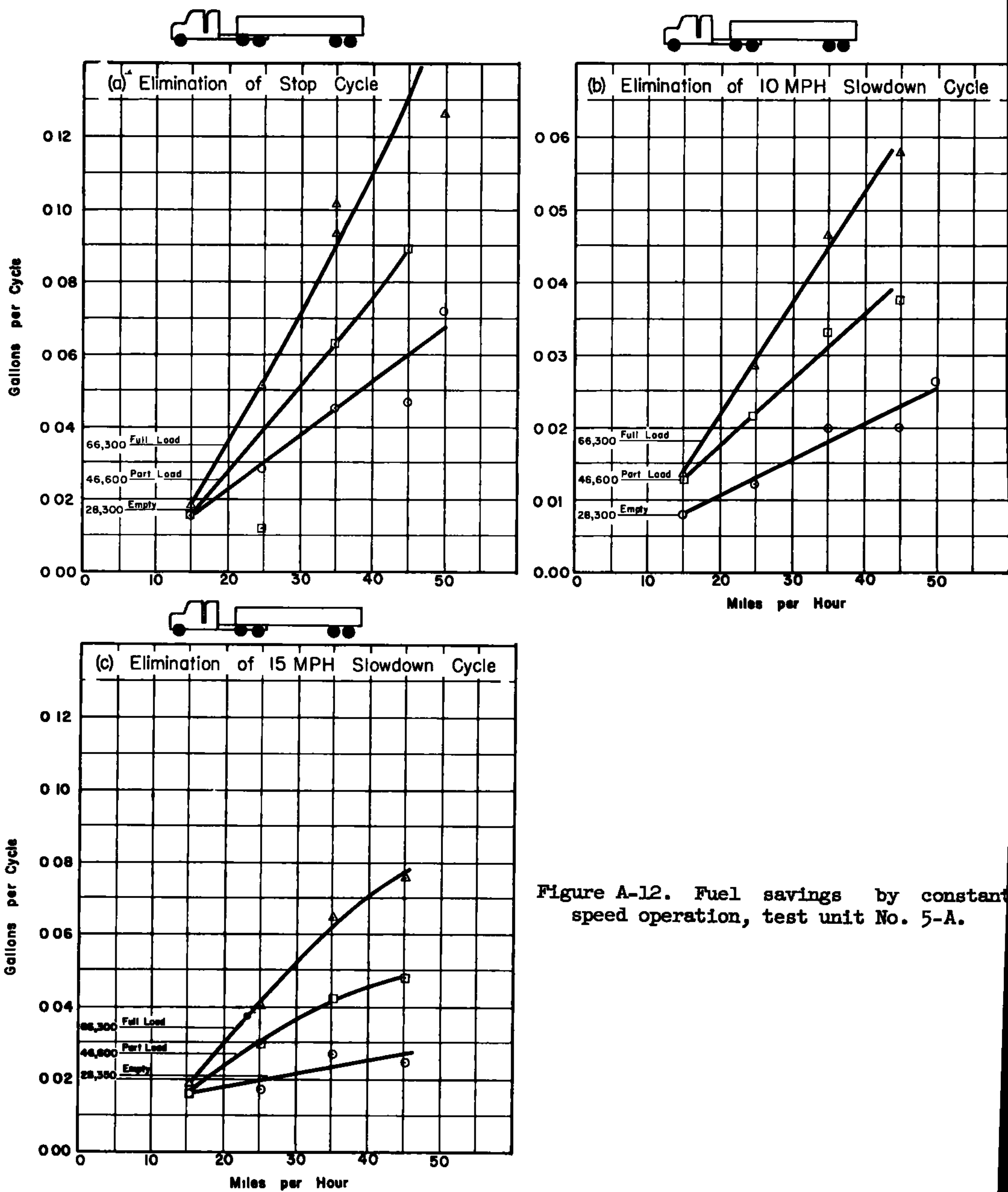


Figure A-12. Fuel savings by constant speed operation, test unit No. 5-A.

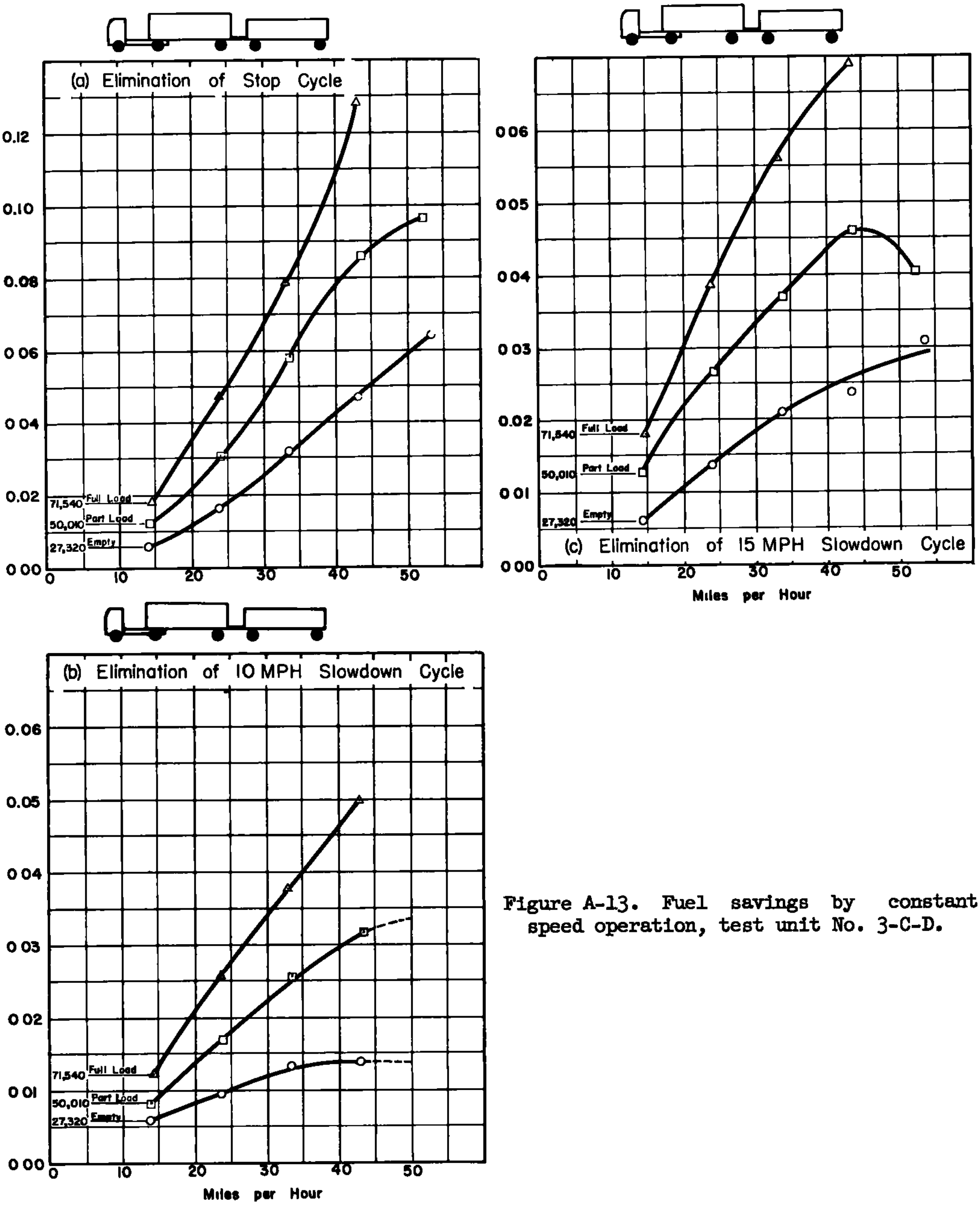


Figure A-13. Fuel savings by constant speed operation, test unit No. 3-C-D.

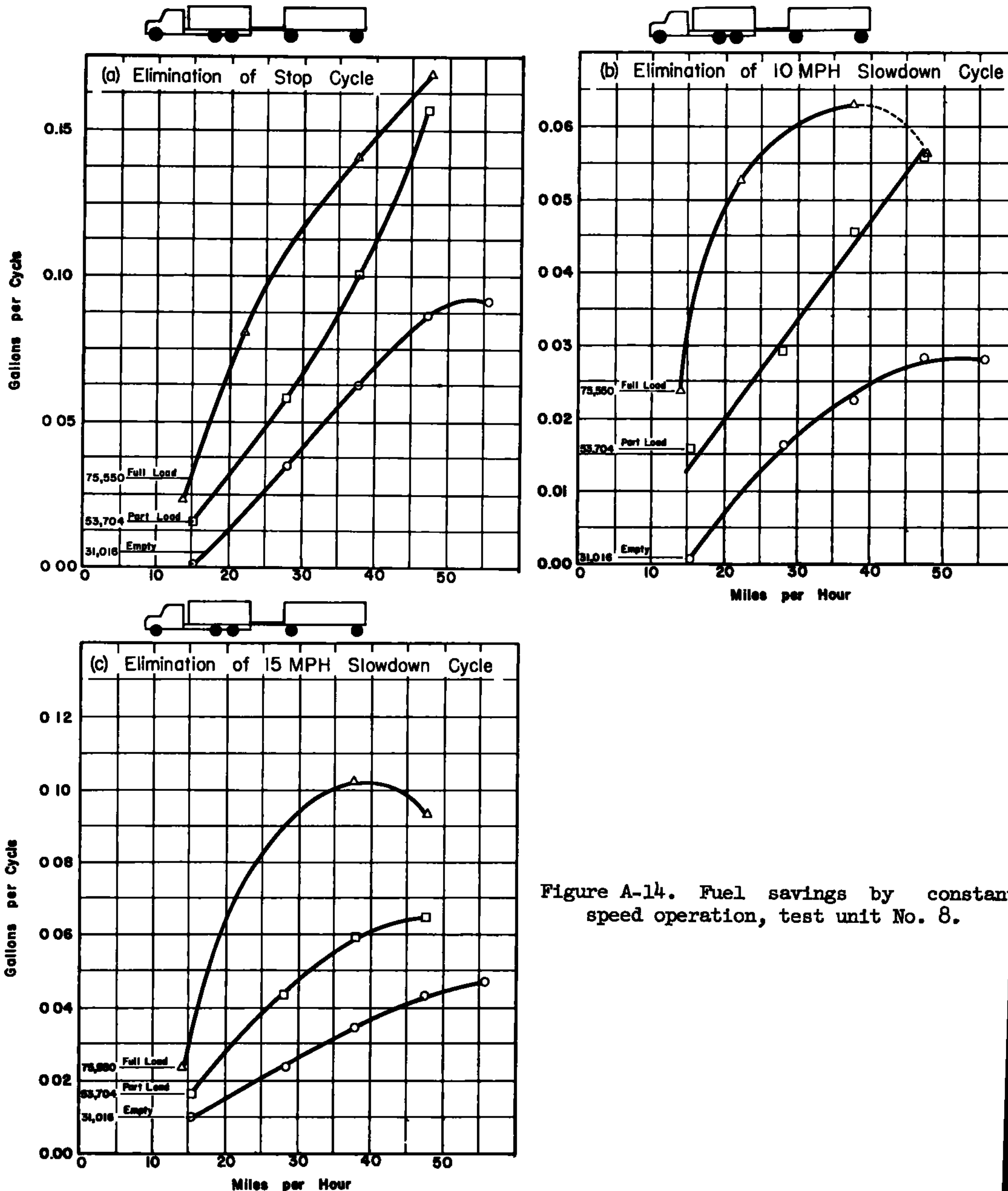


Figure A-14. Fuel savings by constant speed operation, test unit No. 8.

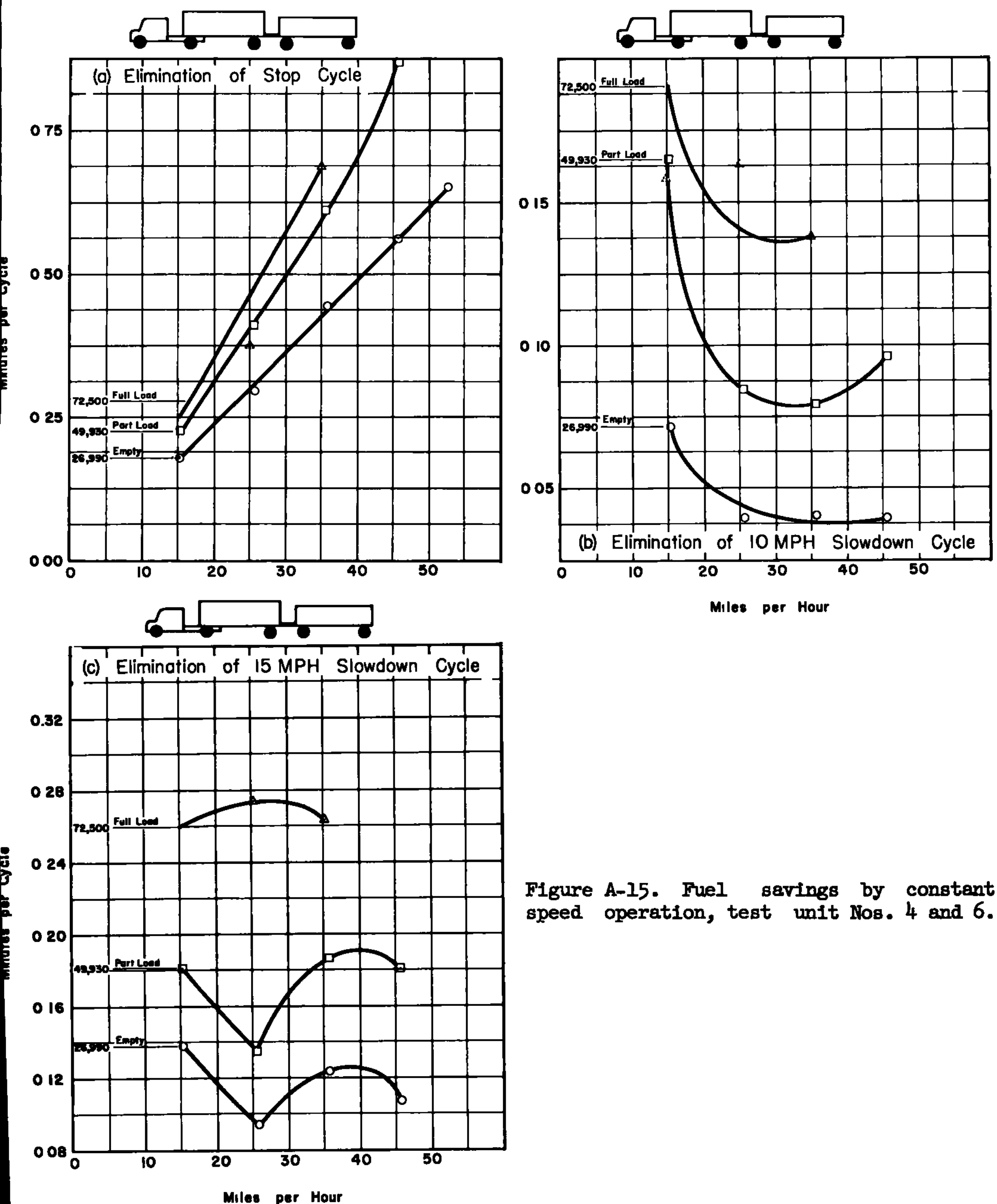


Figure A-15. Fuel savings by constant speed operation, test unit Nos. 4 and 6.

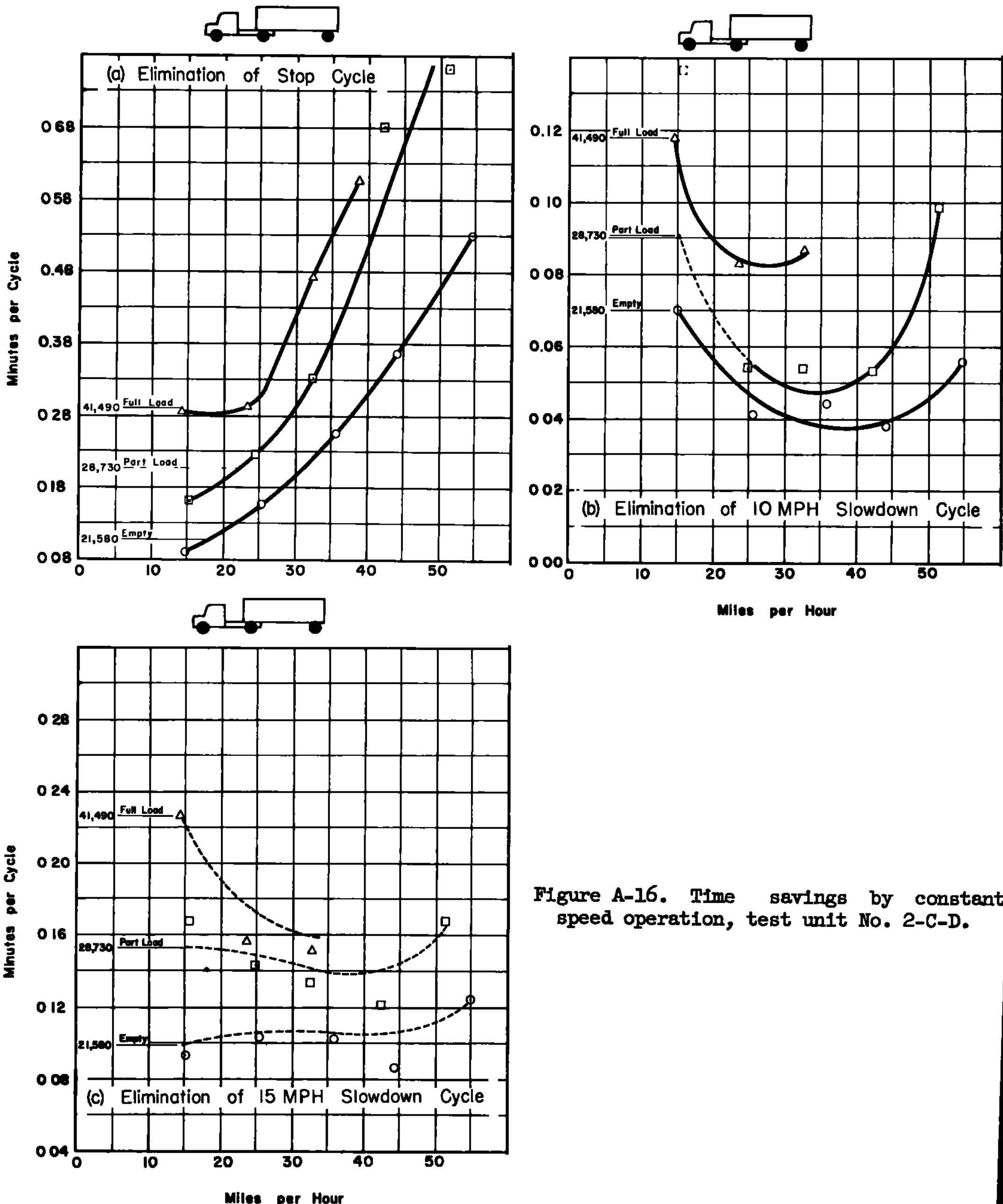
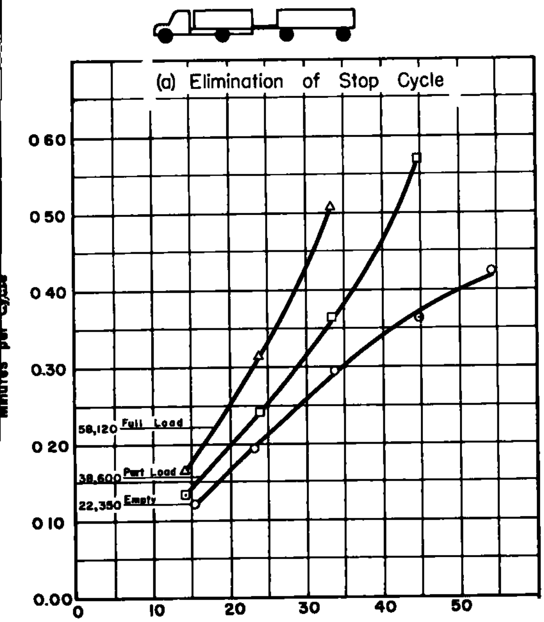
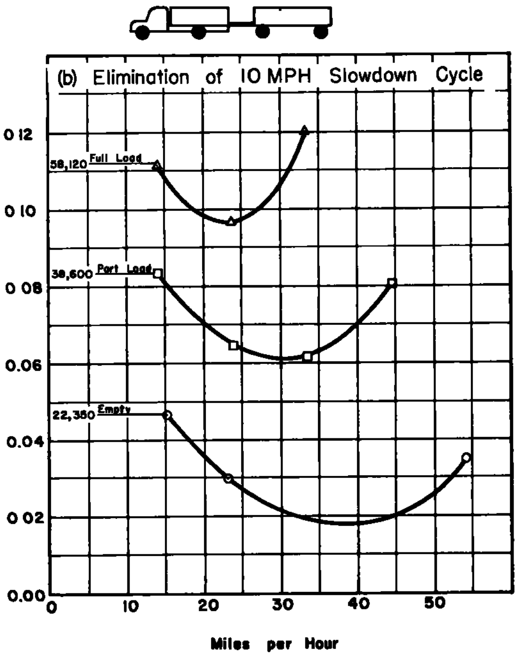


Figure A-16. Time savings by constant speed operation, test unit No. 2-C-D.





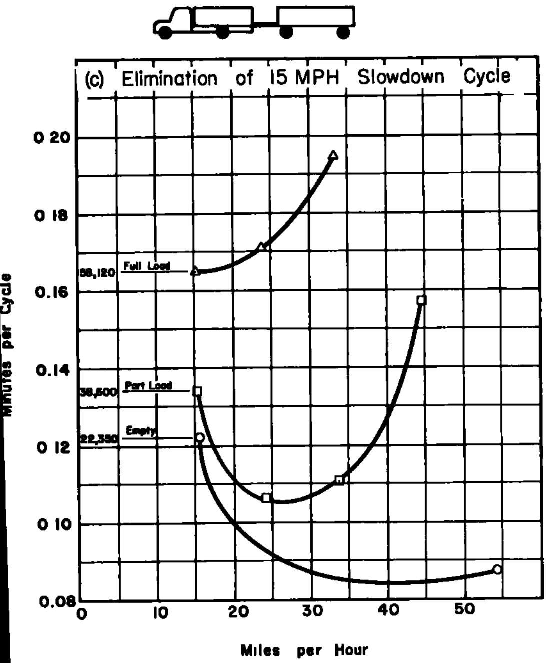


Figure A-17. Time savings by constant speed operation, test unit 7-C.

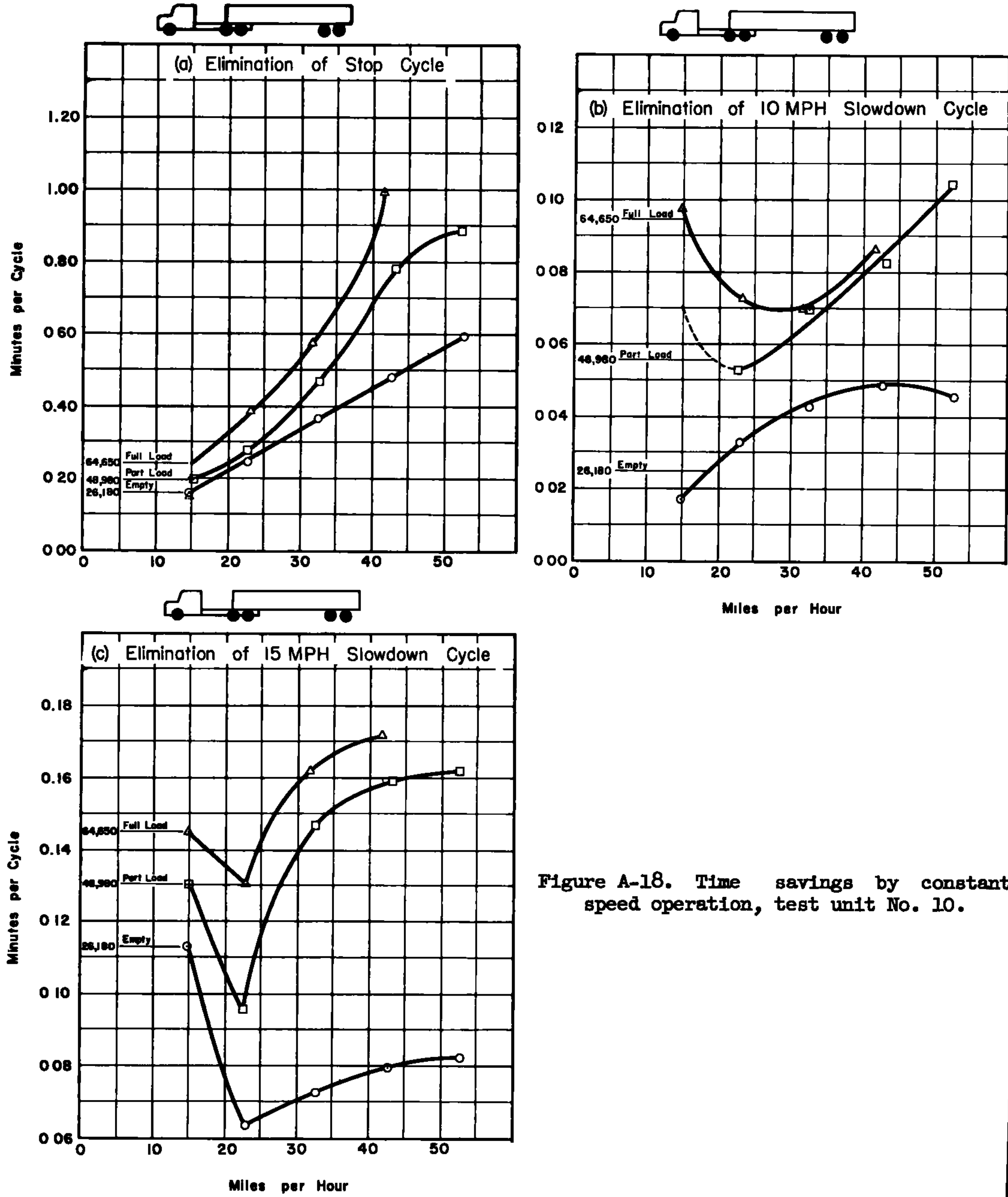


Figure A-18. Time savings by constant speed operation, test unit No. 10.

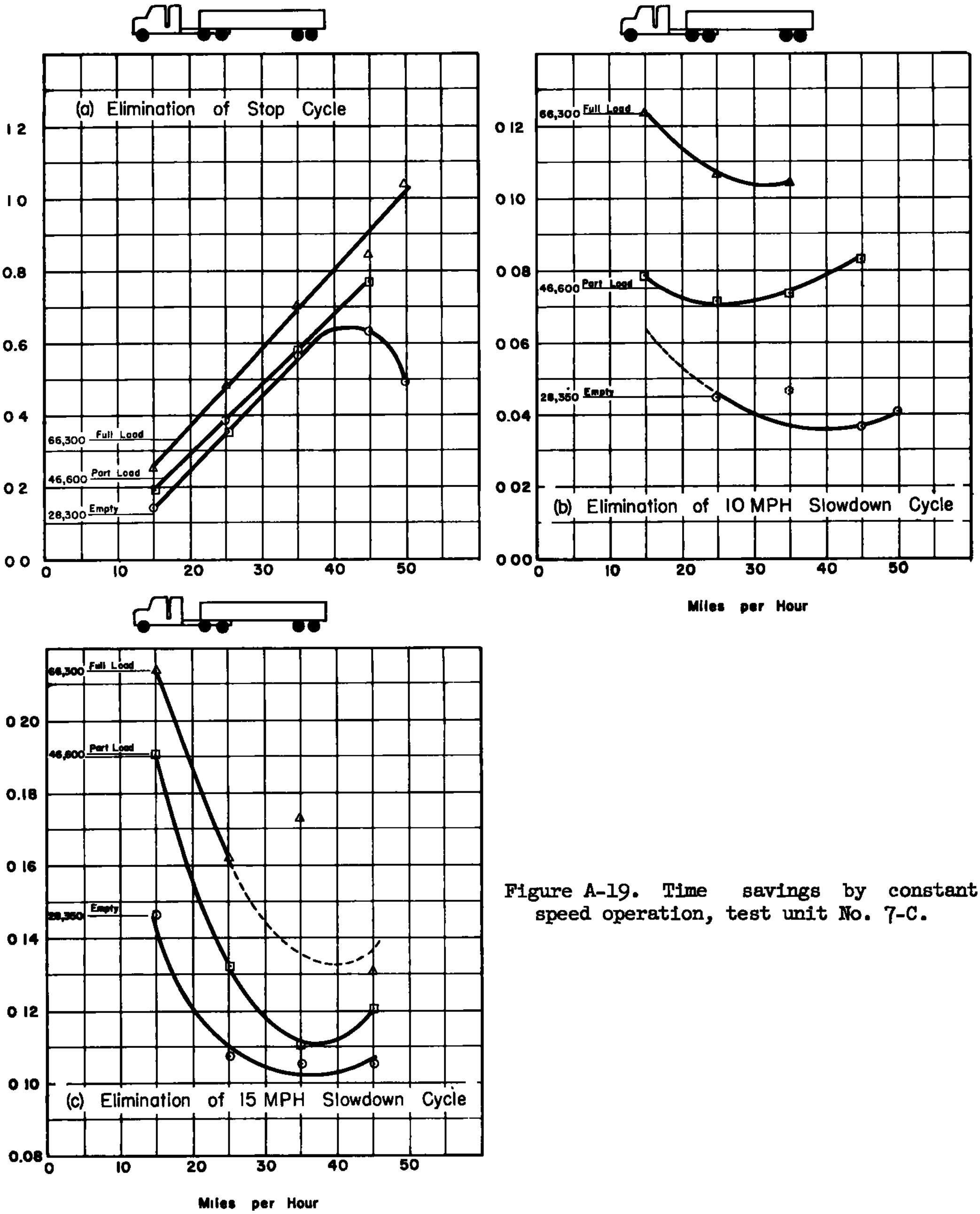
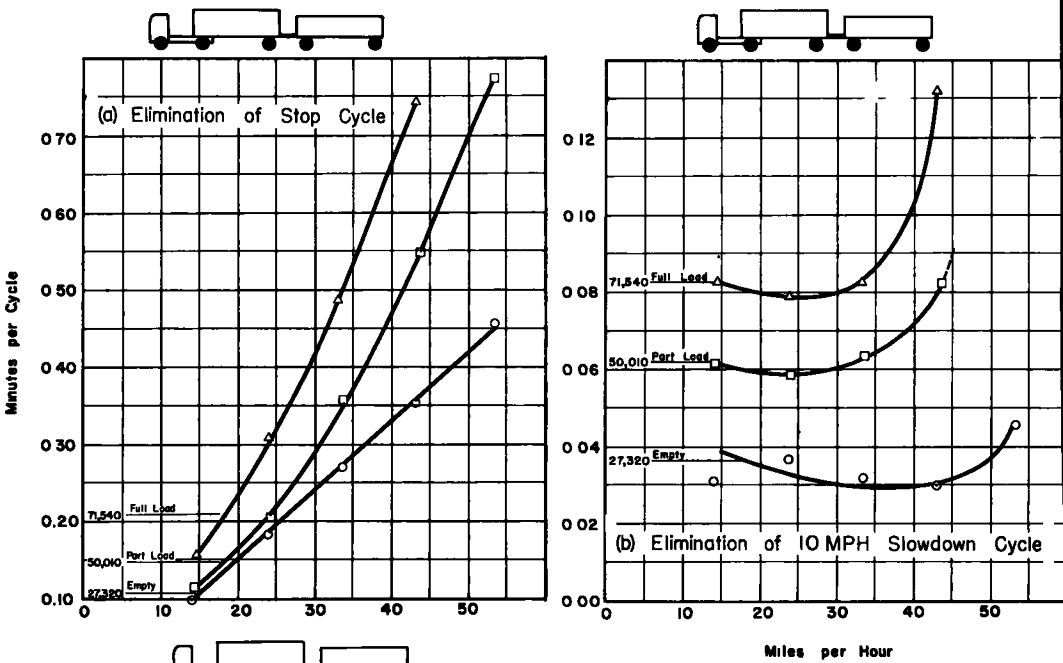


Figure A-19. Time savings by constant speed operation, test unit No. 7-C.



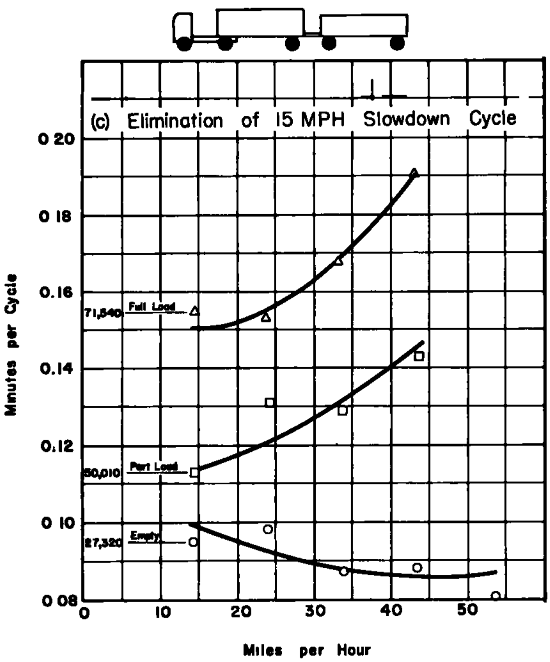
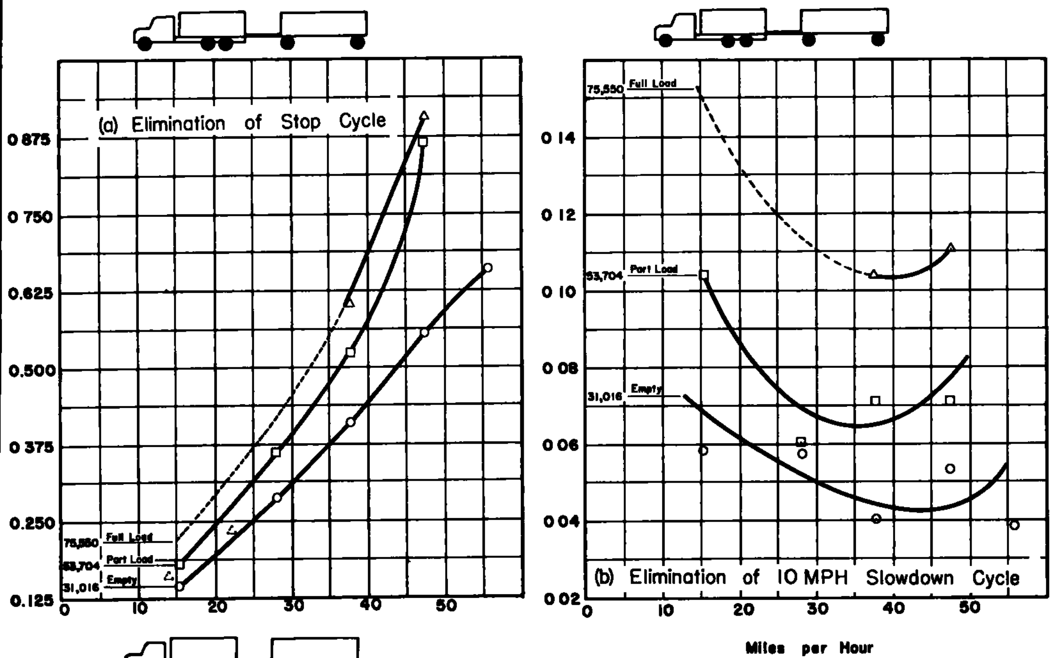


Figure A-20. Time savings by constant speed operation, test unit No. 5-A.



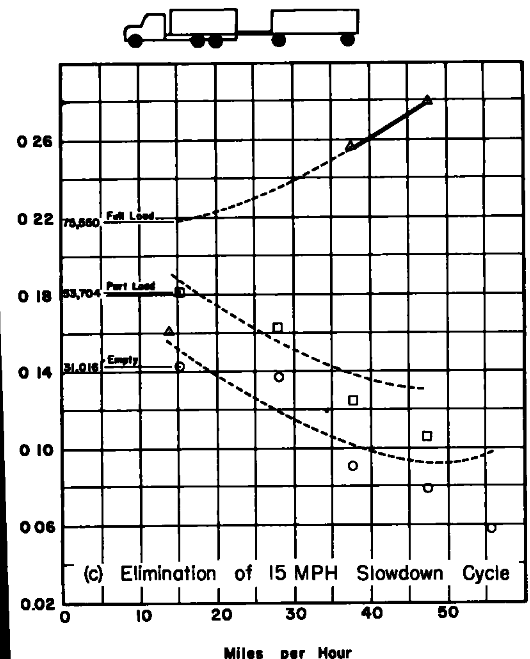


Figure A-21. Time savings by constant speed operation, test unit No. 3-C-D.

ERRATA

BULLETIN 276

In Bulletin 276, titled "Motor Vehicle Time and Fuel Consumption," the following errors have been noted:

Page 80, subcaptions (b) and (c) are interchanged and the truck silhouette should be as in (a) for all three parts.
Page 85, Figure A-15, caption should read "..........test unit No. 2-C-D."
Page 86, Figure A-16, caption should read "..........test unit No. 7-C."
Page 87, Figure A-17, caption should read "..........test unit No. 10."
Page 88, Figure A-18, caption should read "..........test unit No. 1-A."
Page 89, Figure A-19, caption should read "..........test unit No. 5-A."
Page 90, Figure A-20, caption should read "..........test unit No. 3-C-D."
Page 91, Figure A-21, caption should read "..........test unit No. 8."