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Bulletin 276

Motor Vehicle Time and Fuel Consumption

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Motor Vehicle Time and Fuel Consumption

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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."

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Contents

Fuel and Time Consumption Rates for Trucks in Freight Service

MALCOLM F. KENT, Transportation Economist, Bureau of Public Roads, Washington, D.C.

The number of times a truck must change its speed in a mile of travel increases with the density of traffic, according to an analysis of data derived from studies conducted in 1957 and 1958 of rural and urban travel in five States—data necessary in the analysis of highway-user benefits.

Using a congestion index, which indicates that speed changes per mile increase uniformly with average daily traffic for different types of highway, together with the rates of fuel and travel time consumed during a change in vehicle speed, the added cost of operating at nonuniform speed could be assessed.

This article also shows that, for the gross vehicle weights observed, smaller and less powerful engines give better fuel economy, but their use carries a penalty of increased time-consumption (lower road speeds) at the higher gross vehicle weights. Trucks with diesel engines were found to travel about 50 percent more miles on a gallon of fuel than trucks with gasoline engines of approximately equivalent power and gross weight characteristics.

●ONE OF THE greatest voids in the data available for the analysis of highway-user benefits accruing through the improvement of highway facilities has been reliable fuel- and time-consumption rates of commercial motor vehicles operating in actual service. To help fill this void the Bureau of Public Roads developed a program for obtaining this information. Ohio State University, the Universities of Michigan and Washington, and a transportation consultant from the University of Maryland were engaged to measure fuel consumption and over-all travel time of selected trucks in rural and urban line-haul service and in city pickup and delivery service, under traffic conditions ranging from restricted to free flowing. This study group obtained the cooperation of private, government-owned, and for-hire highway freight carriers. Three of the studies were conducted simultaneously during the summer of 1957, and one during the summer of 1958.

A principal concern of highway planners of a few decades ago was the surfacing of dirt roads. Today, a principal concern is the elimination of frictional factors that impede the free flow of traffic on paved roads. Eliminating stops occasioned by stop signs and traffic lights, the widening of pavements or the adding of more lanes, the designing of highways with easier grades and curves, and the upgrading of other features that cause reduction in normal driving speeds are factors that are now of primary importance.

In addition to improving the safety and efficiency of traffic flow, such improvements result in direct benefits to road users. Savings in motor fuel and time costs are two of the principal benefits that result, and they are directly affected by the elimination of frictional factors that impede the free flow of traffic. The over-all purpose of the studies described in this report was to provide data on fuel consumption and travel time for various vehicle types and traffic conditions, which could be used in the economic analyses of road-user benefits.

SUMMARY OF FINDINGS

Major findings of the studies are summarized in the following paragraphs.

1. The fuel consumption in gallons per mile of motor trucks operating in rural and urban line-haul service increased with the power of the engine for equivalent gross vehicle weights.
2. Operating over identical rural line-haul routes, diesel-powered trucks were found to travel about 50 percent more miles on a gallon of fuel than gasoline-powered trucks of approximately equivalent power and gross vehicle weight. In terms of fuel consumption, this means that diesel-powered trucks consumed about 66 percent of the gallonage used by gasoline-powered trucks.
3. The consumption of gasoline per mile by trucks was 25 to 30 percent higher in urban areas than in rural areas.
4. The average truck speeds, including all stops and slowdowns, were found to be 37 mph in rural line-haul operation, 19 mph in urban line-haul operation, and 11 mph in city pickup and delivery. For free-flowing traffic, the comparative speed for trucks in rural line-haul operation was 40 mph.
5. The usefulness of speed changes per mile as a congestion index was demonstrate by proving that speed changes per mile increased uniformly with average daily traffic for different types of highways. Knowing the number of speed changes saved, the proportion of stops and slowdowns, and the magnitude of each, it is possible to use this index to compute the added cost of fuel and time caused by speed changes, when the extra fuel and time consumed during a speed change are known.
6. The stops on rural highways, made from the average truck speed, represented 11 percent of all deviations from desired speeds, whereas the stops on urban streets represented 45 percent of all deviations from desired speeds.
7. The average number of speed changes per mile was found to be 1.66 for rural line-haul, 4.97 for urban line-haul, and 6.91 for city pickup and delivery operations.

DEFINITION OF TERMS

To avoid misinterpretation of the results, certain terms used in this article are defined.

Fuel consumption. —Gallons of gasoline or diesel fuel consumed per mile of highway travel. The conversion from gallons per mile to miles per gallon can easily be made since one is the reciprocal of the other.

Travel time. —Minutes required to travel 1 mile. Minutes per mile can be converte to miles per hour by dividing 60 by the minutes per mile.

Stop. —Bringing a motor vehicle to a complete stop.

Slowdown. —A reduction in speed of a motor vehicle of more than 3 mph without coming to a stop.

Speed change. —All motor vehicle accelerations and decelerations effecting a speed change of more than 3 mph, including both stops and slowdowns.

Average gross vehicle weight. —The average of the individual gross vehicle weights of several vehicles, all falling within the same class interval of gross vehicle weight.

Engine cubic-inch displacement. —The cross-sectional area of a cylinder multiplie by the length of piston stroke, which gives the cylinder displacement; multiplied by th number of cylinders.

Net horsepower. —The brake horsepower of the engine, operating with all its norma accessories, that is available at the clutch or its equivalent. It is the gross horsepow minus the horsepower absorbed by fan, compressor, generator, etc. For all practic purposes, net horsepower is assumed to be 90 percent of the gross horsepower.

Total rise and fall. —The arithmetic sum of the vertical rise and fall in feet for an section of highway. The rise in one direction of travel will become the fall in the opposite direction. The total rise and fall is the same regardless of the direction of travel.

Rate of rise and fall. —The total rise and fall for any section of highway in feet divided by the length of section in hundreds of feet. It is not to be confused with the percent of grade. It is equivalent to the average percent of grade only when either the rise or fall is 100 percent of the total rise and fall.

DESCRIPTION OF TEST ROUTES

The four studies were conducted in the general areas of Maryland-District of Columbia-Virginia, Ohio, Michigan, and Washington. The line-haul (intercity) routes with their origins, destinations, route numbers, mileages, and rates of rise and fall are shown in Table 1. The urban extensions of the line-haul routes in Cleveland and Columbus, Ohio, Detroit, Mich., Baltimore, Md., Washington, D.C., Seattle, Wash., and some smaller municipalities were studied separately from rural line-haul operation. These generally followed the numbered routes until diversion was necessary to reach the trucking terminal or delivery warehouse.

TABLE 1

ROUTE TERMINI, ROUTE NUMBERS, DISTANCES, AND RATES OF RISE AND FALL OF RURAL HIGHWAYS TRAVELED BY OBSERVED LINE-HAUL TRUCKS

Termini				
From	To	Numbered Routes	Mileage[a]	Rate of Rise and Fall[b]
Washington, D.C.	Baltimore, Md.	Md. 193, US 1	32.6	1.58
	Richmond, Va.	Va. 350, US 1	95.5	1.42
Columbus, Ohio	Cleveland, Ohio	Ohio 3, 61, US 42	128.4	1.41
	Parkersburg, W. Va.	US 33, 50	108.8	0.63
	Wheeling, W. Va.	US 40	119.9	1.70
Detroit, Mich.	Lansing, Mich.	US 16	80.5	0.59
	Toledo, Ohio	US 25	55.4	0.16
	Three Rivers, Mich.	US 112, 12, Mich. 60	151.7	0.48
Seattle, Wash.	Aberdeen, Wash.	US 99, 410	95.5	1.25
	Bellingham, Wash.	US 99	75.5	1.28
	Centralia, Wash.	US 99	74.7	1.09
	Chehalis, Wash.	US 99	80.7	1.09
	Everett, Wash.	US 99	18.5	1.87
	Longview, Wash.	US 99, 830	120.7	0.95
	Mt. Vernon, Wash.	US 99	53.9	1.24
	Olympia, Wash.	US 99	53.1	1.29
	Portland, Ore.	US 99	161.2	0.93
	Tacoma, Wash.	US 99	23.9	1.59
	Yakima, Wash.	US 10, 97	139.1	1.35

[a] Between municipal boundaries of terminal cities.
[b] In feet per 100 ft of distance.

City pickup and delivery service was studied in Detroit, Columbus, Seattle, and Washington, D.C. All such operations were on irregular routes except for the postal delivery service trucks which followed the same routes each day to the various substations in Columbus. The types of service varied from large tractor-truck semitrailer combinations delivering grocery products from warehouses to retail stores and motor fuel from wholesale storage tanks to retail filling stations, to panel and van-type trucks engaged in package or linen delivery service. Rise and fall rates were estimated for Columbus, Detroit, and Washington, D.C., at approximately 0.5 ft per 100 ft. Rates of rise and fall for routes were recorded for Seattle, and ranged from 1.9 to 2.3 ft per 100 ft. However, the variations in rates of rise and fall among routes were not of sufficient magnitude to cause significant changes in fuel and time consumption.

DESCRIPTION OF TEST VEHICLES

The gasoline- and diesel-powered tractor-truck semitrailer combinations, made available by commercial carriers for line-haul observation, are described in Table 2 according to type, engine displacement, and net brake horsepower. City pickup and delivery gasoline-powered vehicles, consisting of panel and other single-unit trucks and tractor-truck semitrailer van and tank combinations, are similarly described.

Where the size and weight restrictions of the particular state permitted, three vehicles were observed in each state within each of the following weight groups:

Rural and Urban Line-Haul (lb)	City Pickup and Delivery (lb)
20,000 - 29,999	5,000 - 9,999
30,000 - 39,999	10,000 - 19,999
40,000 - 49,999	20,000 - 29,999
50,000 - 59,999	Over 30,000
60,000 - 69,999	

TEST PROCEDURES

After receiving permission from fleet owners to use their vehicles for test purposes, in the course of their normal runs, a fuel meter was placed in the cab of each gasoline-powered truck and connected to the fuel lines of the engine between the tank and the carburetor. The fuel meter could be read by a person sitting next to the driver The fuel tank was filled at the start of each trip and was filled again at the end of the trip; any fuel added en route was, of course, recorded. This over-all record of fuel consumption was used to check the accuracy of the meters.

Diesel-engine trucks, in which excess fuel is recirculated from the engine to the fuel tank, required a different type of meter installation. To circumvent the multimetering of the same fuel, a small-volume, constant-level tank was installed in the fuel line between the engine and the main fuel supply tank. The engine fuel pump drew only from this feed tank, to which all excess recirculated fuel was returned. Fuel consumed by the engine was drawn from the feed tank, and a constant level was maintained in the feed tank through a float arrangement and an auxiliary fuel pump supplying additional fuel from the main supply tank through a fuel meter unit. In this manner, the fuel meter recorded only the actual quantity of fuel consumed by the engine.

Before the beginning of the test runs each route to be observed was inventoried to locate control points with relation to major changes in traffic flow and to record mileag between control points, rise and fall (through use of an aneroid barometer), number of traffic signs and signals, and number of lanes. Before the start of each run, the observer recorded the vehicle chassis model and year, unladen weight, payload weight, and gross vehicle weight, engine model size and cubic inches of cylinder displacement, and reported net brake horsepower. The weather and condition of the road were also recorded.

The observer, riding in the cab, recorded on each run the following information as he passed the control points: time of day (hour and minute), fuel meter reading (hundredths of a gallon), and odometer reading (tenths of a mile). The magnitude of each speed change of ± 3 mph or more within each section was recorded during the trip. Trips were made at all hours of the day and night, with no change from normal operations being made on account of the study. Drivers were not to change their normal driving habits, and drove at speeds representative of other traffic .

TABLE 2

CHARACTERISTICS OF COMMERCIAL MOTOR VEHICLES

Number of Vehicles	Number of Axles and Body Types[a]	Engine Displacement, cu. in.	Net Brake Hp of Engine[b]	Engine Rpm
Line-haul gasoline:				
1	3-S2-2 van	302	172	3,600
3	3-S2 van	331	128	3,200
1	2-S2 van	377	126	2,800
12	2-S1 van	386	130	2,800
8	3-S1 van	406	156	2,750
4	3-S2 van	450	146	2,600
2	3-S2 van	461	197	3,200
3	2-S2 van	501	165	2,800
1	3-2 van	531	178	2,880
1	3-S2 van	549	230	3,200
4	3-S2 van	590	225	2,800
Line-haul, diesel:				
5	3-S2 van	743	200	2,100
City pickup and delivery gasoline:				
2	2 panel	214	73	3,200
1	2 panel	223	126	4,000
1	2 panel	235	123	4,000
1	2 van	220	89	2,800
5	2 van	228	90	3,000
5	2 van	248	115	3,400
1	2 van	260	90	2,500
1	2 van	261	135	4,000
1	2 van	263	105	3,400
3	2 van	271	114	2,800
2	2 van	272	167	4,400
1	2 van	282	103	3,200
2	2 van	320	103	3,000
1	2 van	386	163	3,000
2	2-S1 van	372	139	3,200
2	2-S1 van	386	145	3,000
3	2-S1 van	406	175	3,200
1	2-S2 van	383	150	2,800
2	2-S2 van	450	150	2,800
1	2-S2 van	505	175	2,800
2	2-S2 tank	464	170	2,800

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[a] Each digit indicates the number of axles of a vehicle or of a unit of a vehicle combination. A single digit, or the first digit of a group symbol, represents a single-unit truck or, if followed by an S, represents a truck-tractor. The S designation represents a semitrailer. A digit, without an S preceding it, in the second or third position of a group symbol represents a full trailer.

[b] Average 140 hp for engine sizes 302-406 cu in., average 171 hp for sizes 450-549.

ANALYSIS PROCEDURES

When the fieldwork had been completed, the first step in the analysis procedure was to list the consumption of fuel, travel time, and mileages traveled on each section for each trip, segregating rural from urban data. Speed changes were similarly listed for each section and trip, with stops being shown separately from slowdowns in the Ohio and Washington data. Gallons per mile, minutes per mile, and speed changes per mile were computed separately for line-haul rural trips, for line-haul urban trips, and for city pickup and delivery trips.

Rate of Rise and Fall

Rise and fall was considered a variable with respect to fuel consumption rates and travel time. No significant variations were found, however, in either parameter for the rather narrow range of rates of rise and fall studied. As shown in Table 1, rates of rise and fall for the rural highways studied ranged from 0.16 for the route between Detroit and Toledo, to 1.87 for the route between Seattle and Everett. Of the total mileage studied, 40.6 percent had a rate of rise and fall below 1.0, 47.7 percent had rates from 1.0 to 1.5, and 11.7 percent had rates from 1.51 to 1.87. The average rate of rise and fall for all rural sections studied was 1.22. The results reported for this study reflect the average values for all highway sections without regard to variations in rise and fall.

Vehicle Weight Groupings

It was not possible to set up a precise schedule of vehicles and gross vehicle weights to be observed, since the demand for commercial freight in normal operations did not permit the selection of a specified gross vehicle weight. It was hoped that the plan to observe a minimum of three vehicles for each of several weight-class intervals would result in an even distribution within the class interval. This, however, was not the case and it was necessary to form new gross vehicle weight groupings in the analyses. The most significant groupings for the line-haul and pickup and delivery vehicles, together with the number of trips and total miles observed in each grouping, are shown in Table 3. It is evident that sizable mileages were logged in each type of service and that a reliable base exists for the development of fuel consumption and travel time rates.

Engine Size Groupings

The gasoline-powered vehicles observed on line-haul operations were grouped, for purposes of analyses, into three engine displacement size groups consisting of 302-406 cu in., 450-549 cu in., and 590 cu in. Vehicles with 743-cu in. displacement diesel engines were also studied as a group. The net horsepower for the four groups of engine displacement were determined to be 140 horsepower for the 302-406-cu in. size group, 171 horsepower for the 450-549-cu in. size group, 225 horsepower for the 590-cu in. size group, and 200 for the 743-cu in. diesel engine.

A grouping of city pickup and delivery vehicles by power characteristics was considered but found impractical for the purposes of analysis because of the irregularity of the service, which resulted in wide variations in the speed of operation, number of deliveries, stops per mile, idling time, and the rate of discharge of cargo.

AVERAGE FUEL CONSUMPTION RATES

A summary of the average rates of fuel consumption is shown in Table 4. Two fuel consumption values are shown for each group of vehicles with similar power characteristics. One is the actual rate and the other is the computed rate (Fig. 1) as straight line relationships, which were derived from the actual average values. The rates of rise and fall were 1.18 ft per 100 ft for the 302-406-cu in. group, 1.20 ft per 100 ft for the 450-549-cu in. group, 1.29 ft per 100 ft for the 590-cu in. group, and 1.22 ft per 100 ft for the 732-cu in. diesel engine. The variation in rise and fall appeared to be rather insignificant and therefore a valid comparison of the motor-fuel consumption rates for the several groupings of vehicles is practical.

TABLE 3

NUMBER OF TRIPS AND TOTAL MILES OBSERVED FOR GASOLINE- AND DIESEL-POWERED MOTOR VEHICLES

Weight Class (lb)	Average Gross Vehicle Weight	Gasoline Vehicles		Diesel Vehicles	
		Number of Trips	Total Miles Observed	Number of Trips	Total Miles Observed
Line-haul vehicles:					
17,000-18,999	17,000	15	1,111	-	-
19,000-23,999	21,300	55	3,085	-	-
24,000-29,999	27,000	25	2,398	1	60
30,000-37,999	34,500	123	11,740	6	545
38,000-47,999	42,000	98	8,906	12	1,641
48,000-53,999	51,200	64	5,381	8	668
54,000-61,999	59,500	42	3,520	9	1,125
62,000 and over	67,900	31	2,111	12	1,503
Total	-	453	38,252	48	5,542
City pickup and delivery vehicles:					
4,400- 4,999	4,600	13	231	-	-
5,000- 8,999	6,000	25	1,172	-	-
9,000-12,999	10,500	89	1,775	-	-
13,000-16,999	14,500	51	603	-	-
17,000-20,999	18,500	6	67	-	-
21,000-24,999	22,500	1	33	-	-
25,000-30,499	27,500	80	480	-	-
30,500-36,999	33,300	18	232	-	-
37,000-39,999	38,500	3	81	-	-
40,000-45,999	42,100	5	171	-	-
51,000-51,999	51,300	3	154	-	-
54,000-59,999	57,000	40	64	-	-
62,000-69,999	66,000	32	70	-	-
Total	-	366	5,133	-	-

It may be noted that the vehicles with the larger power plants used appreciably more gasoline for a given average weight. For instance, Figure 1 shows that gasoline-powered vehicles in the lowest engine power group with an average GVW (gross vehicle weight) of 40,000 lb had a fuel-consumption rate of 0.202 gal. per mi. This compares with 0.233 gal per mi for vehicles in the medium power group, which represents a 15 percent increase; and with 0.262 gal per mi for vehicles in the largest gasoline-engine power group, a 30 percent increase.

Also, the fuel-consumption rate increased with gross vehicle weight. In the medium power group, for instance, a vehicle weighing 20,000 lb consumed approximately 0.181 gal per mi, while a vehicle weighing 60,000 lb consumed 0.285 gal per mi. However, despite the fuel-consumption rate increase with gross vehicle weight increase, there was a decrease in the fuel consumption per 10,000 lb of gross vehicle weight. For example, in the medium power group a 20,000-lb vehicle consumed 0.181 gal per mi or 0.091 gal per mi per 10,000 lb, while a 60,000-lb vehicle which consumed 0.285 gal per mi actually consumed only 0.048 gal per mi per 10,000 lb, indicating that as gross

TABLE 4

SUMMARY OF FUEL-CONSUMPTION RATES FOR LINE-HAUL TRUCKS OPERATING OVER RURAL HIGHWAY[a]

Gross Vehicle Weight (lb)	Fuel-Consumption Rates (gal/mi)							
	302-400 Cu In. Gasoline (140 hp)		450-549 Cu In. Gasoline (171 hp)		500 Cu In. Gasoline (225 hp)		743 Cu In. Diesel (200 hp)	
	Actual	Computed[b]	Actual	Computed[b]	Actual	Computed[b]	Actual	Computed[b]
17,000	0.150	0.154	0.152	0.173	-	-	-	-
21,300	0.163	0.163	0.189	0.185	-	-	-	-
27,000	0.170	0.175	0.210	0.200	0.243	0.241	0.146	0.153
34,500	0.196	0.191	0.229	0.219	0.247	0.253	0.176	0.162
42,000	0.214	0.207	0.246	0.239	0.278	0.266	0.176	0.171
51,200	0.233	0.226	0.256	0.263	0.273	0.280	0.164	0.182
59,500	0.233	0.244	0.289	0.285	0.287	0.294	0.189	0.193
67,900	-	-	0.298	0.307	0.314	0.307	0.212	0.203

[a] Average rate of rise and fall, 1.2 ft per 100 ft.

[b] Computed rates are based on the following formulas: 302-406 cu in., 0.1177+0.00212W; 450-549 cu in., 0.1288+0.00262; 590 cu in., 0.1975+0.00162W; and 743 cu in., 0.1194+ 0.001229W. (W=GVW in thousands of pounds.)

vehicle weight is increased the fuel economy per unit of gross weight is improved.

Gasoline and Diesel Fuel Comparison

For the same gross vehicle weight averages, the diesel-powered vehicles consumed considerably less fuel than the gasoline-powered vehicles with approximately the same power characteristics. For exampl a vehicle with a 590-cu in. gasoline engine and an average GVW of 60,000 lb consume approximately 0.294 gal per mi, while a vehicle with a 743-cu in. diesel engine and a similar weight consumed 0.193 gal per mi. In this case the diesel consumption rate was 66 percent of the gasoline consum tion rate. However, the foregoing comparison does not represent results obtaine over identical routes.

A comparison of gasoline and diesel fue consumption rates for vehicles traveling over identical routes was possible from th data obtained in the State of Washington. The diesel-powered combination units traveled a total of 5,542 mi on 48 trips. Twenty-eight of these trips, totaling a distance of 3,617 mi, were traveled over the same routes used by gasoline-powered trucks on 32 trips, totaling 3,966 mi. By grouping gross vehicle weights into class intervals, it was possible to obtain averag consumption values that were directly com parable with respect to rise and fall rates and gross vehicle weight. Of the vehicles

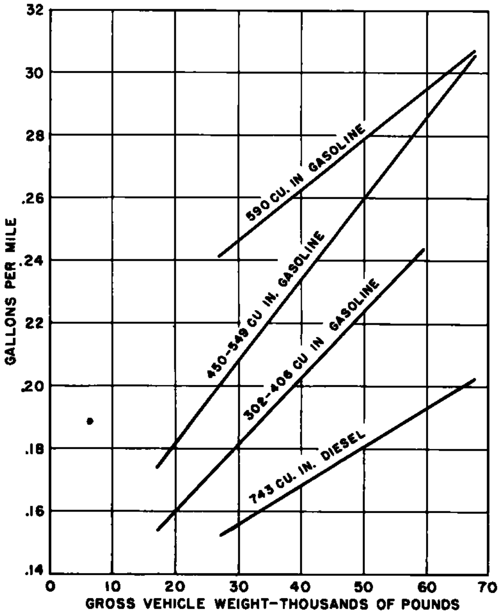


Figure 1. Motor-fuel consumption rates of rural line-haul trucks by size of engine for 1.2 rate of rise and fall.

vith gasoline engines, 21 trips were made by vehicles with engines of 461-cu in. dis-lacement, 3 with engines of 450-cu in. displacement, and 8 with engines of 590-cu in. isplacement. For the 32 trips, the average net horsepower of the vehicles with gaso-ine engines was 199 hp, as compared with the 200-hp diesel engines. The results are ummarized in Table 5 and the relationships derived from the average rates of fuel onsumption are shown in Figure 2.

TABLE 5

GASOLINE AND DIESEL FUEL CONSUMPTION RATES FOR LINE-HAUL TRUCKS TRAVELING OVER THE SAME RURAL ROUTES[a]

ross Vehicle Weight (lb)	Number of Trips	Total Miles Traveled	Total Gallons Con-sumed	Consumption			
				Mi/Gal		Mi/Gal	
				Actual	Comp.[b]	Actual	Comp.[c]
asoline:							
30,400	1	63	14.34	4.393	4.452	0.228	0.221
36,800	2	284	66.77	4.253	4.224	0.235	0.237
46,800	7	993	254.89	3.896	3.867	0.257	0.263
57,900	14	1,831	529.23	3.460	3.472	0.289	0.292
62,500	1	142	42.45	3.345	3.308	0.299	0.303
68,300	7	653	213.25	3.062	3.101	0.327	0.318
otal or avg	32	3,966	1,120.93	3.538	-	0.283	-
iesel:							
32,600	1	65	9.15	7.104	6.723	0.141	0.158
41,500	7	923	163.89	5.632	6.229	0.178	0.168
51,600	6	618	105.17	5.876	5.668	0.170	0.179
58,100	8	1,146	219.87	5.212	5.306	0.192	0.187
69,900	6	865	182.15	4.749	4.651	0.211	0.200
otal or avg	28	3,617	680.23	5.317	-	0.188	-

Average rate of rise and fall, 1.17 ft per 100 ft. [b]Computed miles-per-gallon rates re based on the following formulas: gasoline, 5.53486-0.03563W; diesel, 8.5345-0.0556 . [c]Computed gallons-per-mile rates are based on the following formulas: gasoline, .14217+0.00258W; diesel, 0.12106+0.00113W. (W=GVW in thousands of pounds.)

For a GVW of 70,000 lb (Fig. 2) the asoline consumption rate was 0.322 gal er mi, or 3.11 mi per gal; and the diesel consumption rate was 0.200 gal per i, or 5.00 mi per gal. In effect the diesel-powered vehicles traveled about 53 ercent more miles per gallon of fuel than id the gasoline-powered vehicles. A imilar comparison for a GVW of 50,000 b indicated that the diesel-powered vehicles traveled about 52 percent more iles per gallon of fuel than gasoline-owered vehicles. A comparison of the verage rate for all gasoline-powered ehicles for all 32 trips with that for all iesel-powered trips shows that 51 percent more mileage was obtained by diesel-owered vehicles on the same gallonage of uel. This relative value is based on the

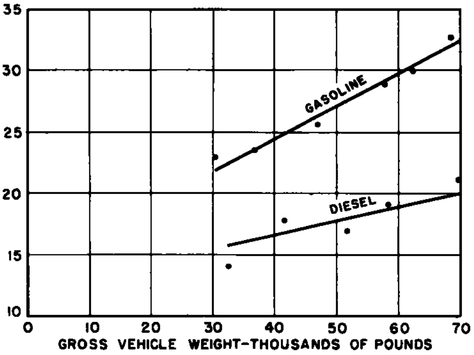


Figure 2. Comparison of gasoline and diesel fuel consumption rates of rural line-haul trucks operating over the same routes.

total miles traveled and total gallons consumed (Table 5). The average diesel consumption rate of 0.188 gal per mi was 66 percent of the average gasoline consumptio rate of 0.283 (Fig. 1).

Rural and Urban Comparison

The fuel consumption rates for all gasoline- and diesel-powered trucks observed i line-haul rural and urban travel are shown in Table 6. The computed rates, obtained from the straight-line relationships shown in Figure 3, were derived from the averag actual rates. The fuel consumption rates for gasoline-powered vehicles in urban trav appear to be considerably greater than the gasoline consumption rates in rural travel. The fuel consumption percentage differences in rural and urban travel range from a 25 percent difference for a GVW of 20,000 lb to a 32 percent difference for a GVW of 70,000 lb.

TABLE 6

GASOLINE AND DIESEL FUEL CONSUMPTION RATES FOR RURAL AND URBAN LINE-HAUL OPERATIONS

Gross Vehicle Weight (lb)	Fuel Consumption Rates (gal per mi)							
	Gasoline Vehicle				Diesel Vehicle			
	Rural		Urban		Rural		Urban	
	Actual	Comp.[a]	Actual	Comp.[a]	Actual	Comp.[a]	Actual	Comp
17,000	0.150	0.152	0.175	0.189	-	-	-	-
21,300	0.166	0.165	0.218	0.207	-	-	-	-
27,000	0.184	0.182	0.232	0.230	-	-	-	-
34,500	0.206	0.204	0.263	0.261	0.176	0.167	0.147	0.14
42,000	0.229	0.227	0.291	0.292	0.176	0.174	0.179	0.16
51,200	0.243	0.254	0.332	0.330	0.164	0.184	0.180	0.19
59,500	0.280	0.279	0.365	0.364	0.189	0.192	0.225	0.22
67,900	0.308	0.304	0.395	0.399	0.212	0.200	0.255	0.25

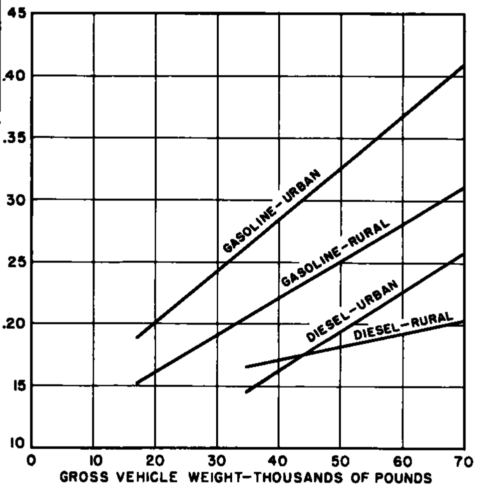
[a] Computed rates are based on the following formulas: gasoline, rural, 0.10115+0.00299W gasoline, urban, 0.11865+0.00413W; diesel, rural, 0.13180+0.00101W; diesel, urban, 0.03924+0.00310W. (W=GVW in thousands of pounds.)

A comparison of the rural and urban fuel consumption rates for diesel-powered trucks observed in line-haul service, however, shows that there was little percentage difference where the GVW was from 40,000 to 50,000 lb, but where the GVW approach 70,000 lb there was a 27 percent higher consumption rate in urban travel.

Again, Figure 3 shows the fuel consumption advantage of the diesel engine.

City Pickup and Delivery Vehicles

City pickup and delivery motor-vehicle gasoline consumption rates are shown in Figure 4 for two different rates of rise and fall. The straightline values were derived from actual average values. In Seattle, where the rate of rise and fall averaged 2.1 f per 100 ft, the gasoline consumption was 18 percent higher at 10,000-lb GVW and 14 percent higher at 40,000-lb GVW than the consumption rate in the other three cities where the rise and fall was about 0.5 ft per 100 ft. It will be noted that gasoline consumption increased as gross vehicle weights increased, as was the case for line-haul operation. It may also be noted that the consumption rates approximate closely the values shown in Figure 3 for gasoline-powered vehicles in urban line-haul service. Consumption rates for wholesale motor-fuel delivery vehicles are shown separately in Figure 4 as they were not considered for this study as multi-stop city delivery vehicles.



igure 3. Comparison of rural and urban
otor-fuel consumption rates of line-haul
trucks.

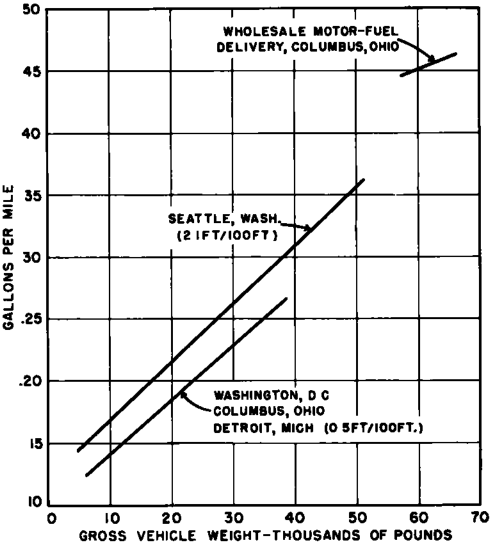


Figure 4. Motor-fuel consumption rates at different rates of rise and fall for city delivery vehicles.

omparison with Previous Studies

Fuel-consumption rates obtained in his study have been compared with results found in two previous studies—a 1937 Oregon tudy (1), and a 1948 Pennsylvania study (2). The comparison of these consumption ates are given in Table 7 and shown graphically in Figure 5. For comparative pur-oses, the average consumption rates found in the 1958 study, rather than the rates ound for the individual groupings of vehicles, were used. Considering the entire gross ehicle weight range, the consumption rates obtained in the 1958 study were found to e approximately 10 percent higher than corresponding data reported in the Pennsylvania

TABLE 7

COMPARISON OF MOTOR-FUEL CONSUMPTION RATES OF THREE STUDIES OF TRUCKS OPERATING OVER RURAL HIGHWAYS[a]

	Motor-Fuel Consumption (gal/mi)							
	1958 Five-State Study					1937 Oregon Study		1948 Pennsylvania Study
	Gasoline Vehicles							
	Engine Displacement (cu in.)							
Average Gross Vehicle Weight (lb)	302-406	450-549	590	Average	Diesel Veh	Gasoline Veh	Diesel Veh	Gasoline Veh
20,000	0.160	0.181	-	0.161	-	-	-	0.135
30,000	0.181	0.207	0.246	0.191	0.156	0.203	0.128	0.170
40,000	0.202	0.234	0.262	0.221	0.169	0.251	0.157	0.200
50,000	0.224	0.260	0.279	0.251	0.181	0.295	0.183	0.228
60,000	0.245	0.286	0.295	0.281	0.193	-	-	0.255
70,000	-	0.312	0.311	0.311	0.205	-	-	0.282

ate of rise and fall for Oregon data was 1.0; for the other study data it was 1.2.

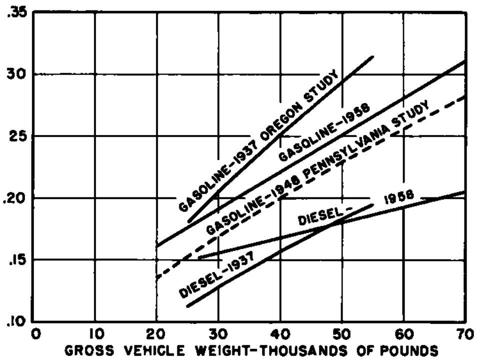


Figure 5. Comparison of data from 3 reports on motor-fuel consumption rates of line-haul trucks.

study, which were obtained by controlled tests on new vehicles. The higher motor-fuel consumption rates in commercial ope ation as compared with the controlled test operation can be ascribed partly to a grea er prevalence of speed changes in commercial operation than had been encounter ed in the test truck operation, and partly to the fact that the commercial truck engines were not kept to the high degree of performance efficiency as the controlled test trucks, which were regularly maintained by factory mechanics.

It appears that the results in the Pennsylvania study, which covered a much wid range of gross vehicle weights and rates o rise and fall, may be increased by 10 percent and used to represent the fuel characteristics of vehicles now in actual commercial service.

Gasoline consumption rates in the 1937 Oregon study and the 1958 study were quite similar in the lower gross vehicle weights but the Oregon study gasoline consumption rates were higher by nearly 20 percent for the gross vehicle weights at 50,000 lb. Diesel-fuel consumption figures in the Oregon study were lower than the 1958 study diesel consumption rates by as much as 30 percent in the lower weight ranges but were almost identical for gross vehicle weights at 50,000 lb.

AVERAGE TIME CONSUMPTION RATES

The travel time consumption rate of commercial motortrucks in rural line-haul ope ation was analyzed in two different ways. The first analysis was made to determine th travel time of vehicles for all trips, without considering rise and fall or traffic frictio This analysis was made in a manner similar to that used for determining the fuel-consumption rates. Actual and computed travel time consumption rates are given in Tabl 8. In Figure 6, straight lines are used to relate travel time and gross vehicle weight for each of the engine characteristic groups. It is seen that vehicles with engine displacement size of 302-406 cu in., which traveled at a rate of 1.59 min per mi with a GVW of 30,000 lb, traveled at 1.85 min per mi when the GVW was 60,000 lb. Vehicle in the 450-549-cu in. engine size group traveled 1.46 and 1.72 min per mi at corresponding weights. The straightline relationships for these two engine groups were approximately parallel, indicating a constant rate of increase in travel time consumed

TABLE 8

RATES OF TRAVEL TIME CONSUMPTION FOR TRUCKS IN RURAL LINE-HAUL SERVICE IN FIVE STATES, 1957-58[a]

Gross Vehicle Weight (lb)	Time-Consumption Rates (min/mi)								
	302-406 cu in., Gasoline (140 hp) Engine		450-549 cu in., Gasoline (171 hp) Engine		590 cu in., Gasoline (225 hp) Engine		Gasoline Engine Average–Actual	743 cu in., Diesel (200 hp) Engine	
	Actual	Computed[b]	Actual	Computed[b]	Actual	Computed[b]		Actual	Computed[b]
17,000	1.434	1.478	-	-	-	-	1.434	-	-
21,300	1.506	1.514	-	-	-	-	1.506	-	-
27,000	1.649	1.563	1.467	1.436	1.606	1.593	1.592	-	-
34,500	1.619	1.627	1.520	1.501	1.590	1.626	1.596	1.636	1.567
42,000	1.687	1.691	1.526	1.566	1.662	1.659	1.620	1.460	1.571
51,200	1.728	1.769	1.626	1.645	1.738	1.699	1.692	1.616	1.576
59,500	1.859	1.840	1.660	1.717	1.724	1.735	1.696	1.569	1.580
67,900	-	-	1.859	1.790	1.761	1.771	1.797	1.598	1.585
Average	1.638	-	1.586	-	1.696	-	1.625	1.559	-

[a] Average rate of rise and fall, 1.2 ft per 100 ft.

[b] Computed rates are based on the following formulas: 302-406 cu in., 1.333+0.008516W; 450-549 cu in., 1.203+0.008642W; 590 cu in., 1.476+0.004347W; and 743 cu in., 1.549+0.000526W. (W=GVW in thousands of pounds.)

with increase in gross vehicle weights.

The vehicles with 743-cu in. diesel engines maintained a much more constant speed with respect to gross vehicle weights than those with the larger gasoline engines, showing an increase of only 0.02 min per mi from 30,000- to 60,000-GVW.

The travel time consumption rates of commercial vehicles in urban line-haul and in city pickup and delivery service are shown in Table 9. Although time-consumption rates were not found to vary in a uniform manner with gross vehicle weight, it was noted that as the power characteristics of engines increased the time consumption decreased. Referring to the average time-consumption rates for all gasoline-powered vehicles (Tables 8 and 9) it will be seen that vehicles in rural line-haul service traveled at an average rate of 1.625 min per mi, or 36.9 mph; vehicles in urban line-haul traveled at 3.156 min per mi or 19.0 mph; and all city pickup and delivery vehicles at 5.443 min per mi or 11.0 mph. Similar figures for diesel-powered vehicles were 1.559 min per mi, or 38.5 mph for rural line-haul operation, and 2.740 min per mi, or 21.9 mph for urban line-haul operation.

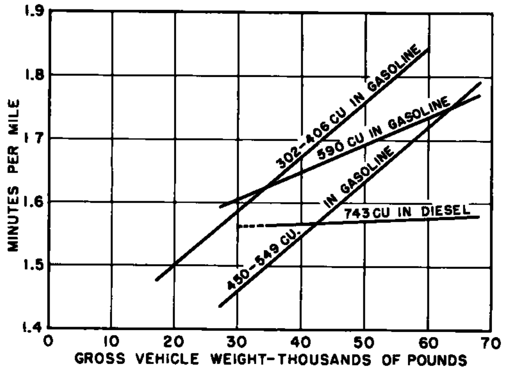


Figure 6. Comparison of average time consumption rates of rural line-haul trucks by engine size for 1.2 rise and fall.

Average Speeds in Free-Flowing Traffic

The second analysis made of travel time for rural line-haul operations involved the desired speeds at which vehicles traveled in free-flowing traffic when they apparently were unrestricted except by speed limits or safe driving speeds. It was possible to study the speeds by analyzing time-consumption rates on certain highway sections in Ohio and Washington where trucks traveled without experiencing more than two slowdowns per mile and no stops. The average operating speeds under these conditions were related to the four groupings of engine sizes and power characteristics and to gross vehicle weight (Table 10 and Fig. 7).

Travel time, in minutes per mile, increased sharply as the gross weight of gasoline-powered commercial trucks in the lowest range of engine size and power increased. Conversely, of course, average road speeds decreased sharply. However, as the engine horsepower and gross vehicle weight increased, the travel time increase was less pronounced. This is reflected by the steepness of the slope of the lines per 10,000-lb

TABLE 9

SUMMARY OF TRAVEL TIME CONSUMPTION RATES FOR URBAN LINE-HAUL FREIGHT VEHICLES AND CITY DELIVERY VEHICLES

Time-Consumption Rates (min/mi) for Urban Line-Haul Vehicles						Time-Consumption Rates (min/mi) for City Delivery Vehicles	
Gross Vehicle Weight (lb)	302-406 Cu In. Gasoline Engine	450-549 Cu In. Gasoline Engine	590 Cu In. Gasoline Engine	Average Gasoline Engine	743 Cu In. Diesel Engine	Gross Vehicle Weight (lb)	All Gasoline Engines
17,000	3.207	2.868	-	3.105	-	4,600	8.854
21,300	2.909	3.473	-	2.987	-	6,000	5.736
17,000	3.388	2.818	2.957	3.182	2.556	10,500	6.181
34,500	3.260	2.973	2.378	3.136	2.353	14,500	5.125
42,000	3.274	3.082	2.728	3.167	2.597	18,500	4.500
51,200	3.513	2.914	2.283	3.253	2.901	22,500	5.502
59,500	4.533	2.987	2.532	3.435	3.043	27,500	4.847
67,900	4.486	2.630	2.815	3.039	2.784	33,300	4.184
Average	3.306	2.997	2.671	3.156	2.740	Average	5.443

TABLE 10

AVERAGE SPEEDS OF GASOLINE- AND DIESEL-POWERED TRUCKS, EXPERIENCING LESS THAN TWO SLOWDOWNS PER MILE AND NO STOPS IN OHIO AND WASHINGTON RURAL LINE-HAUL OPERATION[a]

Gross Vehicle Weight (lb)	Time-Consumption Rates[b]							
	302-406 Cu In. Gasoline Engine		450-549 Cu In. Gasoline Engine		590 Cu In. Gasoline Engine		743 Cu In. Diesel Engine	
	Min/mi	Mph	Min/mi	Mph	Min/mi	Mph	Min/mi	Mph
17,000	1.34	44.8	-	-	-	-	-	-
21,300	1.38	43.5	-	-	-	-	-	-
27,000	1.43	42.0	1.35	44.4	1.36	44.1	-	-
34,500	1.50	40.0	1.40	42.9	1.38	43.5	1.483	40.5
42,000	1.57	38.2	1.44	41.7	1.40	42.9	1.486	40.4
51,200	1.65	36.4	1.50	40.0	1.43	42.0	1.490	40.3
59,500	-	-	1.56	38.5	1.45	41.4	1.493	40.2
67,900	-	-	1.61	37.3	1.47	40.8	1.497	40.1

[a] Average rate of rise and fall, 1.3 ft per 100 ft.

[b] Rates were computed by the following formulas: 302-406 cu in., mpm, 1.18035+0.00916W; mph, 49.1986-0.25747W. 450-549 cu in., mpm, 1.17435+0.00643W; mph, 49.2757-0.17956W. 590 cu in., mpm, 1.2909+0.00264W; mph, 46.0567-0.07742W. 743 cu in., mpm, 1.4696+0.00040W; mph, 41.1719-0.01905W. (W=GVW in thousands of pounds.)

increase in GVW. For the lowest gasoline-powered engine size, the rate increased 0.09 min per mi for each increase of 10,000 lb in GVW. For the medium gasoline-powered engine size, the corresponding increase was 0.06 min per mi, and for the 590-cu in. engine gasoline-powered vehicles and the diesel-powered vehicles the increases were 0.03 and 0.01 min per mi, respectively.

The relative performance of the four groupings of vehicles (Fig. 7) point up the consideration that while better fuel economy is attained with smaller engines for the gross vehicle weights investigated, the penalty of using smaller engines is an increase in travel time consumption at higher vehicle weights.

Time-Consumption Rates Compared

Another important use of the current study data was in comparison with the average time-consumption rates reported in the 1948 Pennsylvania study (2). Travel-time-consumption rates for the two studies are shown in Figure 8, using the average rates for all vehicles.

The time-consumption rates obtained in the 1958 study, considering the average travel time for all conditions of traffic, are labeled "average traffic" (Fig. 8) and were found to be 26 percent higher than corresponding data reported in the Pennsylvania study. A comparison of greater significance, however, can be made between the 1958 study ("free-flowing traffic" and those of 1948 Pennsylvania study, because both were made under similar conditions. The time-consumption rates of

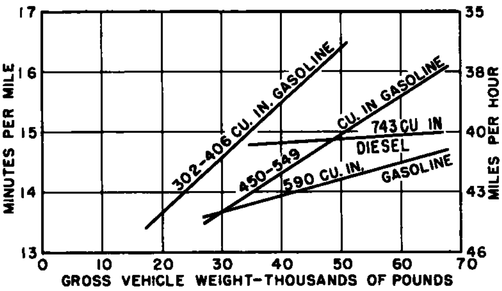


Figure 7. Average time consumption rates for trucks operating in free-flowing traffic on rural line-haul service with an average rate of rise and fall of 1.3 feet per 100 feet.

gasoline-powered trucks traveling in free-flowing traffic were 10 percent higher than corresponding data reported in the Pennsylvania study.

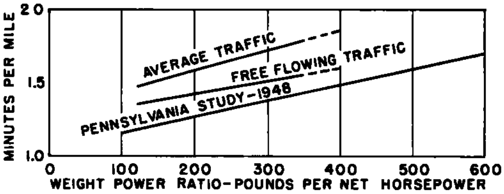


Figure 8. Comparison of 1957-58 travel time rates for rural line-haul gasoline-powered trucks for 1.2 rate of rise and fall with 1948 Pennsylvania study data based on 1.3 rate of rise and fall.

EFFECT OF TRAFFIC ON PERFORMANCE

One of the main objectives of the study was to investigate the effect of varying traffic volumes on the performance of commercial vehicles. Other studies (1 through 4) have made a good start in determining the fuel consumption and travel time for uniform speeds, stops and starts, and slowdowns; and in finding out how certain factors, such as gradient, rise and fall, horizontal curvature, gross vehicle weight, and engine characteristics, affect fuel and time consumption. However, little has been available in the literature as to the effect of varying traffic volumes.

It was hoped that this study would provide a means for estimating the added operating cost brought about by frictions in the traffic stream. The basic approach was one of considering the number of speed changes per mile for varying volume conditions, the percentage of the total number of speed changes that were stops and starts, and the average speed change in terms of miles per hour of a stop or slowdown. It was reasoned that if such information could be provided, the added cost for having to operate other than at a uniform speed could readily be assessed.

Speed Changes per Mile

What are probably the most significant results of this study, speed changes per mile, were computed for trucks with different gross weights operating over three types of rural highways with varying average daily traffic and are shown in Table 11. An attempt was made to develop similar data for urban operation, but the lack of traffic data for the irregular routes traveled made this impossible.

TABLE 11

SPEED CHANGES PER MILE MADE BY TRUCKS OPERATING OVER THREE TYPES OF RURAL HIGHWAYS WITH VARYING AVERAGE DAILY TRAFFIC

Average Daily Traffic	Highway Section Mileage	Number of Trips	Total Miles Traveled	Speed Changes per Mile for Vehicles with Average GVW (1,000 lb)						
				17.0	23.1	27.4	36.3	43.7	52.2	Average
(a) 4-Lane Divided, Controlled Access										
46,700	6.56	54	354.24	1.56	2.05	-	2.38	2.71	2.36	2.19
23,300	3.62	54	195.48	0.62	0.83	-	1.17	1.90	1.99	1.24
12,700	8.19	54	442.46	0.38	0.62	-	0.53	0.66	0.74	0.60
(b) 4-Lane Undivided, Uncontrolled Access										
15,700	31.71	54	1,712.34	1.73	1.79	-	2.12	2.35	2.34	2.03
10,300	48.78	54	2,634.12	1.59	1.55	-	2.07	2.03	2.12	1.82
5,200	5.67	52	153.79	-	1.19	-	1.58	1.47	1.73	1.53
(c) 2-Lane										
8,800	27.30	56	1,528.80	-	-	2.75	2.74	2.61	2.69	2.71
6,000	57.58	56	3,224.48	-	-	2.24	2.14	2.15	2.31	2.18
2,000	20.52	56	1,149.12	-	-	1.59	1.48	1.35	1.70	1.50

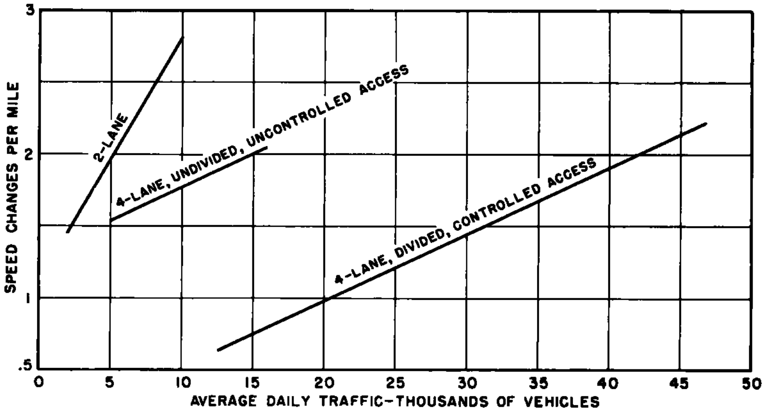


Figure 9. Average speed changes per mile for rural line-haul trucks, by average daily traffic and type of highway.

The average values of speed changes per mile (Table 11) are shown as straightline relationship (Fig. 9) established for the three types of highways. The benefits accruing from the elimination of impediments to free-flowing traffic are clearly illustrated by comparing the speed changes per mile on the 4-lane divided, controlled-access facility with those on the 4-lane undivided, uncontrolled-access facility. For an average daily traffic of 15,000 vehicles, there were an average of 2.0 speed changes per mile on the 4-lane uncontrolled-access highway as compared with a rate of about 0.8 on the 4-lane controlled access highway. Speed changes per mile on 2-lane highways increase from 2.0 to 2.8 where the average daily traffic increased from 5,000 to 10,000. In contrast, speed changes per mile on the 4-lane uncontrolled-access highway increased from 1.5 to 1.8 over the same average daily traffic range.

Data for 4-lane divided highways with no access control were not obtained in sufficie quantity for analysis. It is reasonable to expect that the relationship for this type of highway would fall between that for the two 4-lane highways shown in Figure 9, and would probably lie closer to the 4-lane undivided, uncontrolled-access highway.

Analysis of Speed Changes

Of considerable importance were the percentages of total speed changes representing stops and slowdowns. Speed changes caused by stops and slowdowns are given in Table

TABLE 12

NUMBER AND PERCENTAGE OF SPEED CHANGES OCCASIONED BY SLOWDOWNS AND STOPS OF TRUCKS IN WASHINGTON AND OHIO RURAL AND URBAN LINE-HAUL TRAVEL

	Washington			Ohio			Total		
Speed Changes	Slow-downs	Stops	Speed Changes	Slow-downs	Stops	Speed Changes	Slow-downs	Stops	Speed Changes
Rural line-haul:									
Number	5,358	795	6,153	8,036	935	8,971	13,393	1,731	15,124
Percent	87.1	12.9	100.0	89.6	10.4	100.0	88.6	11.4	100.0
Urban line-haul:									
Number	1,220	613	1,833	1,581	1,688	3,269	2,801	2,301	5,102
Percent	66.6	33.4	100.0	48.4	51.6	100.0	54.9	45.1	100.0

12 from results of the studies made in Ohio and Washington, the only states where stops were recorded. On the average, complete stops occasioned about 11 percent of the speed changes in rural line-haul operations and about 45 percent in urban line-haul operations.

Compiled from the limited data available, an analysis of speed changes in miles per hour was made and it was found that an average stop in rural areas was made from a speed of 26 mph. On city streets the average stop was made from a speed of 18.9 mph. The average change in speed for slowdowns in both rural and urban areas was 11.4 mph.

To illustrate the significance of a speed change in terms of motor-fuel consumption and to confirm that fuel consumption increases with an increasing number of speed changes per mile, gasoline-consumption rates were computed for road sections having different rates of speed change per mile, for different gross-vehicle weights. The average rates are given in Table 13 for the three types of operation.

The straightline relationships established for the data in Table 13 are shown in Figure 10. An increase of one speed change per mile for a vehicle weighing 30,000 lb traveling on a rural highway resulted in an average fuel-consumption increase of 0.010 gal per mi. The corresponding increase for vehicles in urban line-haul operation was

TABLE 13

GASOLINE-CONSUMPTION RATES FOR TRUCKS IN LINE-HAUL AND CITY PICKUP AND DELIVERY OPERATION FOR VARIOUS RATES OF SPEED CHANGE PER MILE

Average Gross Vehicle Weight (lb)	Gasoline-Consumption Rates in Gallons per Mile for Indicated Number of Speed Changes per Mile						
	1	3	4	5	7	9	12
Line-haul, rural:							
17,000	0.134	0.142	-	0.160	0.181	-	
34,500	0.180	0.198	-	0.226	0.250	-	-
42,000	0.200	0.222	-	0.255	0.279	-	-
53,000	0.228	0.257	-	0.300	0.322	-	-
57,000	0.239	0.270	-	0.311	-	-	-
68,000	0.268	0.305	-	-	-	-	-
Average	0.197	0.220	-	0.251	0.279	-	-
Line-haul, urban:							
17,000	0.143	0.149	-	0.153	-	-	-
26,000	0.159	0.180	-	0.198	-	0.324	-
28,000	-	-	-	-	0.246	-	-
52,000	0.206	0.268	-	0.328	0.409	0.426	-
58,000	0.217	-	-	-	-	-	-
59,000	-	0.292	-	-	0.457	-	-
61,000	-	-	-	0.373	-	-	-
62,000	-	-	-	-	-	0.465	-
Average	0.185	0.224	-	0.269	0.333	0.382	-
City pickup and delivery:							
6,000	-	-	0.111	-	-	-	0.145
10,500	-	-	0.131	-	-	-	0.167
18,500	-	-	0.165	-	-	-	0.206
27,500	-	-	0.204	-	-	-	0.250
33,300	-	-	0.229	-	-	-	0.279
Average	-	-	0.143	-	-	-	0.168

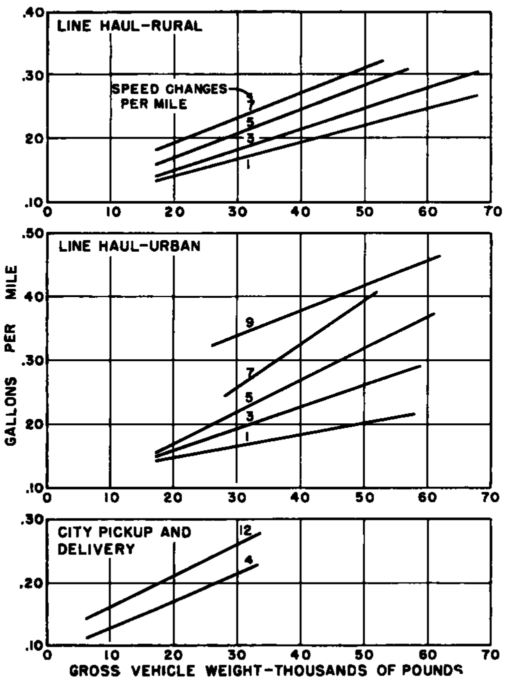


Figure 10. Gasoline consumption rates, by rate of speed change per mile and by gross vehicle weight, for line-haul and city delivery vehicles.

0.021 gal per mi, and for city delivery vehicles the average increase was 0.0056 gal per mi. The greater rate of speed change for urban line-haul operation as compared to rural line-haul operation is probably due to the higher incidence of stops and slowdowns. City pickup and delivery vehicles consume less gasoline per speed change than the urban line-haul vehicles because stops and slowdowns are of lesser magnitude, as evidenced by an average speed of 11 mph.

Also of importance is the indication that fuel consumption attributable to a speed change increases with gross vehicle weight. For example, the fuel consumed for an increase of one speed change per mile for rural line-haul operations was 0.0092 gal for vehicles with 20,000-lb GVW and 0.0142 gal for 50,000-lb GVW.

Data for travel time-consumption rates due to one speed change per mile were also developed (Table 14). The average time-consumption rate did not appear to increase with gross weight but the average value for all gross vehicle weights increased as the speed changes per mile increased.

The average time consumed in one speed change for rural line-haul operation was found to be 0.26 min, or 15.6 sec; for urban line-haul operation 0.27 min, or 16.2 sec; and for city pickup and delivery operation 0.38 min, or nearly 23 sec. In spite of the fact that the speeds from which stops and slowdowns were made were higher in rural than in urban line-haul operation, the time consumption per speed change is about equal, probably because the percentage of total speed changes that are stops is much higher in the urban line-haul.

The increased fuel- and time-consumption rates for one speed change have been developed principally for illustrative purposes, although they can be used in estimating benefits. When data are available from controlled tests (3, 4) on a variety of vehicles, the data herein presented may be refined.

COST OF A SPEED CHANGE

The approximate cost of a stop is included in this article more as a matter of interest than with the idea of establishing valid cost values. Many sections of rural highway studied were traveled by line-haul vehicles without experiencing any stops and with less than two slowdowns per mile. Likewise certain urban sections of highway studied were traveled by line-haul vehicles with a high incidence of stops but with less than two slowdowns per mile.

To estimate the cost of a stop the entire fuel consumption rate for the rural travel with no stops was subtracted from the fuel-consumption rate for urban travel where a high incidence of stops occurred. The difference is attributed solely to the effect of stops because slowdowns were the same in both instances. It should be remembered though, that the average stop was made from 26 mph in rural areas and 19 mph in urban areas. Dividing the total consumption per mile due to traffic stops by the number of stops per mile gave the consumption rates per stop (Table 15). Gasoline consumed per stop showed a definite increase as the GVW increased. For example, if a cost per gallon of fuel of 30 cents is used, the cost of a stop would range from one-half cent for

TABLE 14

AVERAGE TRAVEL TIME-CONSUMPTION FOR TRUCKS IN LINE-HAUL AND CITY PICKUP AND DELIVERY OPERATIONS FOR VARIOUS RATES OF SPEED CHANGES PER MILE

	Average Time Consumption in Minutes per Mile For the Indicated Number of Speed Changes per Mile							Avg Time Lost per Speed Change
Type of Travel	1	3	4	5	7	9	12	(min)
Rural	1.48	1.89	-	2.33	3.05	-	-	0.26
Urban	2.35	2.69	-	3.20	3.81	4.53	-	0.27
City pickup and delivery	-	-	4.39	-	-	-	7.43	0.38

TABLE 15

GASOLINE CONSUMPTION RATES FOR TRUCKS IN LINE-HAUL OPERATION DUE TO TRAFFIC STOPS, BY GROSS VEHICLE WEIGHT

	Gallons per Stop	
Gross Vehicle Weight (lb)	Actual Rate	Computed Rate[a]
17,000	0.014	0.017
21,300	0.030	0.024
27,000	0.034	0.034
34,500	0.044	0.046
42,000	0.054	0.058
51,200	0.076	0.073

[a] Computed from straightline formula 0.001625W-0.0103. (W=GVW in thousands of pounds.)

a GVW of 17,000 lb to more than 2 cents for a GVW of 51,000 lb.

Knowing the number of speed changes saved, the proportion of stops and slowdowns, and the magnitude of each, it is possible to compute the added cost of fuel and travel time of a speed change if the extra fuel and time consumed during the speed change is known. Thus, using speed changes per mile as a measure of congestion, the benefits may be computed that accrue from highway improvements that reduce congestion. It is realized that at present the tool is rough, but it can be refined. This is planned, using digital recorders instead of human observers.

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Time and Fuel Consumption for Highway User Benefit Studies

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Time savings and fuel savings are two of the more important benefits that accrue to users through highway improvement.

User time savings result whenever highway improvements reduce travel distance, permit higher speeds, or reduce the frequency of stop-and-go and slowdown maneuvers. User fuel savings accrue when improvements reduce travel distance, mitigate any of the resistances encountered by moving vehicles, or reduce the frequency of stop-and-go and slowdown operations.

The reduction of travel distance, frequency of stop-and-go and slowdown events, and resistance to movement, as well as increase in speed, resulting from highway improvements can be estimated from data available in published reports and by making traffic studies at locations where improvements are planned. However, information on current savings in time and fuel use associated with these effects of highway improvements have been insufficient for benefit analyses.

During the summer of 1959 the Bureau of Public Roads conducted a study of passenger cars and single-unit trucks to determine the effect of variation of pavement surface type and operating speeds on fuel consumption, and the effect of the elimination of both a stop-and-go and a slowdown operation on fuel and time consumption at various operating speeds. This study also included the determination of the fuel consumed while vehicles are stopped with engine idling. The results of this investigation are presented in this report in graphical and tabular form.

●**THE OBJECTIVE** of highway user benefit studies is the evaluation of the advantages or gains accruing to users as a result of highway improvements. Two of the more important of these advantages are reduced fuel consumption and reduced travel time. The relationship between highway vehicles and the roadway over which they travel is so clos that even small changes in the characteristics of the road will be reflected in the amount of time and fuel needed for highway trips. Minimum values of time and fuel consumption are possible only when the roadway is ideally suited to the vehicle and to the traffic volumes with which it must operate. The ideal highway from the fuel saving point of view would be straight and level, have a smooth surface, and be so designed that the movements of each vehicle would be completely unaffected by the presence of other vehicles. Although in practice no highway can be built to such standards, all improvements are directed towards this ideal. When properly engineered, the improvement of a highway makes it possible for users of that highway to complete trips in less time and frequently with less fuel consumption. Highway user benefit analyses, if they are to be complete and accurate, must include consideration of these savings.

IMPROVEMENTS RESULTING IN TIME AND FUEL SAVINGS

Time savings are brought about through changes in highway facilities which reduce travel distance, the number of stop-and-go and slowdown operations, the amount of time vehicles are stopped at traffic signals, stop signs, etc., as well as through improvements which permit vehicles to be operated safely at higher speeds. Every mile of travel distance eliminated from the trips saves the time needed to cover that distance. Elimination of stop-and-go and slowdown operations saves the time consumed while decelerating and accelerating, that would not be consumed if constant speed could be maintained, as well as the time spent delayed at stops in the case of stop-and-go operations.

Highway changes which improve sight distance or add to highway capacity will generally result in increased nominal highway speeds where nominal highway speed is defined as the modal operating speed of all vehicles of a given class while moving on sections of a highway where they are not slowed or stopped by highway impedances such as traffic signals and sharp curves. On two-lane roads carrying traffic volumes less than practical capacity, the nominal highway speeds of vehicles with low weight horsepower ratios will be increased if sight distances are improved through reduction of rise and fall and curvature, since this will permit a greater number of the drivers wishing to travel at the higher speeds to pass the slower drivers. On any road carrying a traffic volume equal to or greater than practical capacity, the nominal highway speeds of these vehicles will be increased by providing greater capacity through lane widening or construction of additional lanes.

The nominal highway speed for vehicles having high weight horsepower ratios will be increased mainly through reduction of grades.

All improvements which lessen travel distance and the resistances to movement at constant speed plus those which reduce the frequency of stop-and-go and slowdown operations result in fuel savings. Improvements which decrease resistance to vehicular movement reduce the energy requirements needed for operation; this results in fuel savings since the energy output of an engine is provided by the fuel it uses. Reducing the frequency of stop-and-go and slowdown operations reduces fuel consumption by reduring the number of times vehicles must overcome the inertia resistance encountered during accelerations. Furthermore, the elimination of stop-and-go operations saves the fuel that would be used when vehicles are stopped with engine idling.

A reduction in fuel use at any given speed will result from each of the following types of improvement: reduction of surface roughness, reduction of rate of rise and fall, and reduction of curvature. These improvements will frequently permit higher operating speeds which, because of greater air and rolling resistances at higher speeds, will result in an increased rate of fuel consumption; but for the same speed before and after improvement, fuel consumption will be reduced.

The frequencies of stop-and-go and slowdown operations are reduced through the construction of grade separation structures to eliminate intersections at grade, through provision for access control to reduce the number of access points, and through construction of additional lanes where they are necessary to provide capacity to relieve congestion. In addition, the frequency of slowdown operations is reduced when curves sharp enough to require vehicles to reduce speed are removed through alignment changes. Reduction of standing delays is brought about through elimination of intersections at grade or, where conflicting traffic flows at an intersection are not separated, by improving signal or signing arrangements.

TIME AND FUEL SAVINGS IN BENEFIT STUDIES

The saving in either fuel or time consumption due to any one type of highway improvement is the difference between what the amount consumed would be if the improvement were made, and what the amount would be if the improvement were not made. Where two or more types of improvement are made at the same location at the same time, the savings for each can be computed by assuming that the other improvement is completed since, in general, the saving resulting from one improvement is independent of the effect of other improvements. For example, if a highway reconstruction project involving the upgrading of surface and reduction of rise and fall is considered, the savir or difference in fuel consumption for operation on the improved surface rather than on the gravel surface for the new rate of rise and fall will be the same regardless of the fact that the rate of rise and fall had been changed; and the saving due to reduction of rise and fall of the improved surface is unchanged by the fact that the surface had been upgraded.

The difference in fuel saving for the conditions before and after an improvement is a true measure of fuel benefit even when the particular improvement makes possible higher operating speeds which usually increase fuel consumption. An example of this is surface improvement. When a gravel surfaced road is improved with a bituminous or concrete surface, the nominal highway speed will increase due to the smoother running surface. The fuel saving that users will realize through surface improvement is the difference between the fuel consumption on the gravel surface at the nominal highway speed for the gravel road before improvement, and what the fuel consumption would be at the same speed but on the improved surface. The fact that users elect to travel at a higher speed on the improved road with the corresponding increase in the rate of fuel use does not nullify the saving in fuel use at the lower speed made possible by the improvement. Any increase in fuel consumption due to the higher operating speeds should be considered separately and included in benefit studies as a negative fuel benefit.

The analysis of user benefits for any highway improvement project can be made most satisfactorily by computing separately the savings for each type of improvement involved and then summing these savings to obtain total savings. For example, a proposed highway reconstruction project may include three types of improvement: reduction of curvature, lane widening, and a reduction of the average rate of rise and fall. The amount of fuel and time saving obtainable through each may be determined separately, then added together to give the total savings. Care must be exercised when summing these savings that the same saving is not counted twice. An illustration of this danger is where a two-lane gravel road is reconstructed as a four-lane divided highway with a concrete pavement. Both upgrading the surface and increasing the number of lanes permit higher operating speeds with the consequent reduction of time consumption but the time saving for the higher speed can be included only once. The danger of double counting savings is not great, however, when savings are determined directly since the effects responsible for each saving are clearly evident.

The data needed for the computation of annual time and fuel savings are the following

1. The average gross operating weight of each class of highway vehicle that will use the route being studied.
2. The number of vehicles of each class expected to use the road per year.
3. Complete and accurate information on the planned improvement.
4. The effect each type of improvement will have on speeds, frequency of stops and slowdowns, and length of stopped delays.
5. The saving in time and fuel consumption for each class and weight of vehicle due to reduction in distance, reduction of the rate of rise and fall, changes in speed, elimination of stop-and-go and slowdown maneuvers, and the saving in fuel consumption which will result from surface upgrading and reduction of standing time with engine idling.

Items 1 and 2 concern data which are peculiar to each project and should be secured by traffic volume and loadometer studies on the routes where improvements are planne The information on the physical changes to result from construction (Item 3) should be obtained from an investigation of the site and a study of improvement plans. Much information on the effect of improvements on highway operations (Item 4) is available in the literature. Schwender, Normann, and Granum (1) present curves that make it possible to estimate how vehicle speeds will change with variations in traffic volume, lane width, number of lanes, and sight distance. It will, however, frequently be necessary to investigate traffic operations at the site. For example, when a grade intersection is to be eliminated, the best way to obtain data on percentage of drivers delayed and the average length of delay is by measuring these factors at the intersection which is to be eliminated.

In connection with the magnitude of savings of time and fuel due to change in route length, reduction of resistances to movement at constant speeds, and change in traffic operations (Item 5), satisfactory data are incomplete for current vehicle classes and weights. In 1950, Saal reported on a comprehensive study (2) made in 1948 on the time and fuel consumption of trucks as affected by rate of rise and fall. This report contains graphs showing how the time and fuel consumption of vehicles of 10,000 lb and more gross weight varies for changes in rate of rise and fall. Particularly important to benefit studies is a graph published in a subsequent report (3) which demonstrates how the fuel consumption of passenger cars varies with rate of rise and fall.

Useful data are also available in the literature on the fuel consumption of a few vehicle classes for stop-and-go and slowdown operations. These data, however, are limited in scope to only certain vehicle classes and gross operating weights and do not include all ranges of operating speeds; therefore, they are not sufficiently comprehensive for a general benefit analysis.

The lack of complete data on the variation in time and fuel consumption as affected by changes in traffic operations and surface conditions for all vehicle types and weights led to an extensive investigation of the use of time and fuel by highway vehicles during the summer of 1959. The Bureau of Public Roads conducted such a study in the Washington, D.C., area using passenger cars and single unit trucks while the University of Washington made a similar study using buses and tractor-trailer combinations. The objective of both these studies was to measure under controlled conditions the savings in time and fuel consumption by highway vehicles, whether positive or negative, resulting from changes in vehicle speeds, surface upgrading, elimination of stops and slowdowns, and reductions in grades. Sawhill has prepared a report on the results obtained for the tractor-trailer combinations and buses (4).

TIME AND FUEL CONSUMPTION OF PASSENGER CARS AND SINGLE-UNIT TRUCKS

The time and fuel consumption of three vehicles was investigated in the Bureau of Public Road study: a passenger car, a pickup truck, and a two-axle, six-tire, dump truck. These three classes of vehicles accounted for over 92 percent of the total vehicle miles of travel in 1956 and over 98 percent of the vehicle miles of travel accumulated in that year by all highway vehicles other than buses and tractor-semitrailer, or truck full-trailer combinations (5). Data for the passenger car were obtained for one loading condition only. Data for the trucks were taken for enough different loads to cover the lower range of gross vehicle weights for single-unit trucks. The loading for the passenger car tests was two persons, the driver and one observer. The pickup truck was operated with no load except for the driver and one observer, and with a load approximately equal to full load capacity. The dump truck was operated with no load and with one-half full load only. There was not enough time in the test period to include runs with the dump truck at full load.

A popular make of passenger car was selected as being typical. It was a six-cylinder 1957 standard 4-door sedan with a 3-speed automatic transmission. It had been in service for two years and had traveled 30,000 miles. Data on this vehicle are given in Table 1.

A new six-cylinder 1959 popular make 4,900 lb G.V.W. truck with a manual shift was used for the pickup tests, and a six-cylinder 1950 medium-type dump truck which had been in service for 50,000 mi was used for the dump truck tests. Both trucks were checked on a dynamometer previous to the tests and the efficiency of combustion measured with an exhaust analyzer at a wide range of loads. Necessary mechanical repairs

TABLE 1

VEHICLE DATA

	Gross Weight (lb)						
Type of Vehicle	No Load	Half-Full Load	Full Load	No. of Axles	Net Horse power	No. of Cylinders	Trans-mission
Passenger car	3,850	-	-	2	123 at 4,200 rpm	6	Automatic
Pickup truck	3,860	-	5,340	2	120 at 4,000 rpm	6	Manual
Dump truck	10,200	15,300	-	2	89 at 2,800 rpm	6	Manual

were made so that at the time of the tests the vehicles were operating at near optimum efficiency. Data on these trucks are also given in Table 1.

Data on the time and fuel consumption of these vehicles were obtained from a series of test runs made over a nearly straight section of Va. 350 (Shirley Highway) between the Edsall and Fort Belvoir interchanges. This is a divided highway of four 12-ft lanes of portland cement concrete with well built shoulders of firmly compacted gravel 10 ft wide. The test runs were made between two fixed end points set 8,000 ft apart. These points were at nearly the same elevation and the rate of rise and fall between them was less than 0.2 ft per 100 ft.

The following types of test runs were made between end points of the test section:

1. Constant speed runs on the paved surface at indicated speeds of 15, 25, 35, 45, and 55 mph.
2. Constant speed runs on the gravel shoulders at indicated speeds of 15, 25, 35, and 45 mph.
3. Stop-and-go runs on the paved surface at indicated operating speeds of 15, 25, 35, 45, and 55 mph.
4. Slowdown runs (10-mph speed reduction only) on the paved surface at indicated operating speeds of 15, 25, 35, 45, and 55 mph.

Three runs of each type were made for each vehicle and load in each direction at each of the given speeds. The idling fuel consumption was obtained for each vehicle at engine speeds of 450, 550, 650, and 750 revolutions per minute.

The runs were conducted by driving the vehicle over the test section and recording the amount of time and fuel consumed between end points, the direction of travel, time of day, fuel temperature, and run speed as indicated on the vehicle speedometer. For the constant speed runs no other data were taken. On the stop-and-go and slowdown runs the vehicle was brought to a stop or the speed reduced by 10 mph and immediately accelerated back to speed as many times as possible between the end markers, passing each end marker at a constant speed equal to the given run speed. Additional data recorded for these runs were the time during which acceleration took place after each stop or slowdown, the number of stops and slowdowns, and the number of gear changes for each acceleration. The rates of speed change used for both the stop-and-go and slowdown operations during deceleration and acceleration were those of the typical driver under ordinary conditions (6).

Recording the time of day made it possible to determine wind direction and velocity at the time of each run by reference to wind data collected by the Weather Bureau at the nearby Washington National Airport.

The first step in the analysis of the field data was to compute the true speed of each test vehicle for each indicated run speed. The indicated run speeds recorded in the field were as read on the speedometer and generally were in error. They were used during the test because it was easier for the driver to maintain a given speed consistently if he had a definite reading on the speedometer rather than to attempt to hold the speedometer needle at a point where the run speed would be the true speed. The true speed was computed from the known run distance and the run time recorded for the constant speed runs. Since the fuel consumption was measured directly by noting the amount of fuel drawn out of the reservoir of a burette type fuelmeter, no correction was required for errors in the fuel measuring equipment. However, since the volume of fuel measured varied with the temperature of the fuel, a necessary step in the analysis was correction of all fuel readings to what they would have been if the fuel temperature had been 30 C (86 F) at the time of each reading. A temperature of 30 C was chosen for this purpose since it was approximately the average fuel temperature during the period of the tests. Because an accurate stop watch was used to measure the over-all run times from end marker to end marker, it was not necessary to apply any correction to the recorded run times.

APPLICATION OF RESULTS

Corrected fuel consumption values in gallons per mile were computed for each constant speed run on both the paved and gravel surfaces. The average of these values for runs on the paved surface at each speed was determined for each vehicle type and weight and plotted against true speed in Figure 1. Similarly, the average of the corrected fuel

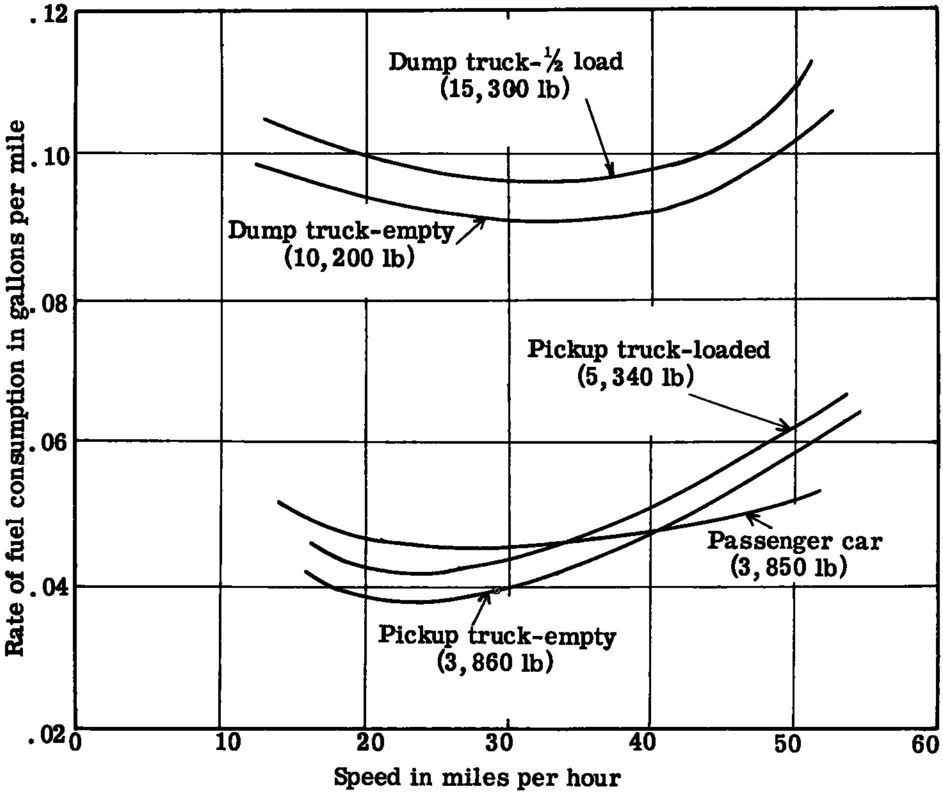

Figure 1. Fuel consumption rates at constant speed on a level, straight, concrete pavement.

consumption values in gallons per mile for runs on the gravel surface were plotted against true speed in Figure 2.

Figures 1 and 2 may be used to estimate the change in rate of fuel consumption in gallons per mile which will result when nominal highway speeds are increased through highway improvement on roads carrying traffic volumes somewhat less than their capacity volume. Since nominal highway speed is the operating speed between points where vehicles are slowed or stopped by highway impedances, the application of these curves is not restricted by the effect of such highway impedances. Wider lanes and improved sight distance are examples of highway improvements which will result in higher nominal highway speeds; the amount of speed increase to be achieved from such improvements can be estimated from previously published curves (1).

Where more lanes are added to a route to provide greater capacity when capacity before improvement is less than the 30th-hr volume, Figures 1 and 2 may be used to estimate the fuel consumption after improvement when vehicle speeds are relatively uniform. However, the lower speeds before improvement are largely due to congestion and are not uniform but include the frequent decelerations and accelerations associated with traffic congestion. The rate of fuel consumption before improvement ma be estimated by adding to the values given in Figures 1 and 2 the amount of additional fuel consumed by slowdowns. The average number of slowdowns may be determined b

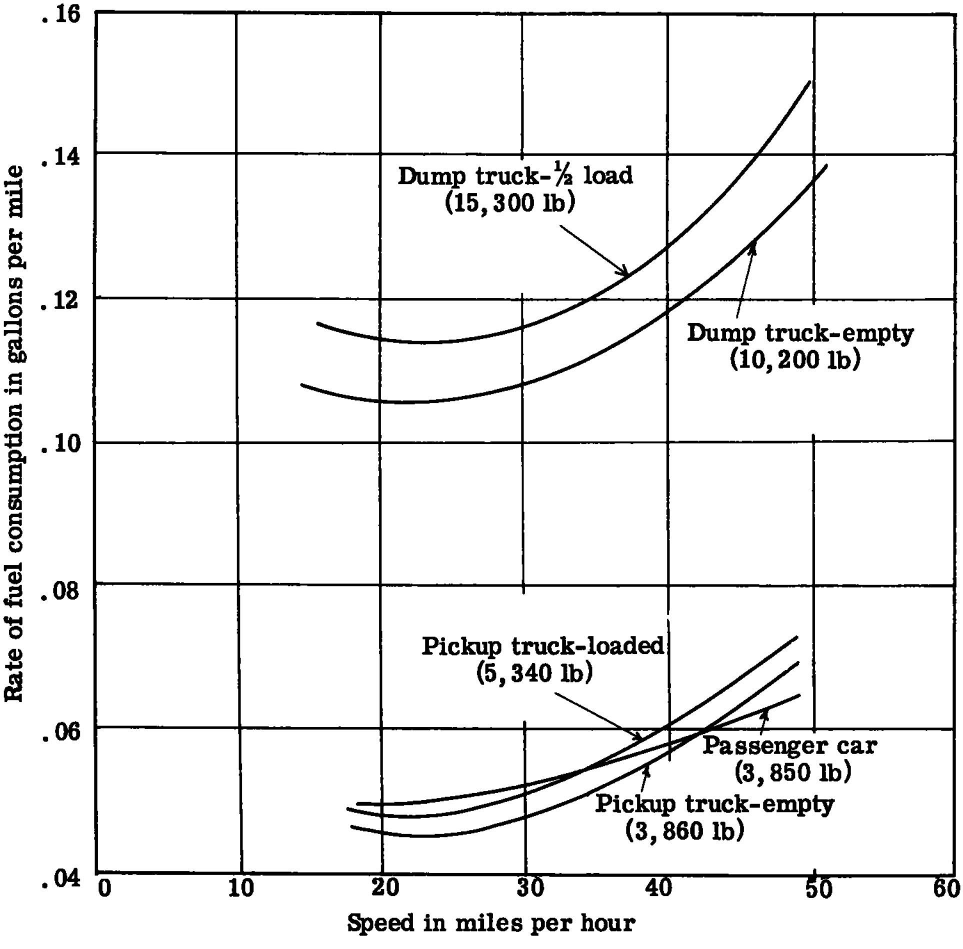

Figure 2. Fuel consumption rates at constant speed on a level, straight, gravel surface.

making suitable speed-delay studies over the route before improvement and the additional fuel consumption due to a slowdown may be estimated using Figure 6.

Figure 3 shows the fuel saving in gallons per mile for operation on a paved surface rather than on a gravel surface at each speed. Most users take advantage of a reduction in road roughness to operate at increased speed on the better surface even though speeds above 35 mph increase fuel consumption. It is at the user's discretion whether he operates on the improved surface at the same speed as on the loose surface and saves on fuel use, or operates at a higher speed and pays for the higher speed and time saving through increased fuel consumption. In either case this saving is made available to the user. The nominal highway speed of modern vehicles on a gravel or loose-surfaced road is between 30 and 35 mph; for any particular loose-surfaced road it should be obtained by making a spot speed study.

The fuel consumed for a stop-and-go operation was found by dividing the number of such operations on each stop-and-go run into the difference between the amount of fuel used for the stop-and-go run and the average amount of fuel used for the constant speed runs on the paved surface at the same speed. This is the amount of fuel used by a vehicle to come to a stop and accelerate back to speed which would be saved if the vehicle could proceed without stopping. Fuel consumption for stop-and-go operations at various speeds is shown in Figure 4. For example, Figure 4 shows that a passenger car uses 0.009 gal of fuel to come to a stop from 30 mph and accelerate back to this speed. At 30 cents per gal, the stop-and-go operation would cost approximately ¼ cent.

The procedure used to compute the time consumption for a stop-and-go operation was the same as that used to compute stop-and-go fuel consumption. Figure 5 shows stop-and-go time consumption as a function of true speed. Time consumption as well as fuel consumption for stop-and-go operations does not include the time or fuel consumed while a vehicle is stopped but only that consumed for the actual stop-and-go maneuver itself.

Idling fuel consumption is given in Table 2. The data were obtained with the vehicle stationary and the engine warm. In the case of trucks, idling fuel consumption was obtained in forward gear with the clutch disengaged. The idling fuel consumption of the passenger car was measured with the transmission in (a) drive position with the brakes set, and (b) neutral position. Idling fuel consumption values in gallons per minute are given for four different engine speeds; the average of these should be used in benefit studies.

TABLE 2

IDLING FUEL CONSUMPTION

	Fuel Consumption (gpm)				
Vehicle	450 rpm	550 rmp	650 rpm	750 rpm	Average
Passenger car:					
Transmission in neutral	0.005	0.006	0.006	0.007	0.006
Transmission in drive	0.005	0.008	0.009	0.014	0.009
Average	0.005	0.007	0.007	0.010	0.007
Pickup truck	0.006	0.007	-	0.008	0.007
Dump truck	0.009	0.010	0.011	0.013	0.011

Figures 4 and 5 and Table 2 are useful for estimating the fuel and time savings which will result if an intersection at grade, controlled by traffic signals or stop signs, is eliminated through construction of a grade separation structure. Additional information needed for computation of benefits in this case are: traffic volumes, nominal highway speed, average length of stopped delays, and percentage of vehicles stopped by traffic signals.

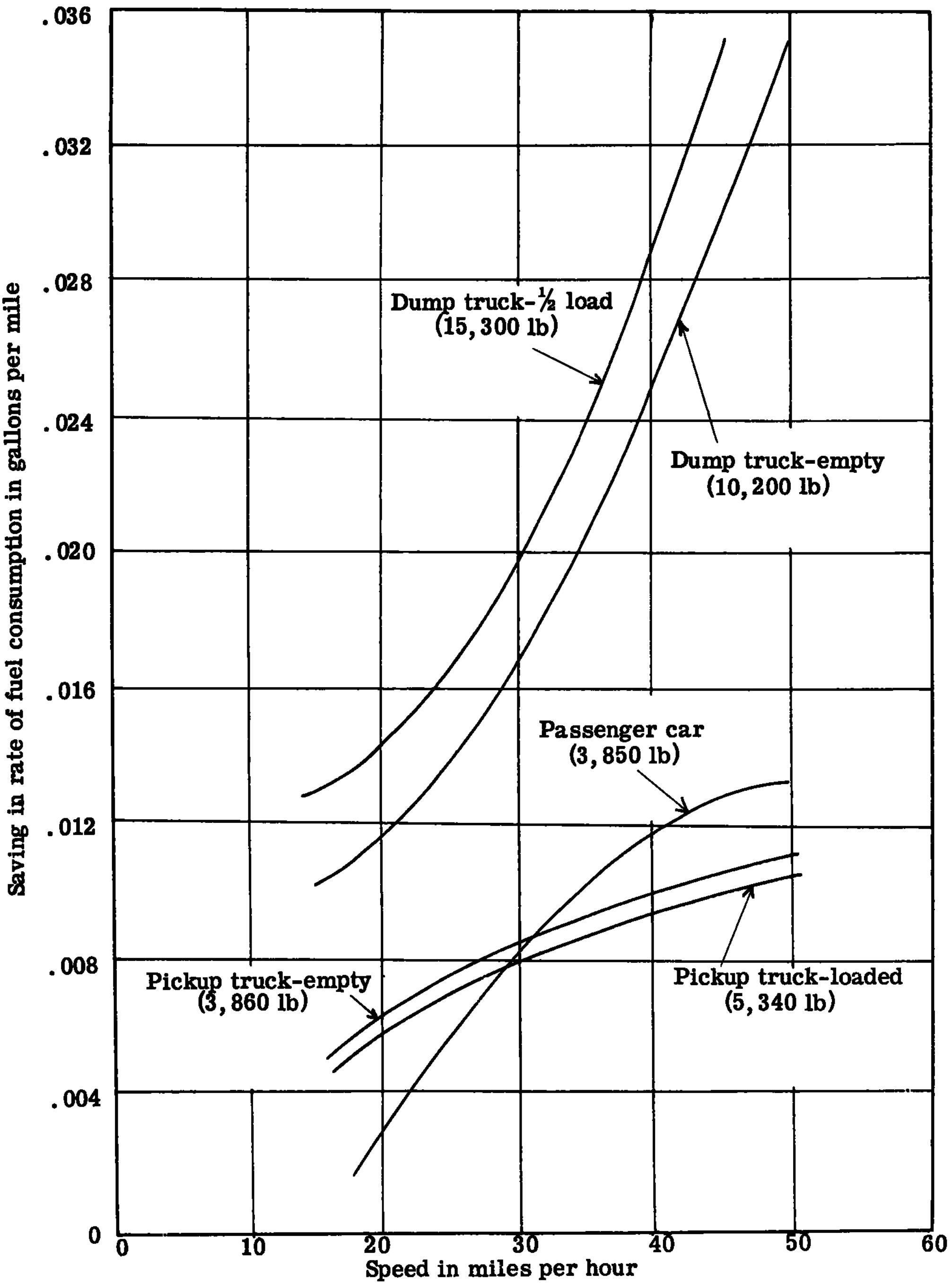

Figure 3. Saving in fuel consumption for operation on concrete pavement rather than on a gravel surface at constant speed.

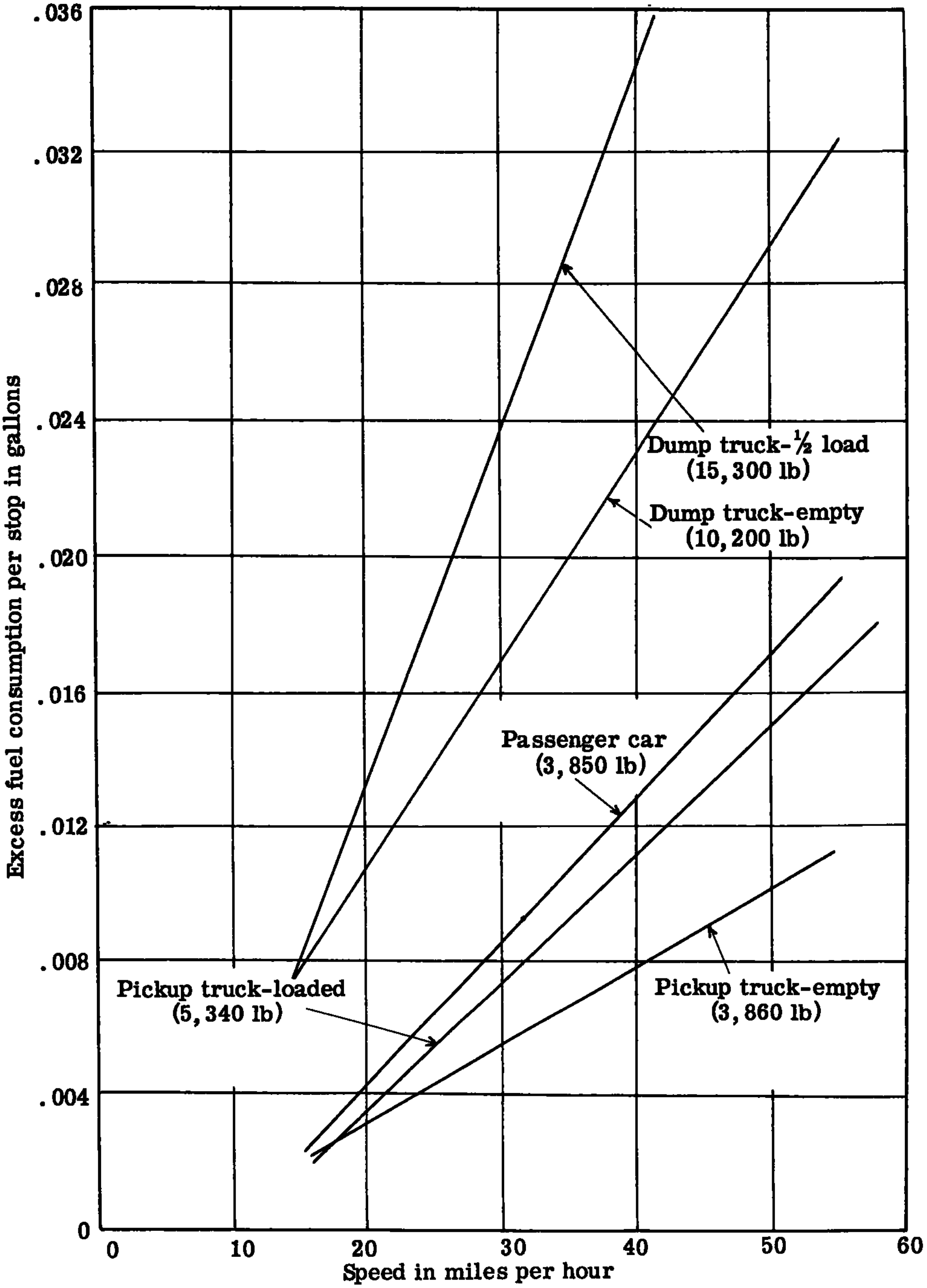

Figure 4. Fuel consumed for coming to a stop from a given speed and immediately accelerating back to that speed in excess of the fuel consumption if given speed were maintained.

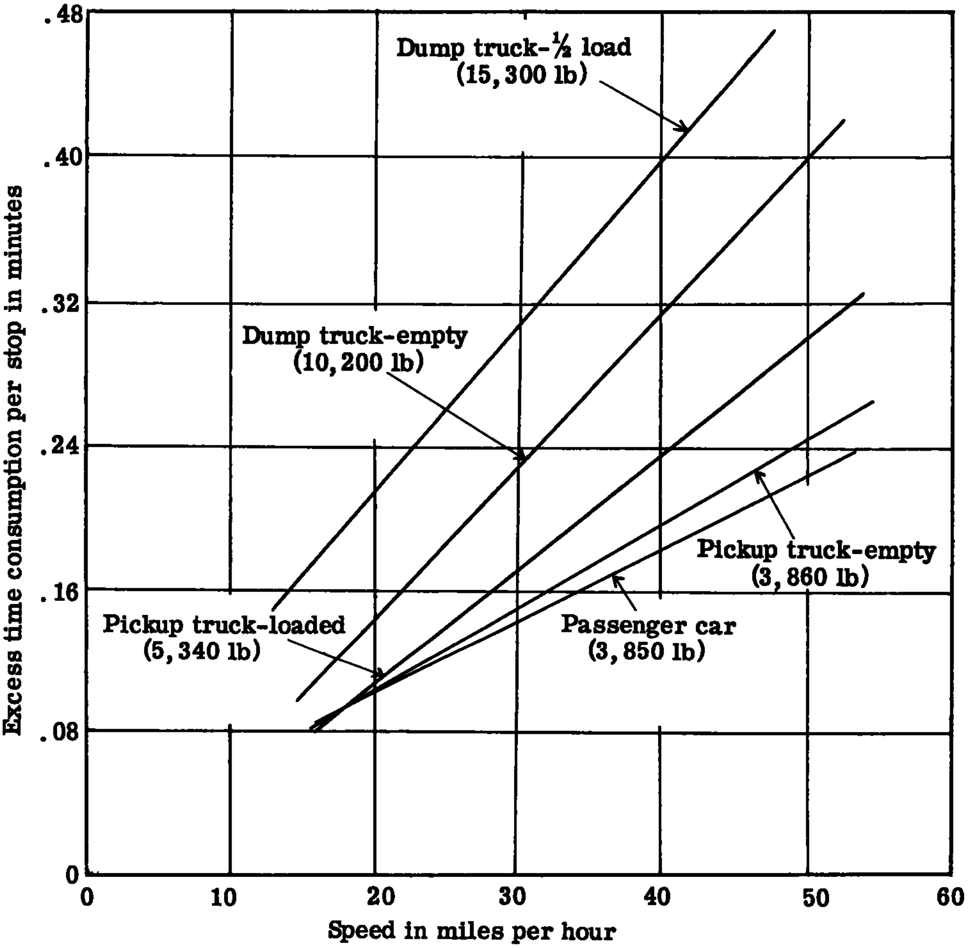

Figure 5. Time consumed for coming to a stop from a given speed and immediately accelerating back to that speed in excess of time consumption if given speed were maintained.

Figure 6 shows the additional fuel consumption for a slowdown of 10 mph at various speeds; Figure 7, the additional time consumption. The procedures used for computing the fuel and time consumption due to slowdowns were similar to those described previously.

Figure 6 shows that the fuel consumption for slowdowns for passenger cars increase continuously for all speeds while the corresponding fuel consumption for trucks decreases somewhat at higher speeds. This difference is largely due to the passenger ca being the only vehicle equipped with automatic transmission. A slowdown is a reductio of speed followed immediately by acceleration back to original speed; it does not include any period of operation at the reduced speed. The applicability of these curves is limited to improvements that eliminate highway impedances which cause vehicles to reduce speed by about 10 mph. This limitation is not serious because most slowdowns of importance in benefit studies are on the order of 10 mph. Preliminary analysis of data taken from extensive speed-delay studies made with a passenger car during the summer months of 1958 and 1959 shows: (a) speed reductions of up to 3 mph are p of uniform driving and are not eliminated through highway improvements, and (b) the average of the speed reductions in excess of 3 mph is about 10 mph. Furthermore, it has recently been established that the average speed reduction of motor trucks when slowed by highway or traffic impedances is 11.4 mph (7).

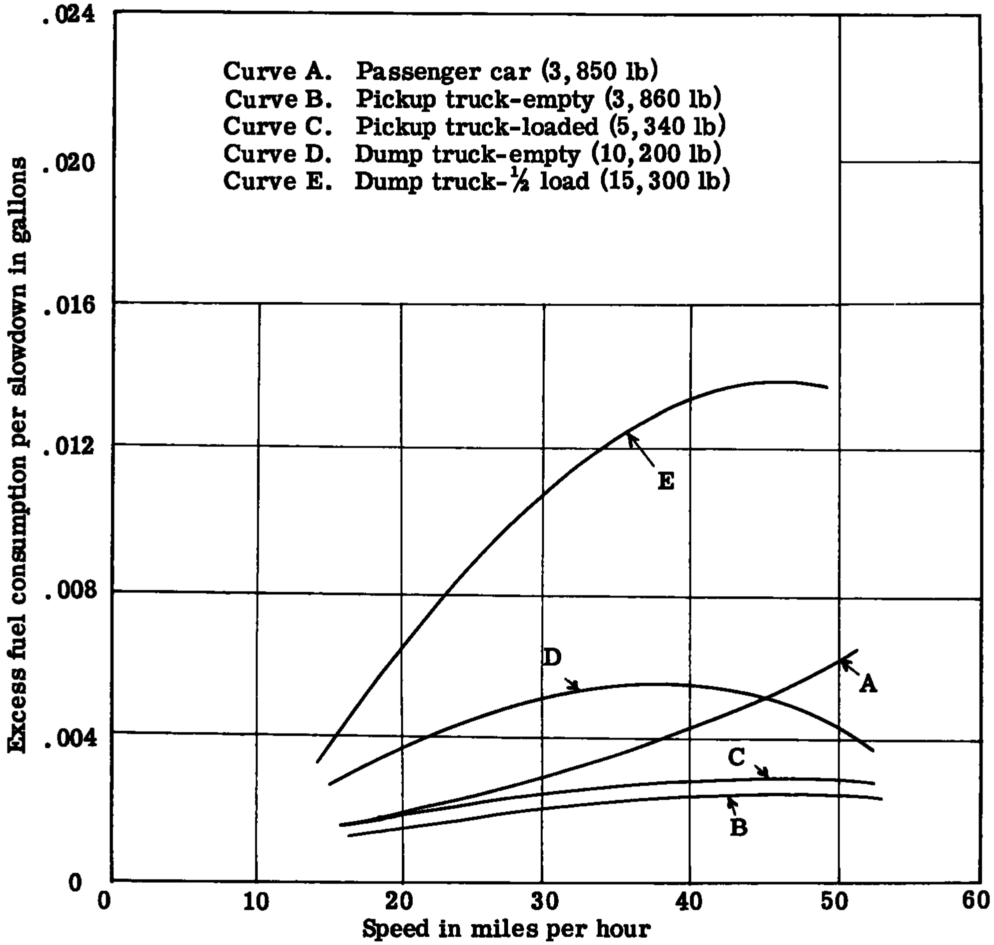

Figure 6. Fuel consumed for reducing speed by 10 mph from a given speed and immediately accelerating back to that speed in excess of fuel consumption if given speed were maintained.

Figures 6 and 7 may be used to estimate the fuel and time consumption saved through the elimination of sharp curves and driveway entrances. In the case of a curve elimination, test runs should be made before improvement to determine the average amount of slowdown caused by the presence of the curve. Where driveway entrances are to be eliminated, test runs should be made beforehand to establish the average percentage of driveways at which through vehicles are forced to reduce speeds and the average value of such speed slowdowns. When the analyses of the speed-delay studies are completed, average values of speed reductions for curves and driveway entrances and the average percentage of driveways at which the movement of through vehicles is affected will be available for use in benefit studies. If the average speed reductions found for curves and driveway entrances are between 8 and 12 mph, Figures 6 and 7 may be used to compute fuel and time savings. If the average speed reduction is more than 12 mph or less than 8 mph, the fuel and time savings may be estimated from Figures 6 and 7 assuming that the magnitude of these savings is proportionate to the magnitude of the speed change.

Two examples will illustrate how Figures 1 through 7 and Table 2 may be used to compute the fuel and time savings arising from particular improvements.

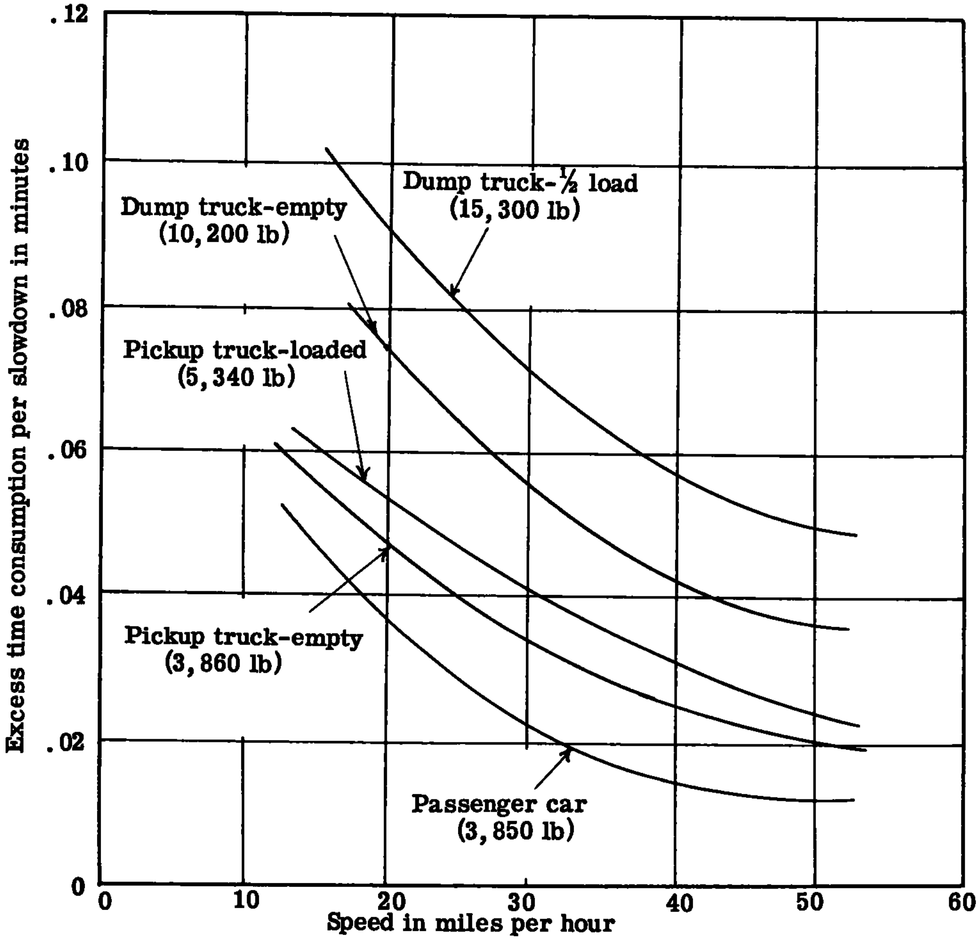

Figure 7. Time consumed for reducing speed by 10 mph from a given speed and immediately accelerating back to that speed in excess of time consumption if given speed were maintained.

Example 1

A 2-lane gravel surfaced road 24 ft wide is to be surfaced with a concrete pavement for 10 mi. Average annual daily traffic on the route is 4,000 vehicles per day. Eighty percent of the vehicles are passenger cars and 20 percent are two-axle single unit trucks having an average gross vehicle weight of 10,000 lb. The nominal highway speed on the route before improvement was 35 mph for all vehicles. It is expected that this will be increased to 45 mph after improvement. Compute the average annual fuel savings which may be attributed to this improvement.

Total number of vehicles using route per year:

Passenger cars	4,000 x 0.80 x 365 = 1,168,000
Trucks	4,000 x 0.20 x 365 = 292,000

Savings in fuel use per vehicle mile due to surface improvement at nominal highway speed of 35 mph (Fig. 3):

Passenger cars	0.010 gal per mi
Trucks	0.021 gal per mi

Increase in fuel consumption per vehicle mile due to speed increase from 35 to 45 mph on paved surface (Fig. 1):

Passenger cars 0.003 gal per mi
Trucks 0.004 gal per mi
Annual saving in fuel use (10 mi):
Passenger cars 1,168,000 (10) (0.010-0.003) = 81,760 gal
Trucks 292,000 (10) (0.021-0.004) = 49,640 gal
Total 131,400 gal

Example 2

A grade separation is planned at the intersection of a 4-lane divided parkway and a 2-lane crossroad where traffic signals now control vehicle movements. The average annual daily traffic volumes on the 4-lane and 2-lane routes are 20,000 vehicles per day and 4,000 vehicles per day, respectively. All vehicles on the parkway are passenger cars. Eighty percent of the vehicles on the crossroad are passenger cars and 20 percent are 2-axle single unit trucks having an average gross weight of 10,000 lb. The nominal highway speed on the 4-lane route is 45 mph and on the 2-lane route, 30 mph (all vehicles). Turning movements at this intersection are so few that they may be neglected. It was determined from a study of traffic movements that on both routes traffic signals caused 25 percent of the vehicles to stop with an average delay per stop per vehicle of 20 sec (0.33 min). Compute the annual fuel and time savings which will result from this improvement.

Annual number of vehicles stopped at the intersection:
Four-lane divided highway:
Passenger cars 20,000 (365) (0.25) = 1,825,000
Two-lane crossroad:
Passenger cars 4,000 (0.80) (365) (0.25) = 292,000
Trucks 4,000 (0.20) (365) (0.25) = 73,000
Unit fuel and time savings:
Passenger cars: Fuel savings per stop-and-go at nominal highway speed of 45 mph (Fig. 4) = 0.015 gal
Time savings per stop-and-go at nominal highway speed of 45 mph (Fig. 5) = 0.21 min
Fuel savings per stop-and-go at nominal highway speed of 30 mph (Fig. 4) = 0.009 gal
Time savings per stop-and-go at nominal highway speed of 30 mph (Fig. 5) = 0.14 min
Fuel use while idling (Table 2) = 0.007 gal per min

Trucks: Fuel savings per stop-and-go at nominal highway speed of 30 mph (Fig. 4) = 0.017 gal
Time Savings per stop-and-go at nominal highway speed of 30 mph (Fig. 5) = 0.23 min
Fuel use while idling (Table 2) = 0.011 gal per min

Annual fuel savings:
Four-lane divided highway:
Passenger car (stop-and-go) = 1,825,000 (0.015) = 27,375 gal
Passenger car (idling) = 1,825,000 (0.33) (0.007) = 4,216 gal

Two-lane crossroad:
Passenger car (stop-and-go) = 292,000 (0.009) = 2,628 gal
Passenger car (idling) = 292,000 (0.33) (0.007) = 674 gal
Trucks (stop-and-go) = 73,000 (0.017) = 1,241 gal
Trucks (idling) = 73,000 (0.33) (0.011) = 265 gal
Total 36,399 gal

Annual time savings:
Four-lane divided highway:

Passenger car (stop-and-go) = 1,825,000 (0.21) = 383,250 min
Passenger car (idling) = 1,825,000 (0.33) = 602,250 min

Two-lane crossroad:
Passenger car (stop-and-go) = 292,000 (0.14) = 40,880 min
Passenger car (idling) = 292,000 (0.33) = 96,360 min
Trucks (stop-and-go) = 73,000 (0.23) = 16,790 min
Trucks (idling) = 73,000 (0.33) = 24,090 min
Total 1,163,620 min = (19,394 hr)

SUMMARY

Much of the saving in time and fuel as a result of highway improvement arises because of increased vehicle speeds, upgrading of pavement surface, and reduction of the frequency of stop-and-go and slowdown operations. On paved surfaces the rate of fuel consumption of passenger cars and single unit trucks decreases as speed increases fro 15 mph to between 25 and 35 mph depending on vehicle type and gross weight. At highe speeds the rate of fuel consumption increases. On gravel roads the relationship betwee rate of fuel consumption and speed for these vehicles is similar to that for paved surfaces except that the lowest rate of fuel consumption is between 20 and 25 mph.

The effect of upgrading a gravel surface to a concrete surface on the rate of fuel consumption of passenger cars and single unit trucks increases with vehicle speed. At speeds of 15 mph the increase in fuel consumption for the gravel surface is less than 7 percent but at 45 mph it is over 20 percent for passenger cars and pickup trucks and over 30 percent for single unit trucks with gross weights of 10,000 lb or more.

The additional time and fuel consumption for stop-and-go operations increases uniformly with speed. At any speed the additional time consumption is greater for the vehicles with the greater weight horsepower ratio. The additional fuel consumption increases as vehicle gross weight increases except that the passenger car uses more fuel than the heavier pickup truck at all speeds. This was probably due to the fact that the passenger car used for the study was equipped with an automatic transmission and the pickup truck had a manual transmission.

The additional time consumption for a slowdown of 10 mph decreases with increased vehicle speed. The additional fuel consumption of passenger cars for slowdowns increases with speed up to at least 50 mph. The additional fuel consumption of single unit trucks increases with speed up to between 35 and 50 mph but decreases somewhat at higher speeds.

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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.

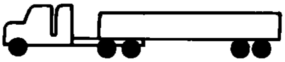
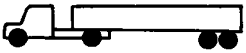
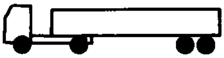
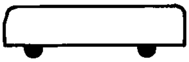
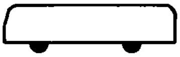
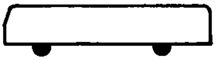
TEST VEHICLE DESCRIPTIONS					
TEST UNIT	AXLE CLASS.	GASOLINE	TEST UNIT	AXLE CLASS.	DIESEL
1-A	3-S2		5-A	3-S2	
2-B	2-S2		3-B	2-S2	
2-C-D	2-S1-2		3-C-D	2-S1-2	
10	2-2		8	3-2	
7-C	2-S1		9	2-Bus (Rural)	
6	2-Bus (Urban)		4	2-Bus (Urban)	

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		$6\frac{1}{6}$	$4\frac{1}{11}$	$6\frac{1}{6}$	U8.28 O 5.99	$5\frac{2}{3}$	U9.77 O 7.17
g. (1) Transmission ratio, main 1st	8.08	7.33	7.33	7.53	7.53			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	Torque Converter	Torque Converter	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.

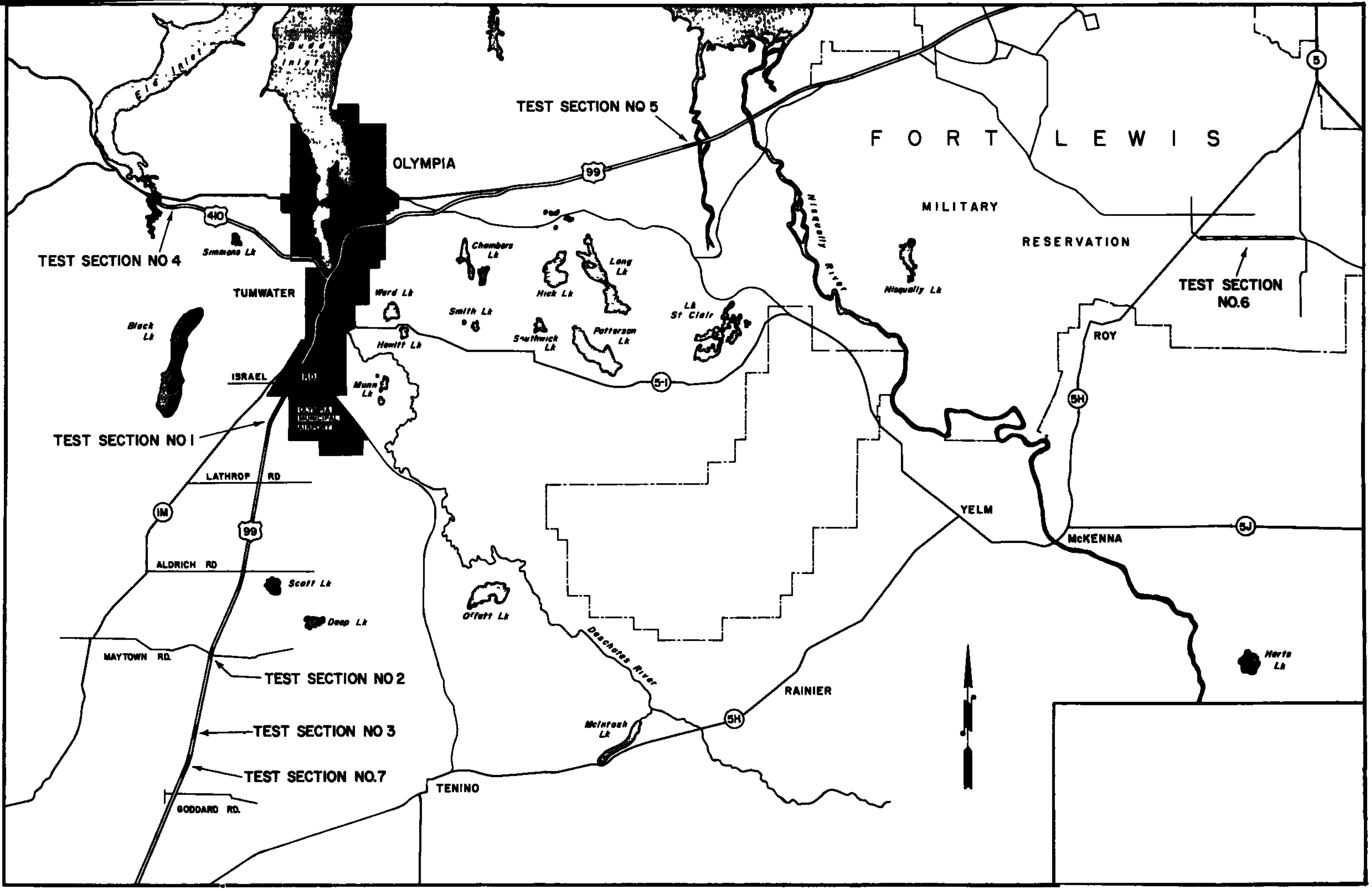
The operating conditions on the level gravel section 6 were similar to level section 1, except the higher speed operation could not be obtained with safety.

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


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

Figure 2.

TABLE 2

SUMMARY OF TEST ROADWAY CHARACTERISTICS

Test Section	Surface Type	Ave. Grade (%)	Horiz. Curve		Lanes (no.)	Lane Width (ft)	Highway Type	Section Length[1] (ft)	
			Δ	D				N	S
1	Asph. conc.	0.09	18°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°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)	(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

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

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.

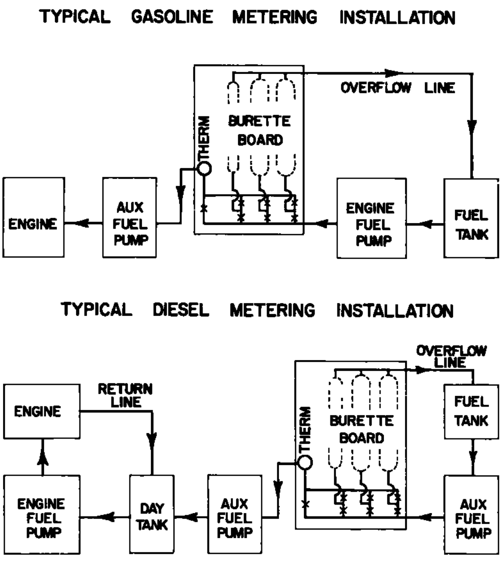

Figure 3.

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

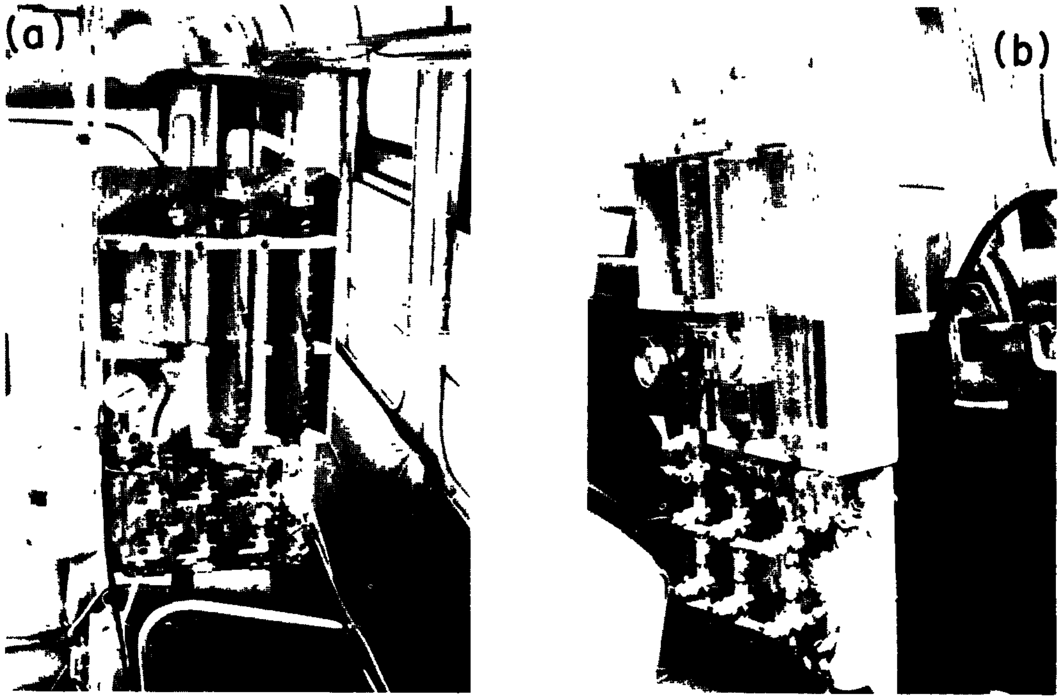

Figure 4. Burette installation in (a) bus and (b) tractor.

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:

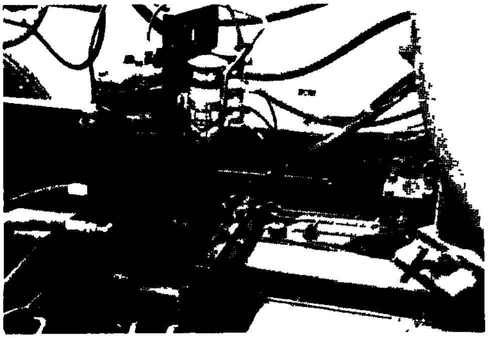

Figure 5. Day tank installation in diesel unit.

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

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

Values of $\frac{-\mathrm{d(mph)}}{\mathrm{dt}}$ 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

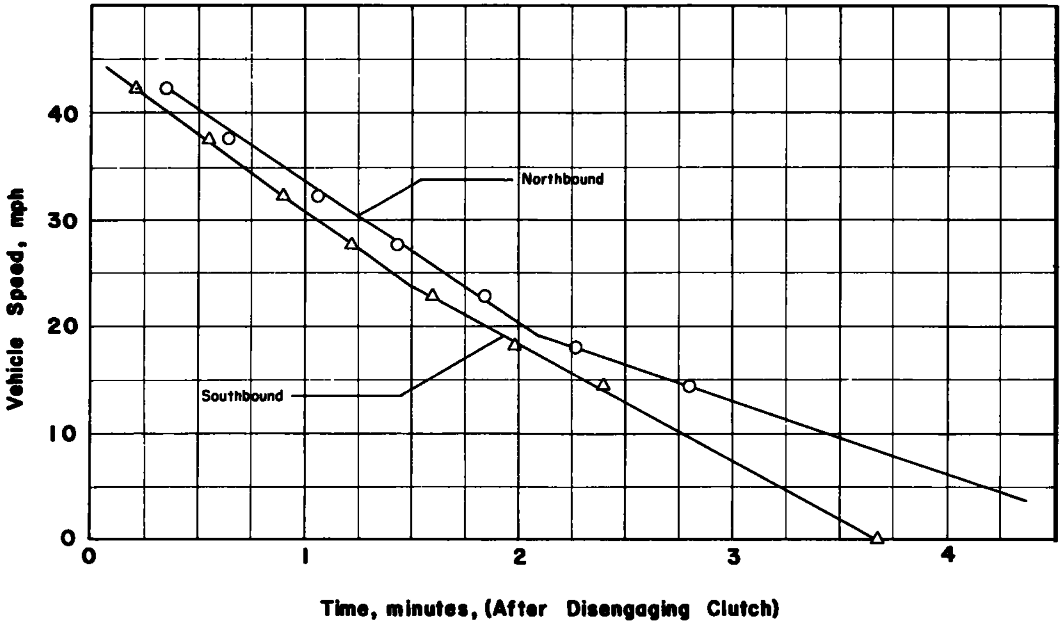

Figure 6. Typical rolling resistance test data, vehicle 1-A, out of gear, GVW=48,985 lb.

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

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

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

$$\text{FHP} = \text{K}\,\text{N}_{\text{E}}^{2} \qquad (4)$$

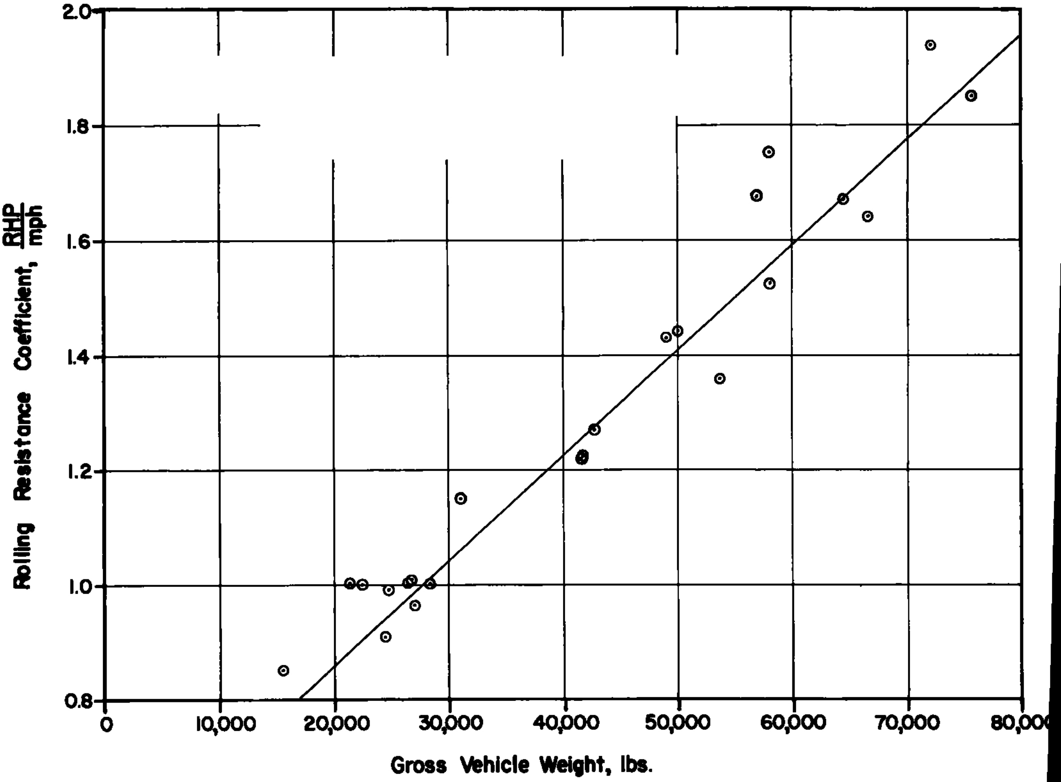

Figure 7. Coefficient of rolling resistance as a function of GVW.

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

$$IHP_{WOT} = FHP + RHP + AHP \qquad (9)$$

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

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

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 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 fue

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 calculate

TABLE 6

WIDE-OPEN THROTTLE POWER OUTPUT

Power Unit No.	Used in Veh. Comb.	Measured IHP_{WOT}	BHP_{WOT}		Ratio, Est./Rated
			Est.[1]	Manuf. 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,

$$IHP = FHP + RHP + PHP \tag{11}$$

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

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

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;

$$gpm = \frac{(0.0204)(IHP_{WOT})}{n_i\,(\text{mph})} \tag{13}$$

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.

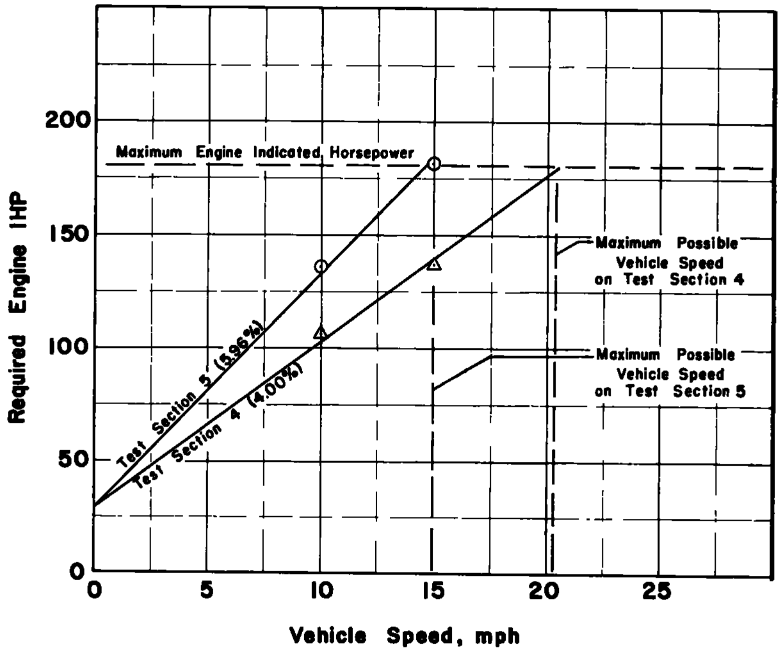

Figure 8. Required engine IHP at various vehicle speeds on two grades, vehicle 2-B, GVW=57,000 lb.

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			Measured		
		Max. Speed (mph)	Gpm	Gear Used	Max. Speed (mph)	Gpm	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,

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

The value of $\frac{d(\text{mph})}{dt}$ 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,

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

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

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,

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

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.

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

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,

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

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.

$$\text{IHP} - \text{AHP} = \text{RHP} + \text{FHP} + \text{HPB}_d \tag{23a}$$

or

$$\text{HPB}_d = \text{IHP} - \text{AHP} - \text{RHP} - \text{FHP} \tag{23b}$$

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, togethe with the measured test results. With the exception of the 35-25-35-mph cycle with vehic 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

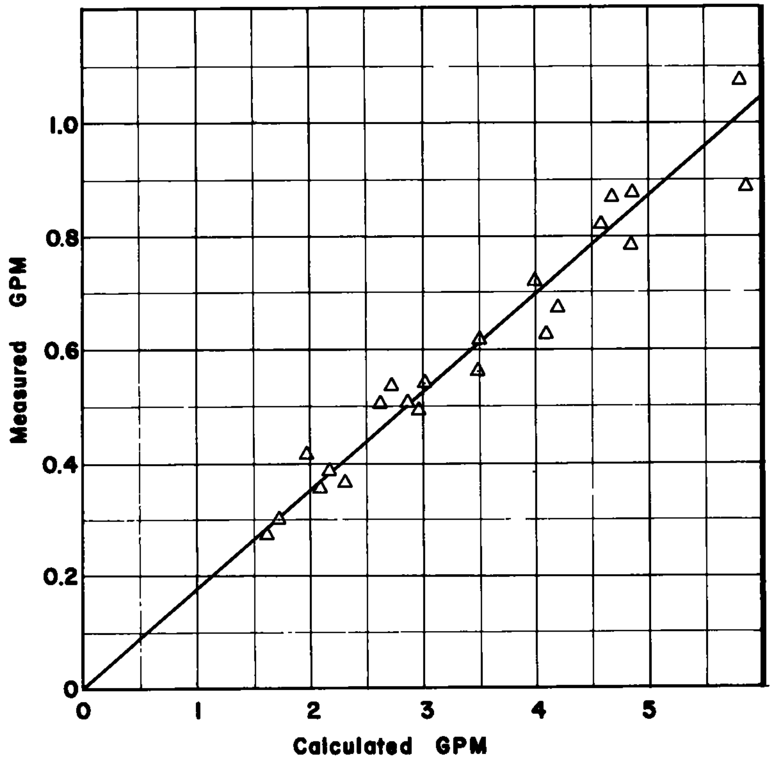

Figure 9. Comparison of measured fuel consumption to fuel consumption calculated from vehicle pretest results; uphill on grade 4 (4.00 percent) and grade 5 (5.96 percent; vehicles 1-A, 2-B, 3-C-D, 5-A and 10 at empty and full loads.

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 ($\times 2.642 \times 10^{-4}$).
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.

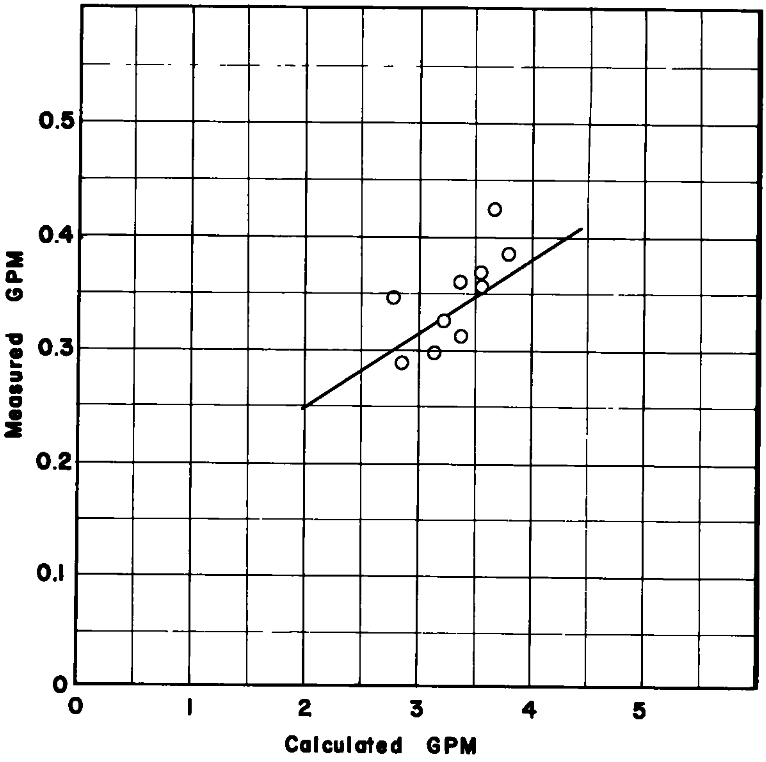

Figure 10. Comparison of measured fuel comsumption with fuel consumption calculated from vehicle pretest results (acceleration method); slowdown cycle tests on level road; vehicles 1-A and 2-B at all tested loads.

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-analysi 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 uppe 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.

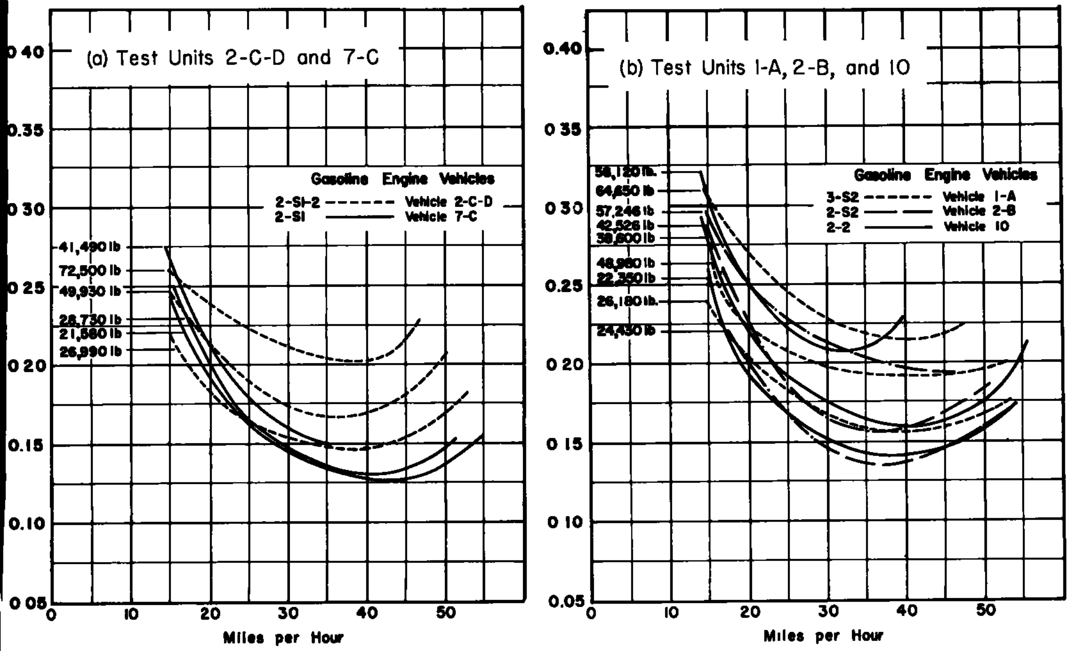

Figure 11. Fuel consumption for varying loads, gasoline-powered vehicles, level paved section 1.

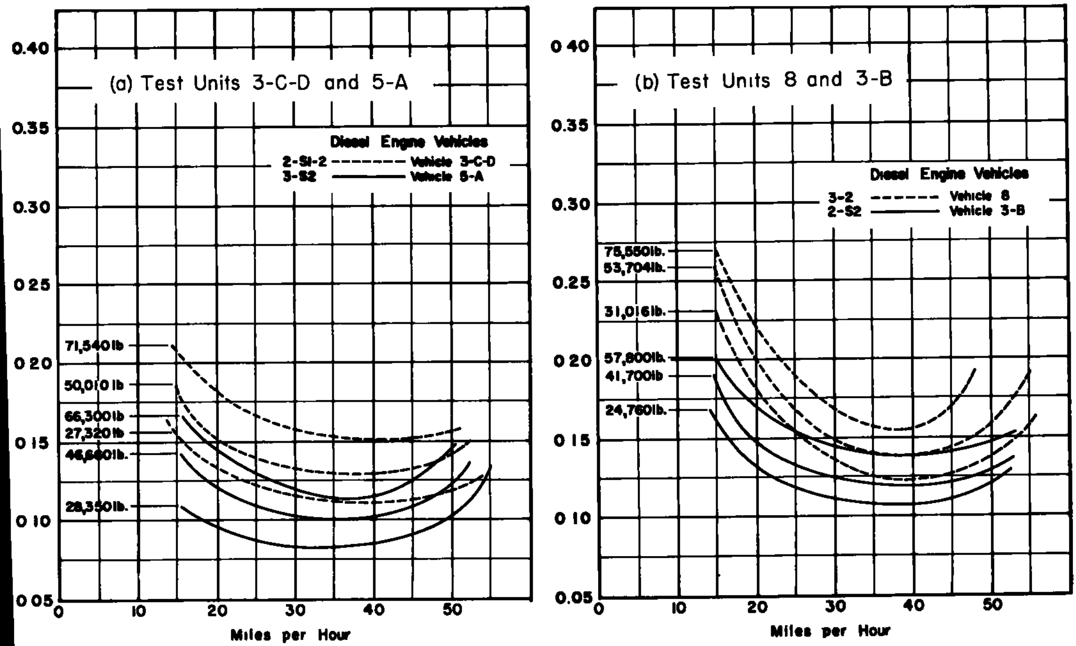

Figure 12. Fuel consumption for varying loads, diesel-powered vehicles, level paved section 1.

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:

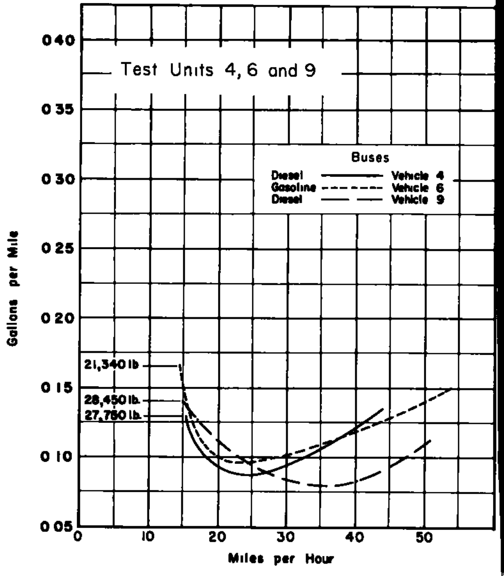

Figure 13. Fuel consumption for buses, level paved section 1.

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 vehicle 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 tha their diesel counterparts at part load and optimum speed.

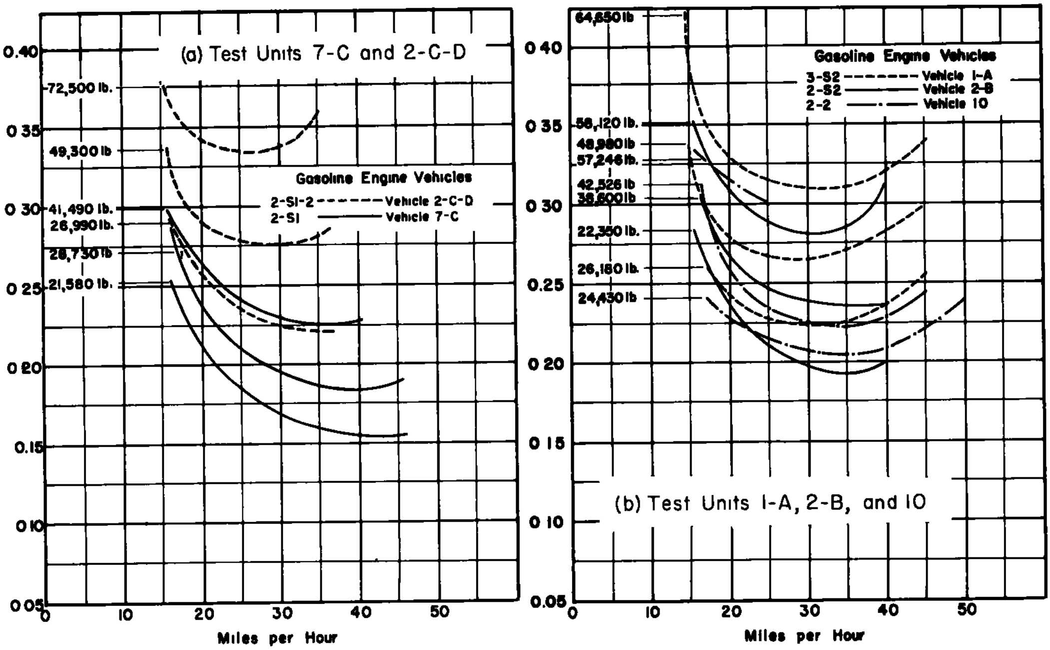

Figure 14. Fuel consumption for varying loads, gasoline-powered vehicles, level gravel section 6.

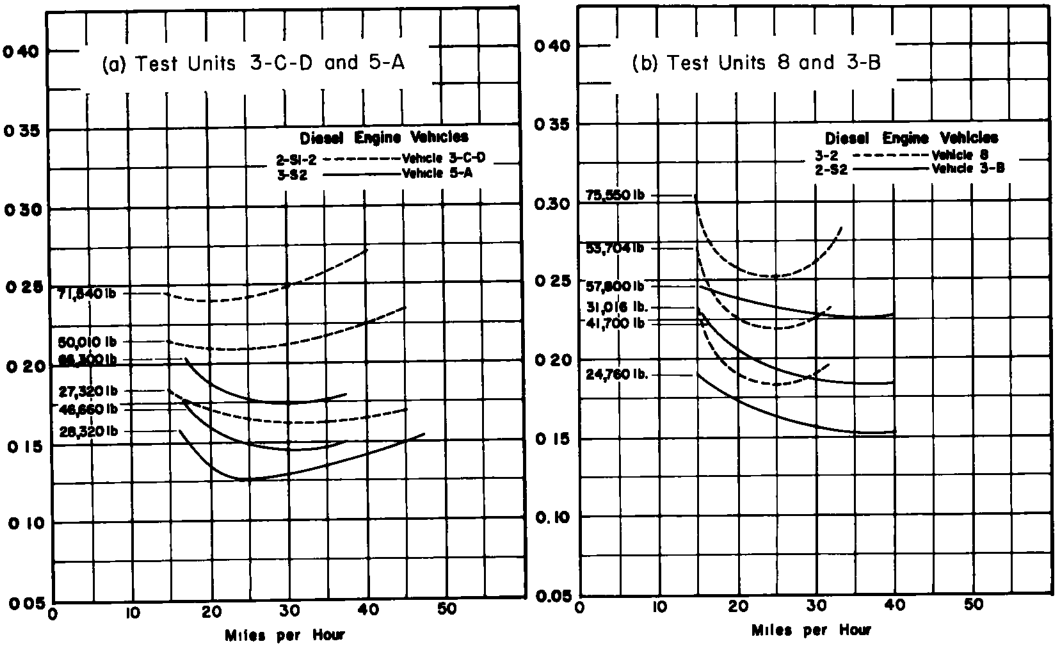

Figure 15. Fuel consumption for varying loads, diesel-powered vehicles, level gravel section 6.

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.

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

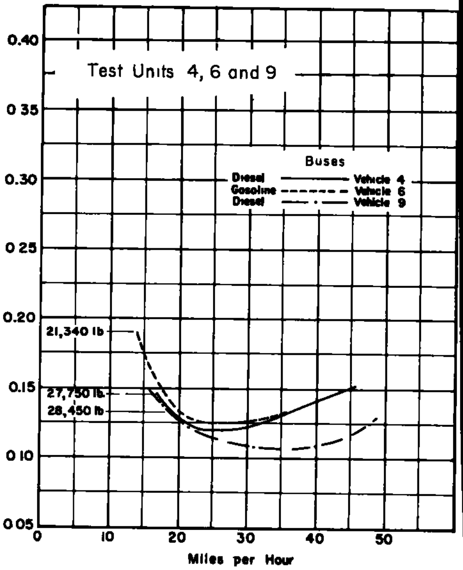

Figure 16. Fuel consumption for buses, level gravel section 6.

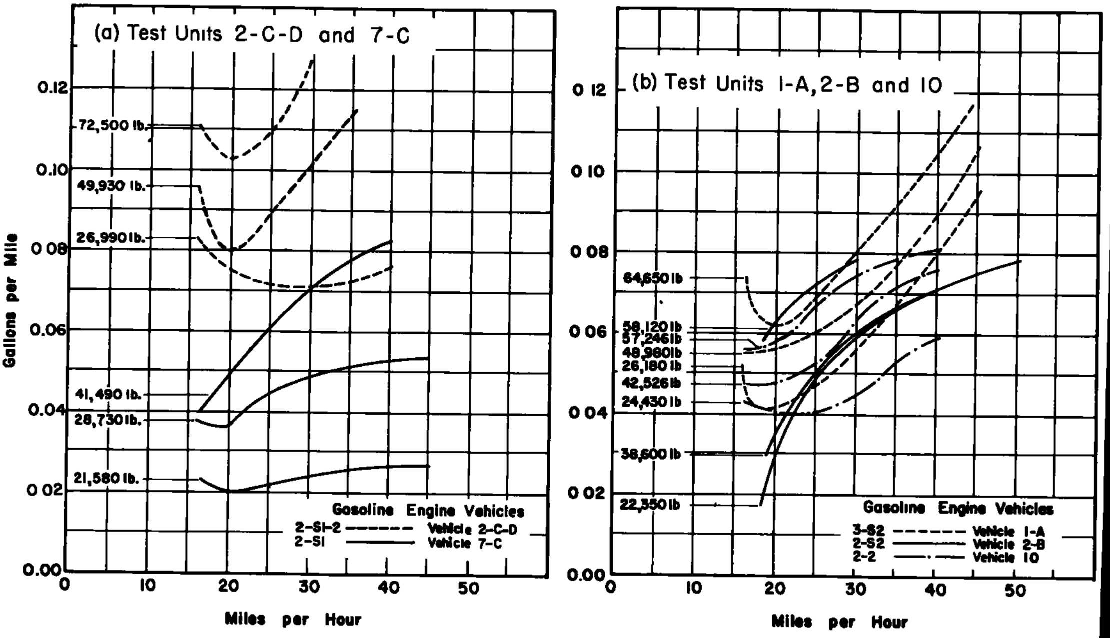

Figure 17. Fuel savings by improvement in surface type, gasoline-powered vehicles.

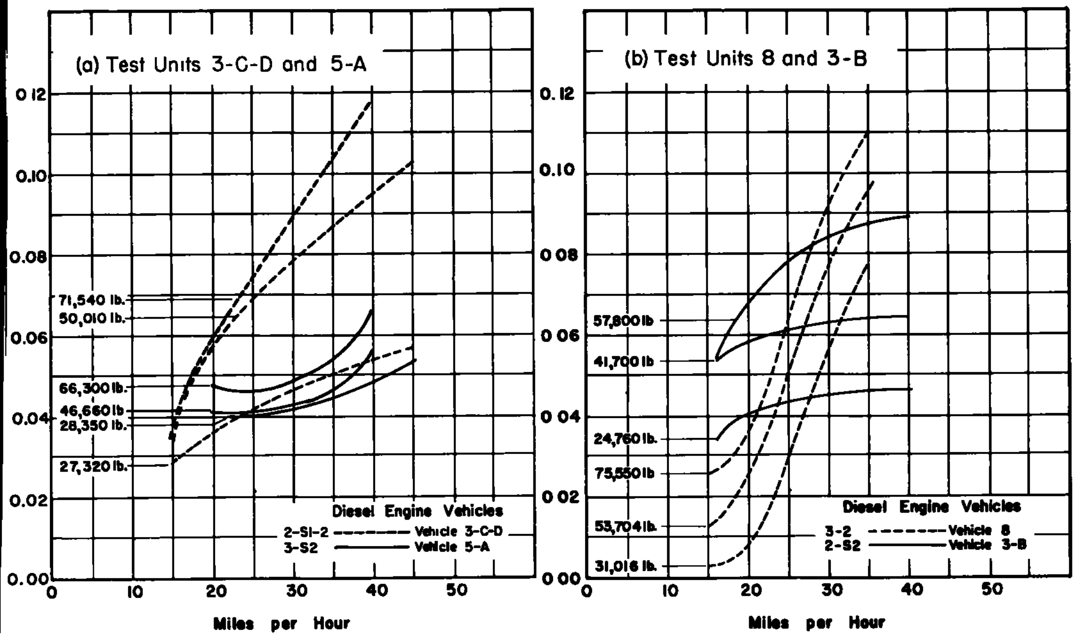

Figure 18. Fuel savings by improvement in surface type, diesel-powered vehicles.

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.

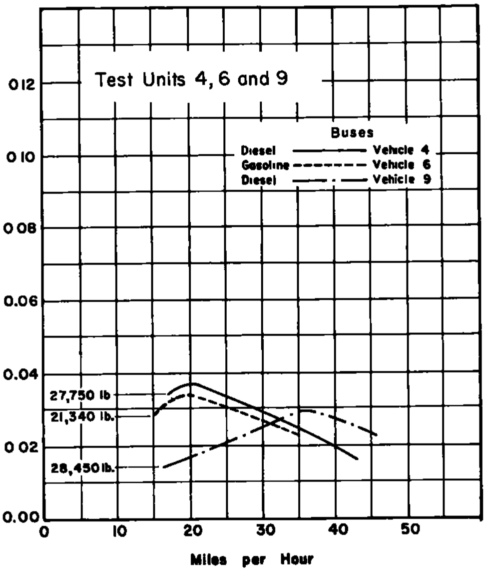

Figure 19. Fuel savings by improvement in surface type, buses.

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.

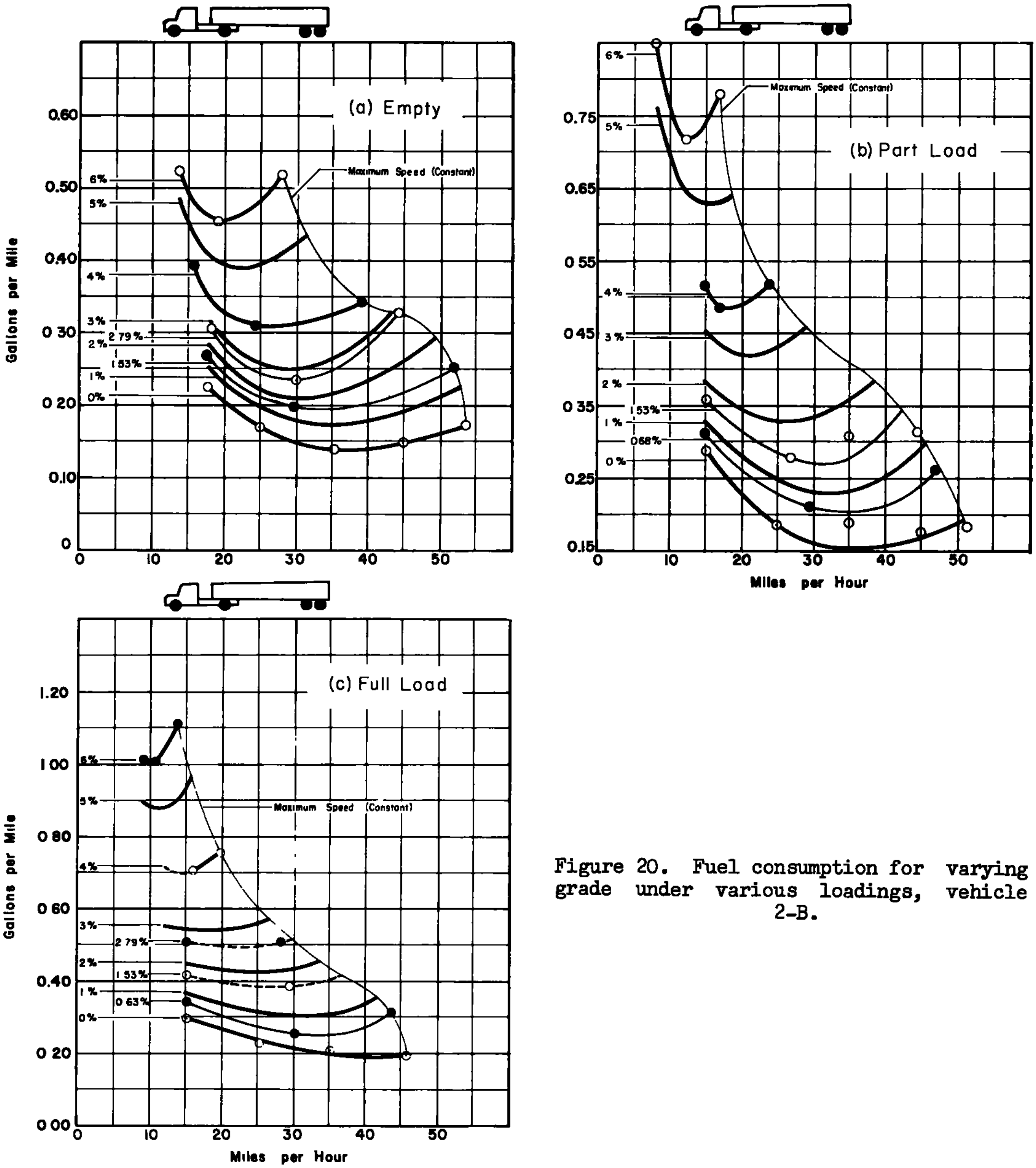

Figure 20. Fuel consumption for varying grade under various loadings, vehicle 2-B.

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.

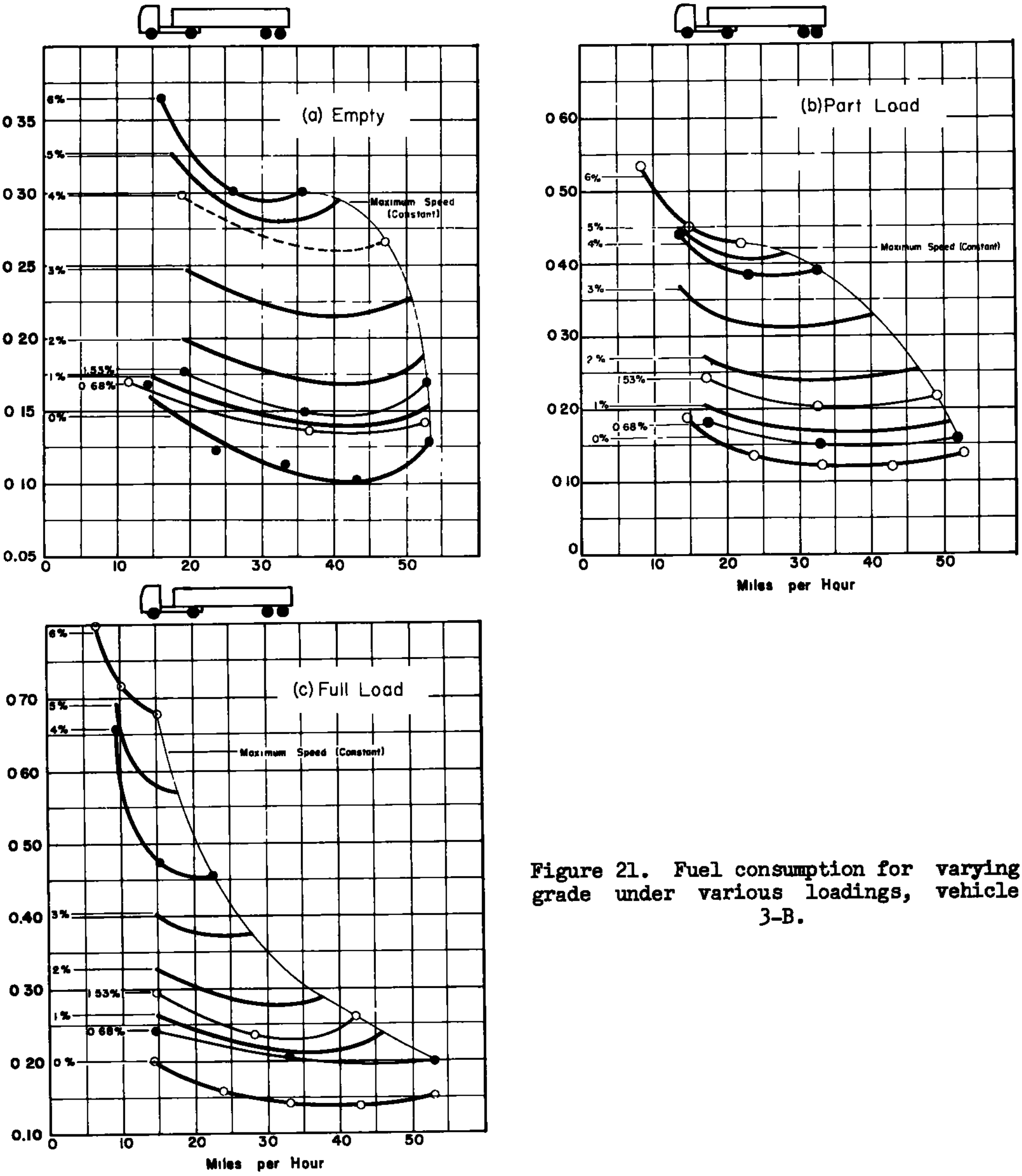

Figure 21. Fuel consumption for varying grade under various loadings, vehicle 3-B.

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

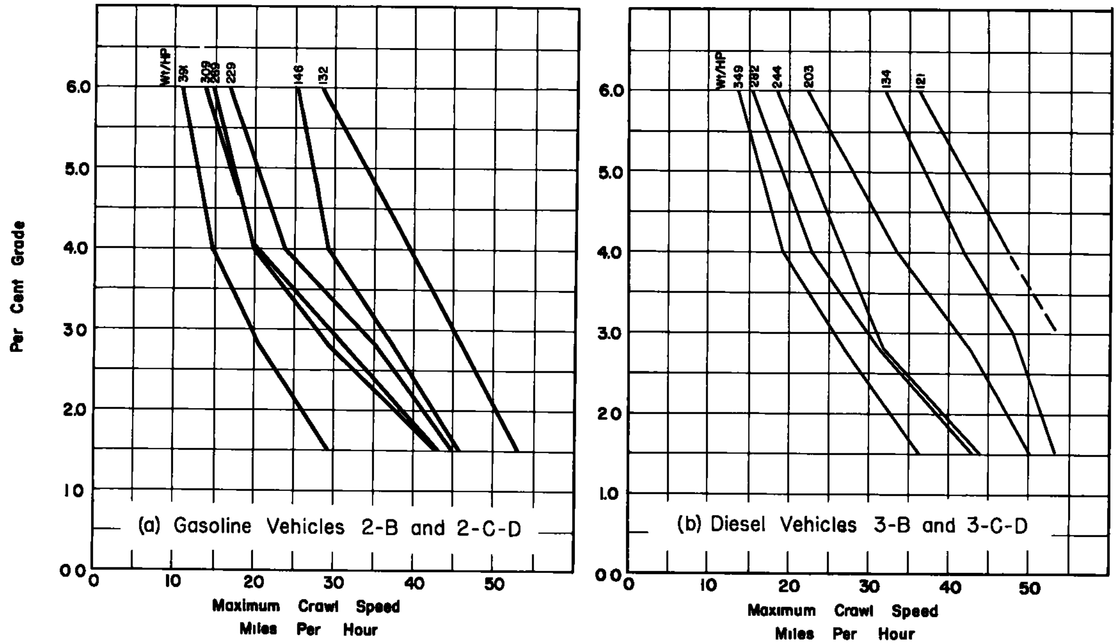

Figure 22. Maximum crawl speed vs grade for weight-to-horsepower ratio.

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.

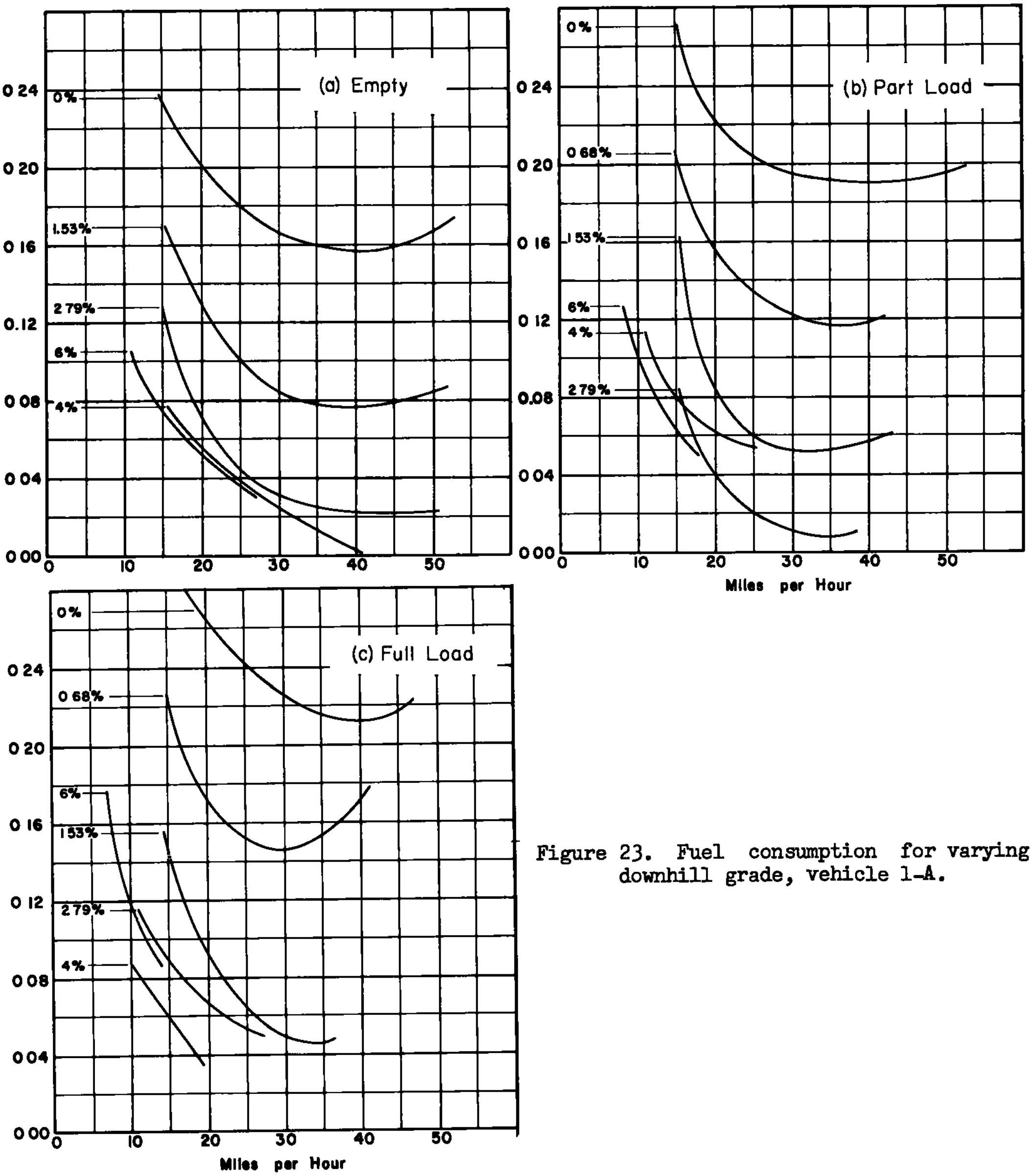

Figure 23. Fuel consumption for varying downhill grade, vehicle 1-A.

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:

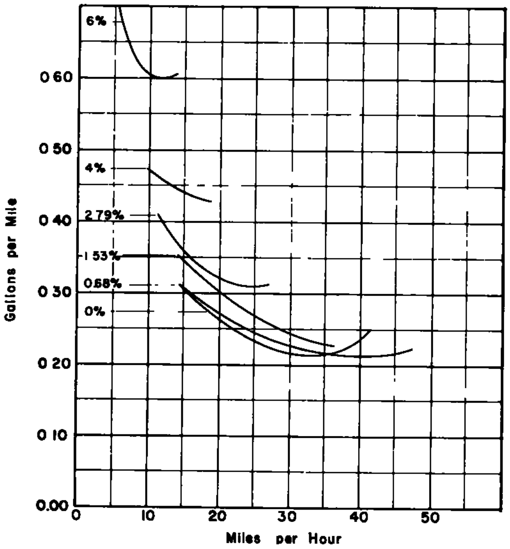

Figure 24. Fuel consumption for varying uphill and downhill grade, vehicle 1-A under full load.

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 greate 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.

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

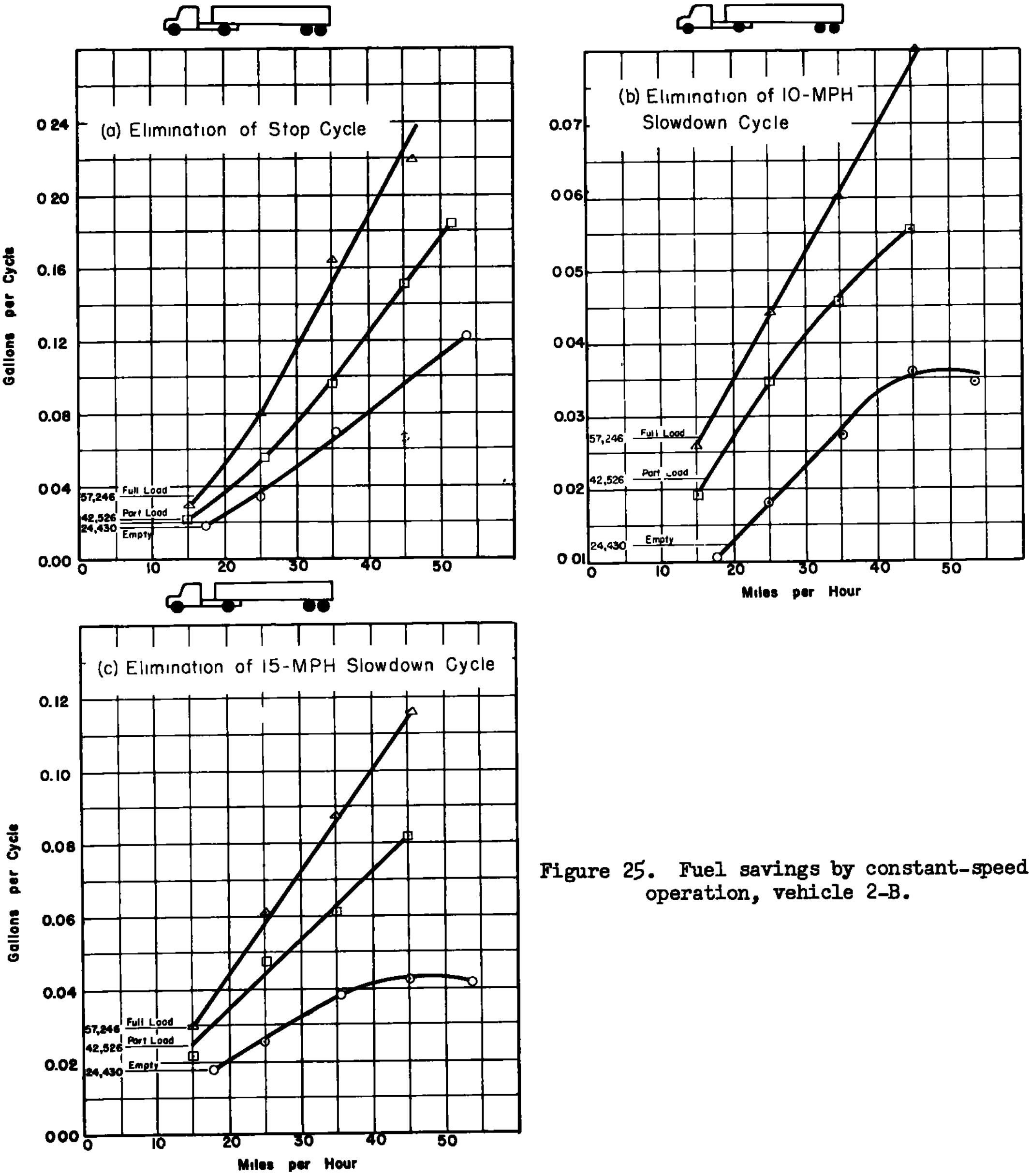

Figure 25. Fuel savings by constant-speed operation, vehicle 2-B.

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

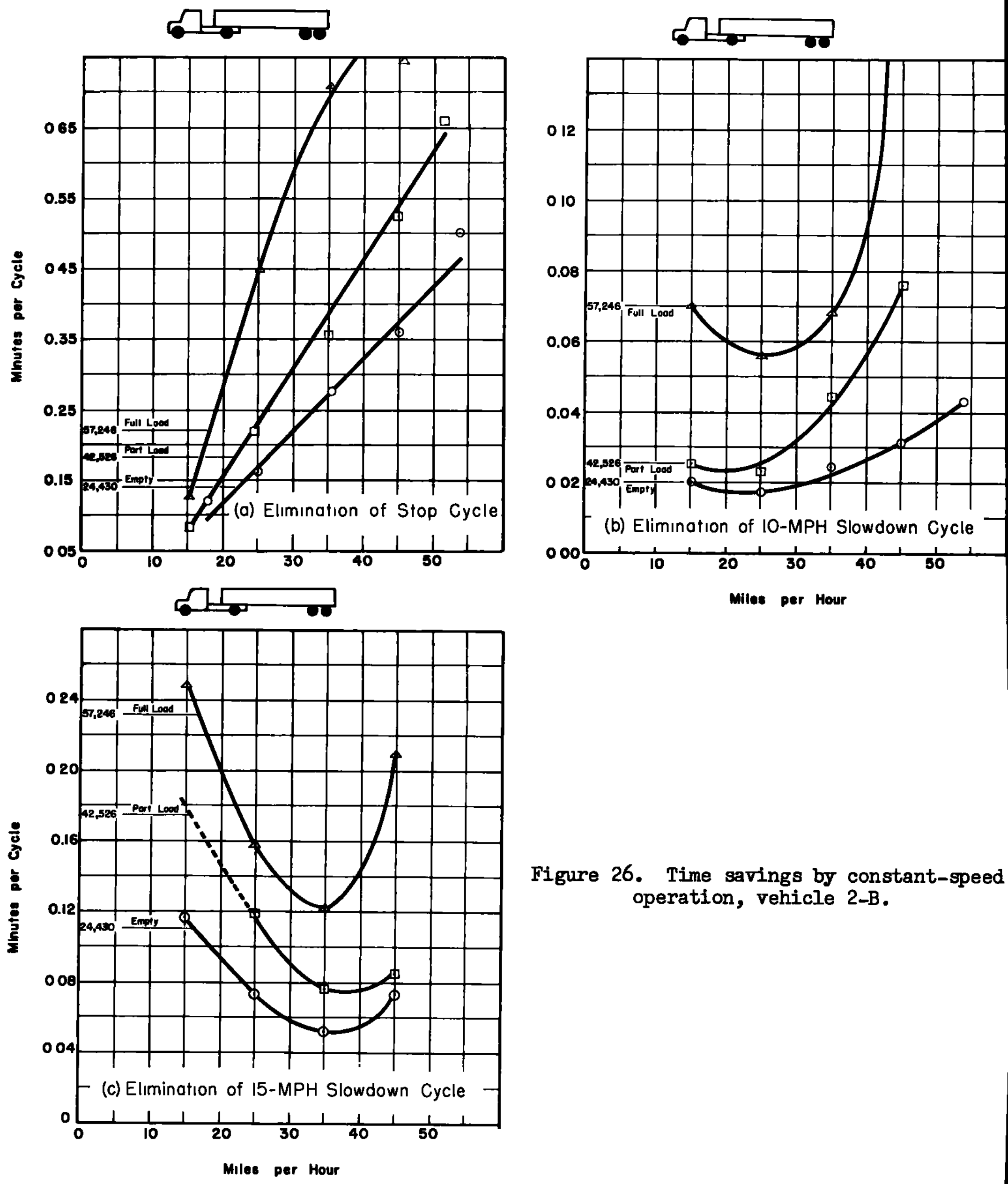

Figure 26. Time savings by constant-speed operation, vehicle 2-B.

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 th traffic control measures eliminate 10 of the slowdowns.

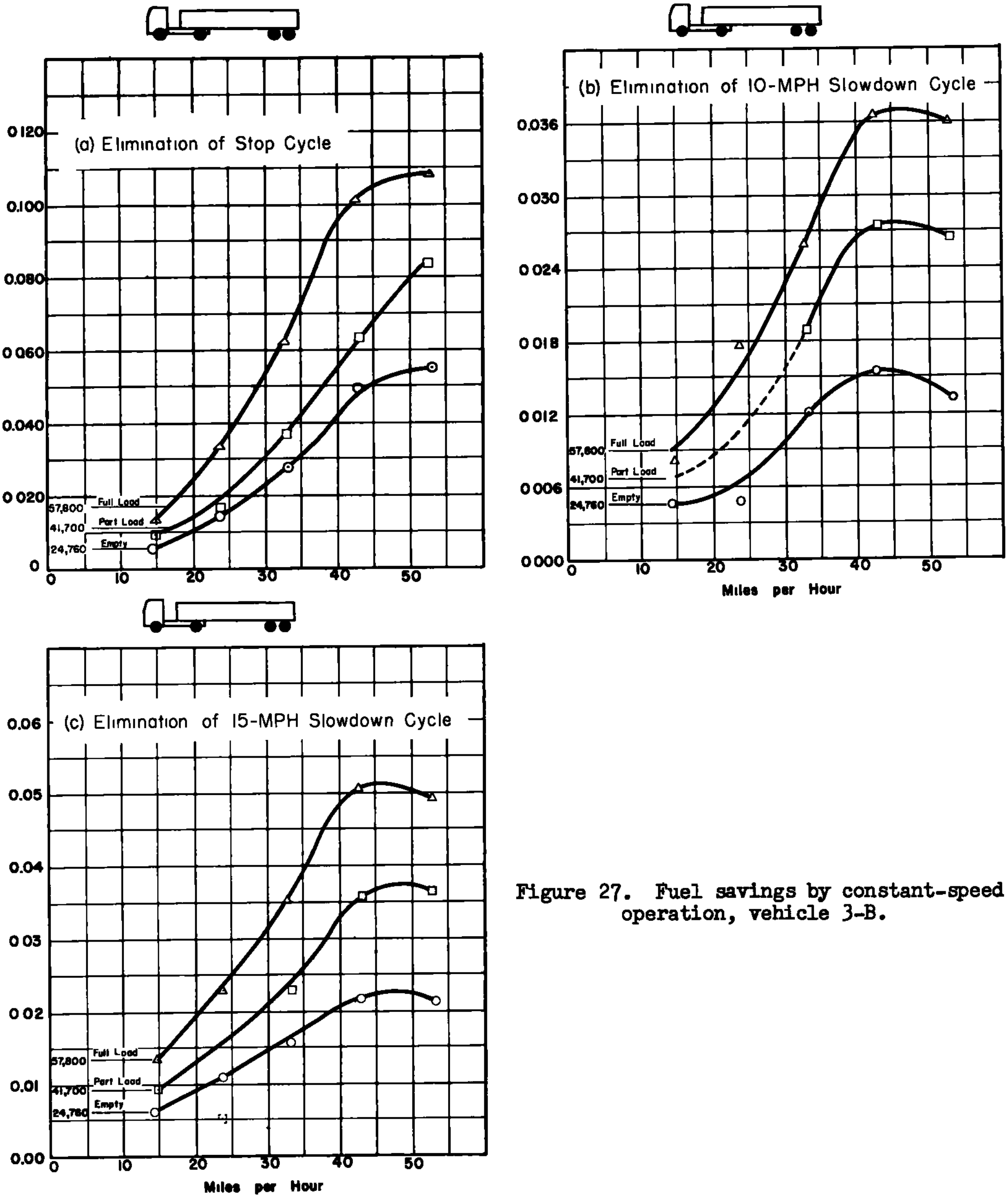

Figure 27. Fuel savings by constant-speed operation, vehicle 3-B.

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

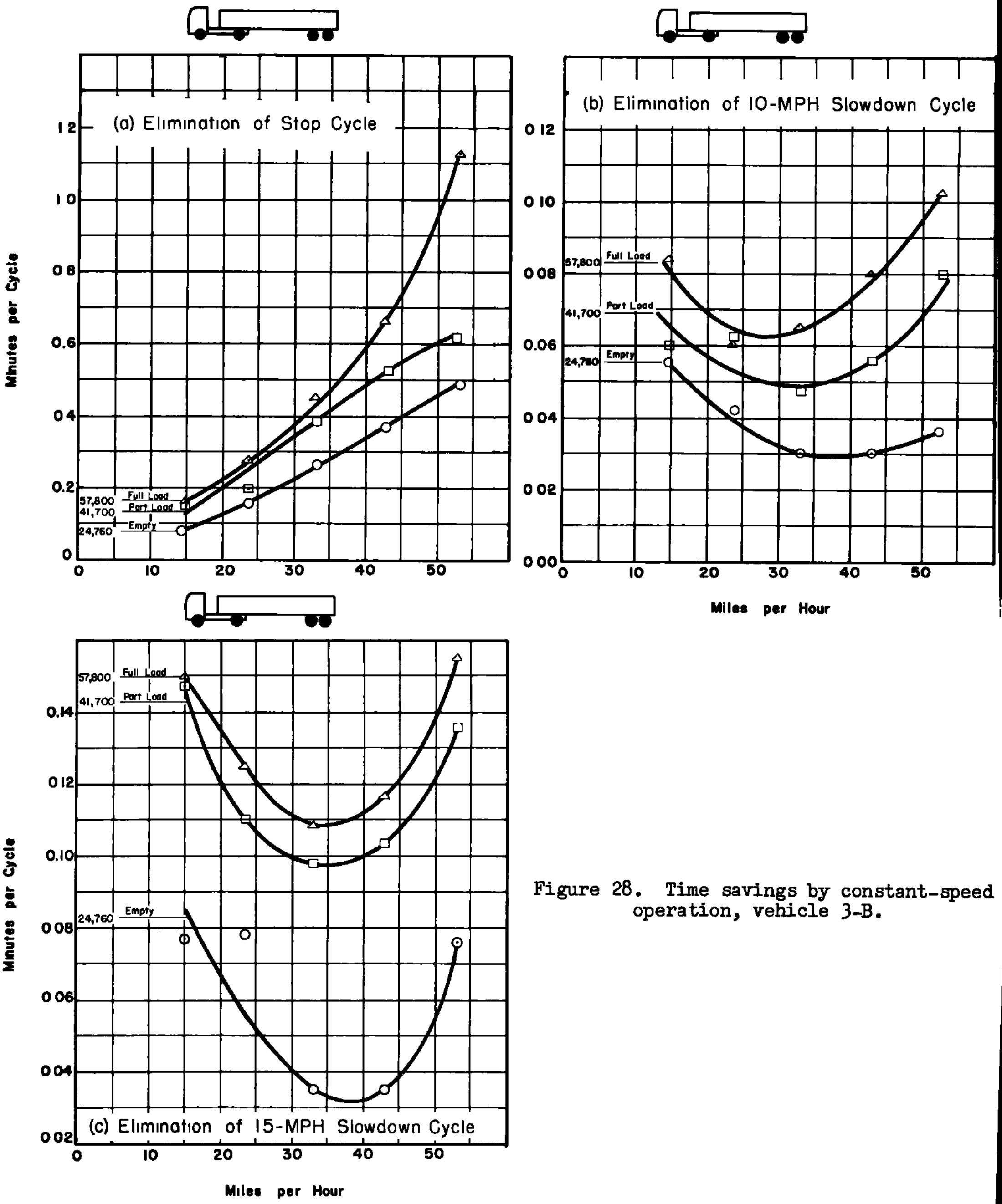

Figure 28. Time savings by constant-speed operation, vehicle 3-B.

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 calculations 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 benefits 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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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

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
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
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
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)

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

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 Cycl
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

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

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

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

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

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

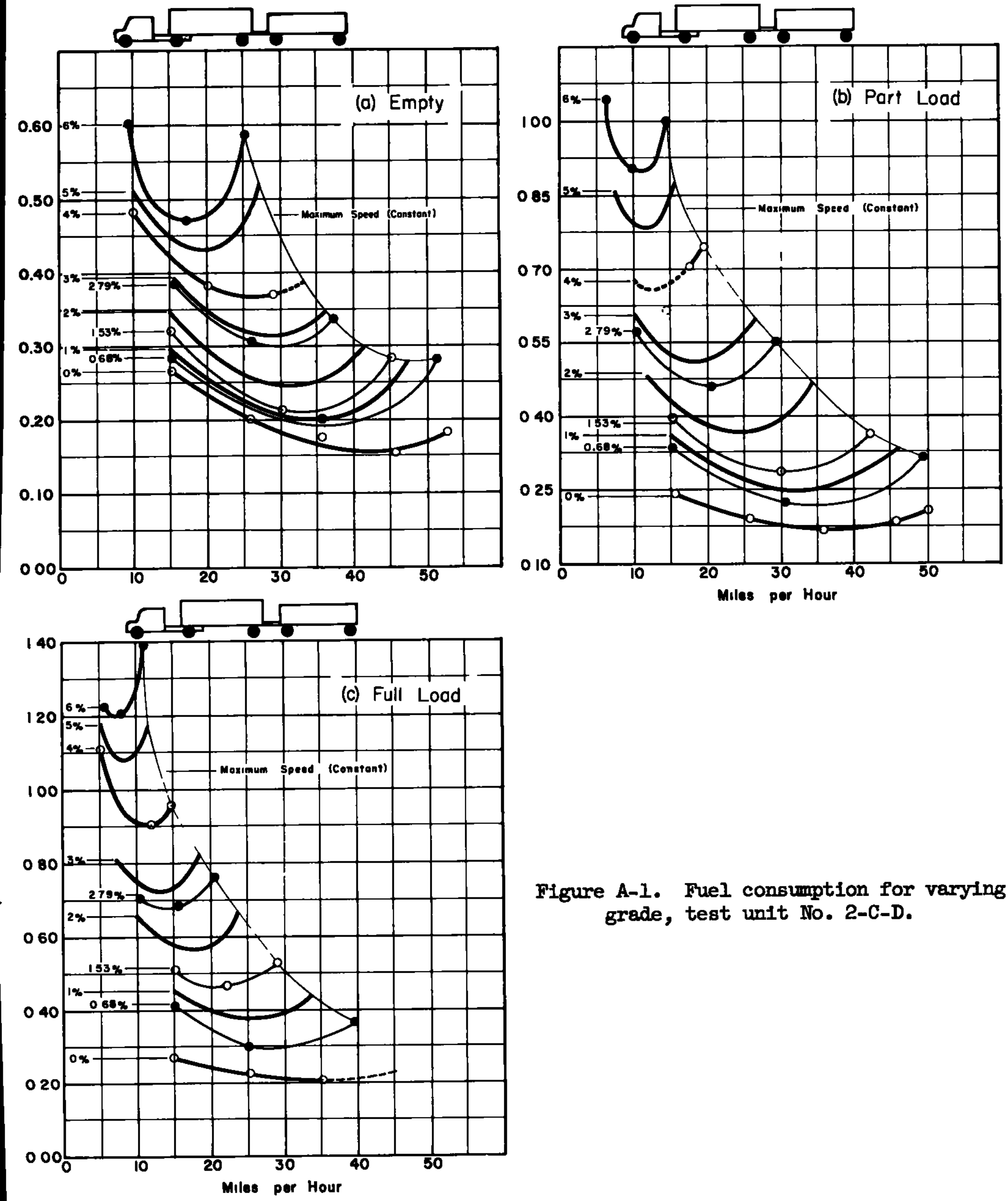


Figure A-1. Fuel consumption for varying grade, test unit No. 2-C-D.

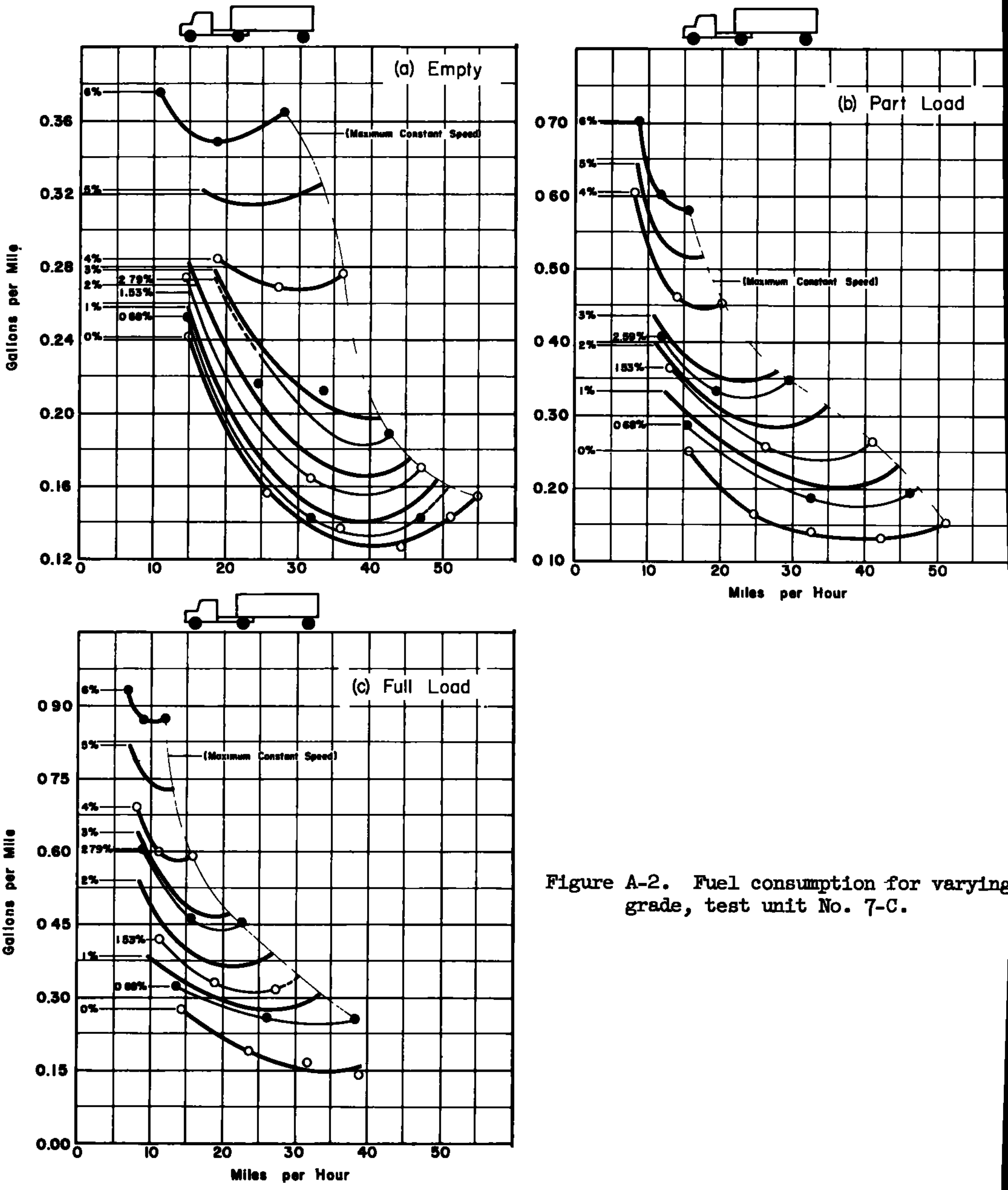


Figure A-2. Fuel consumption for varying grade, test unit No. 7-C.

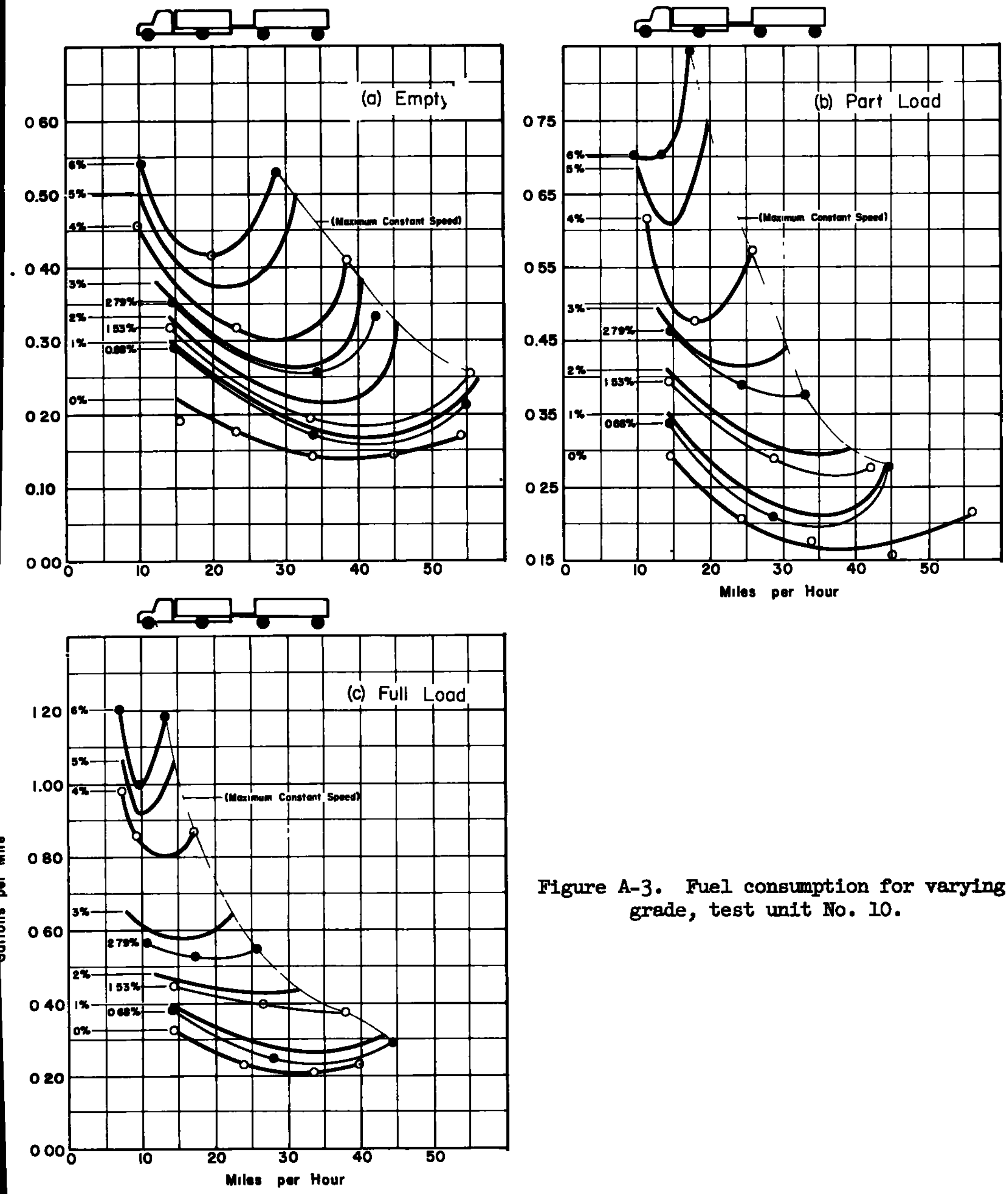


Figure A-3. Fuel consumption for varying grade, test unit No. 10.

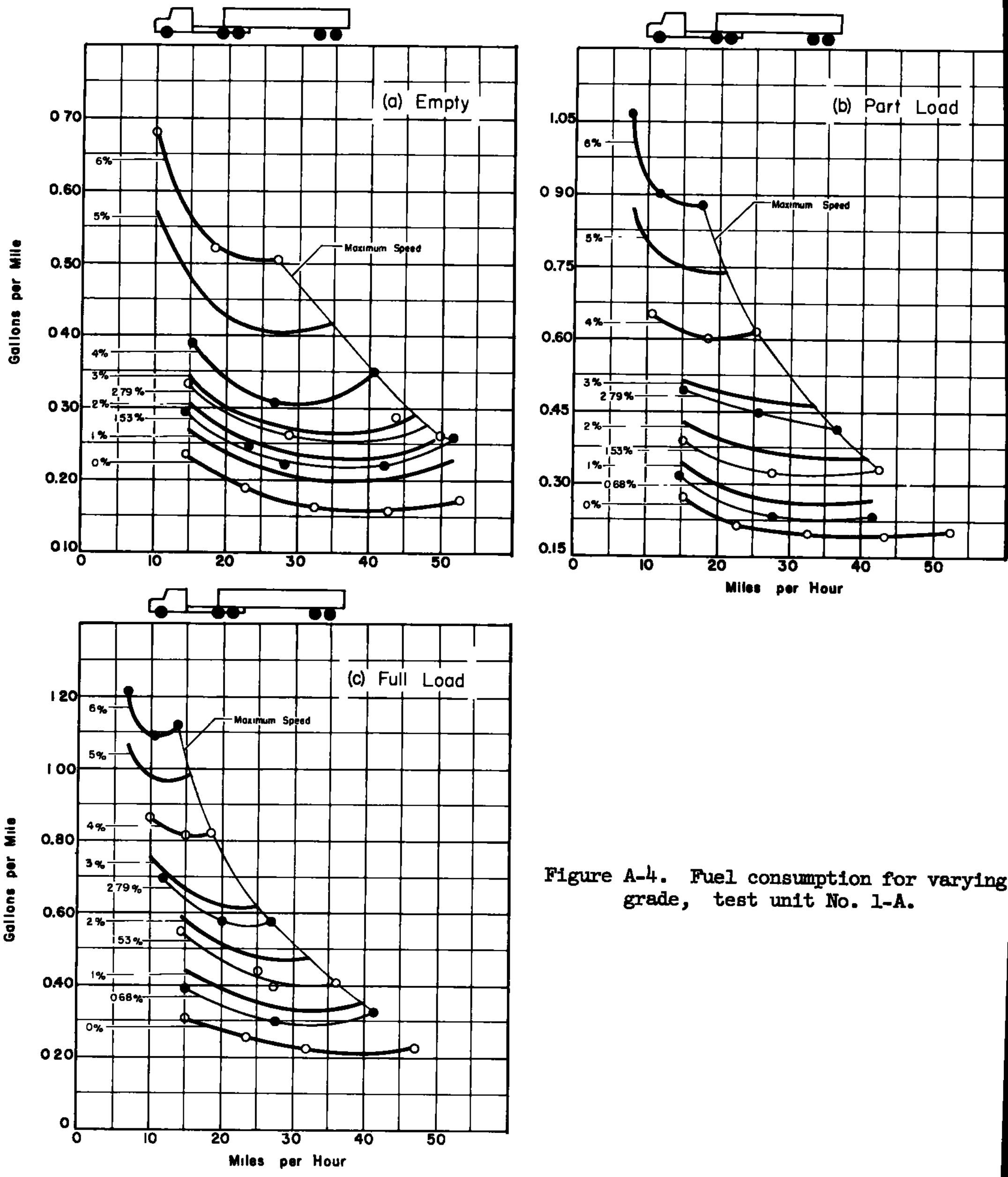


Figure A-4. Fuel consumption for varying grade, test unit No. 1-A.

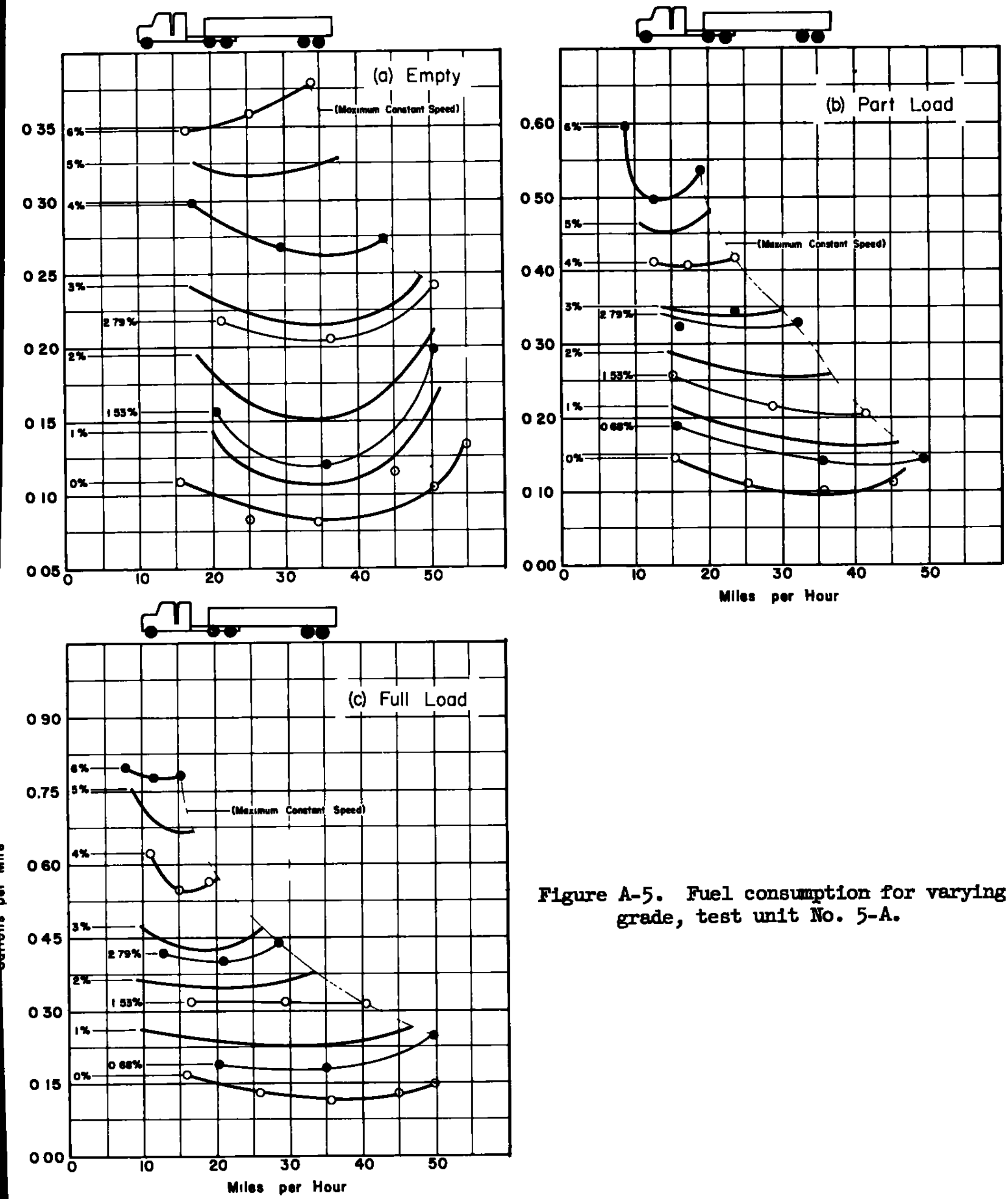


Figure A-5. Fuel consumption for varying grade, test unit No. 5-A.

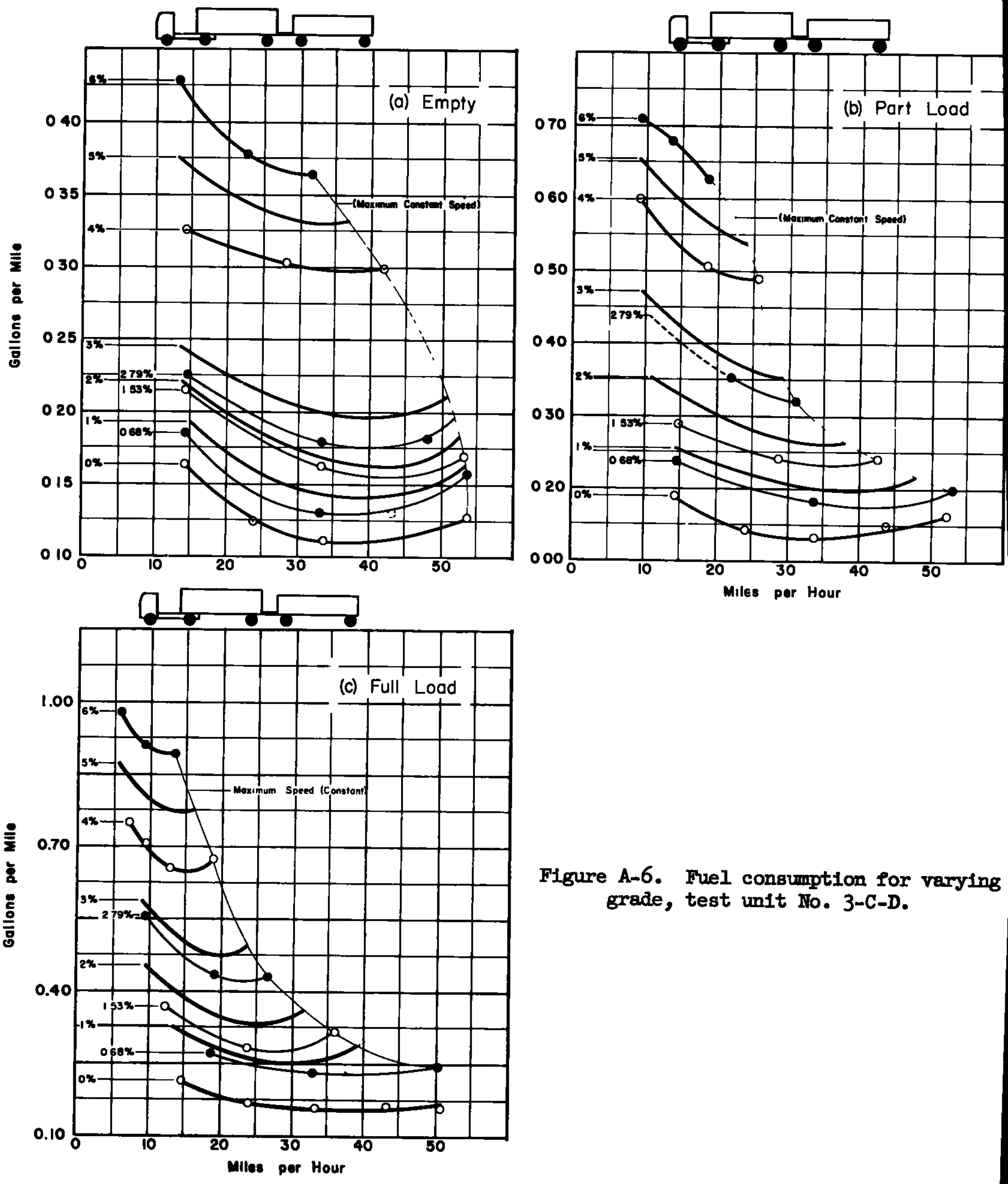


Figure A-6. Fuel consumption for varying grade, test unit No. 3-C-D.

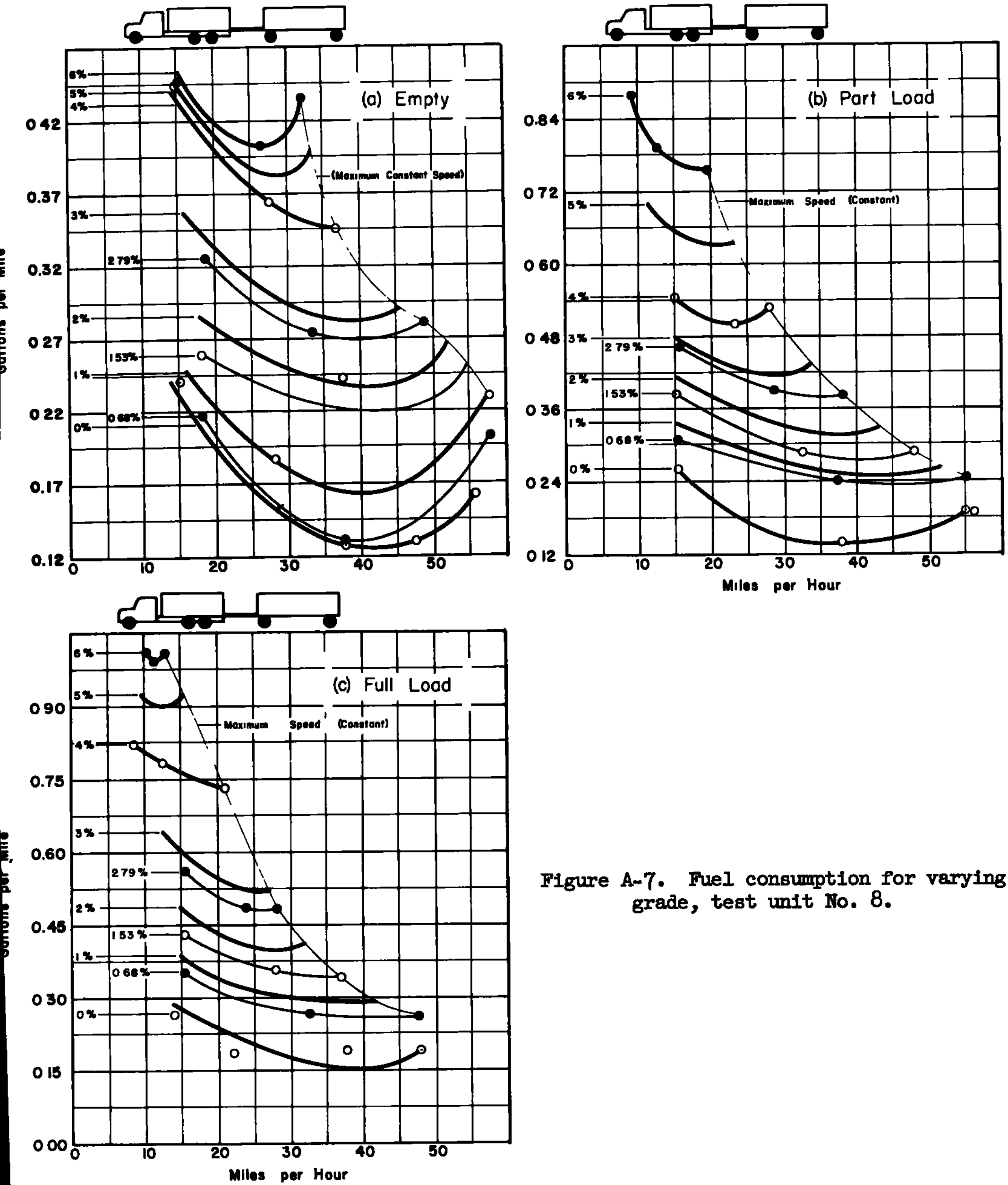


Figure A-7. Fuel consumption for varying grade, test unit No. 8.

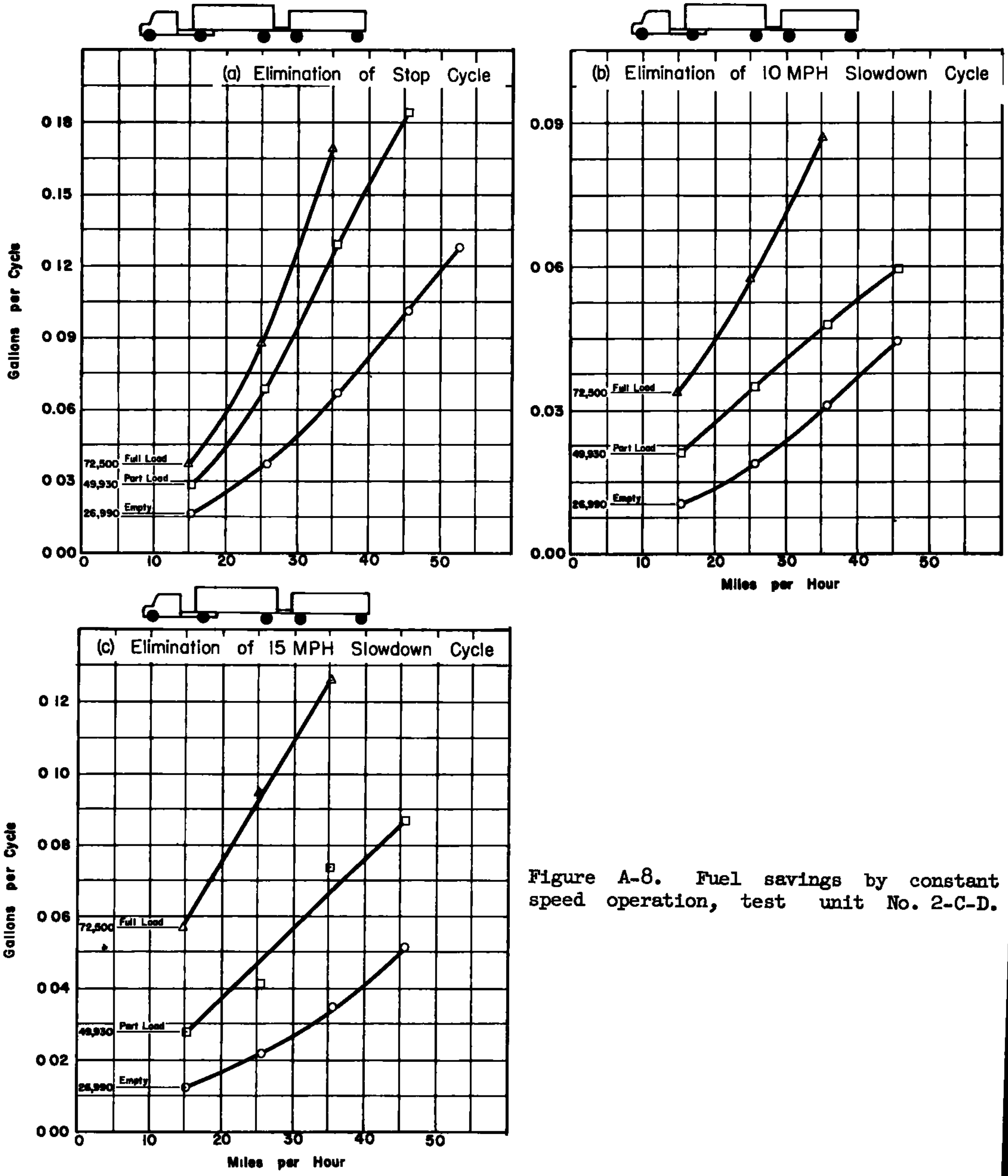


Figure A-8. Fuel savings by constant speed operation, test unit No. 2-C-D.

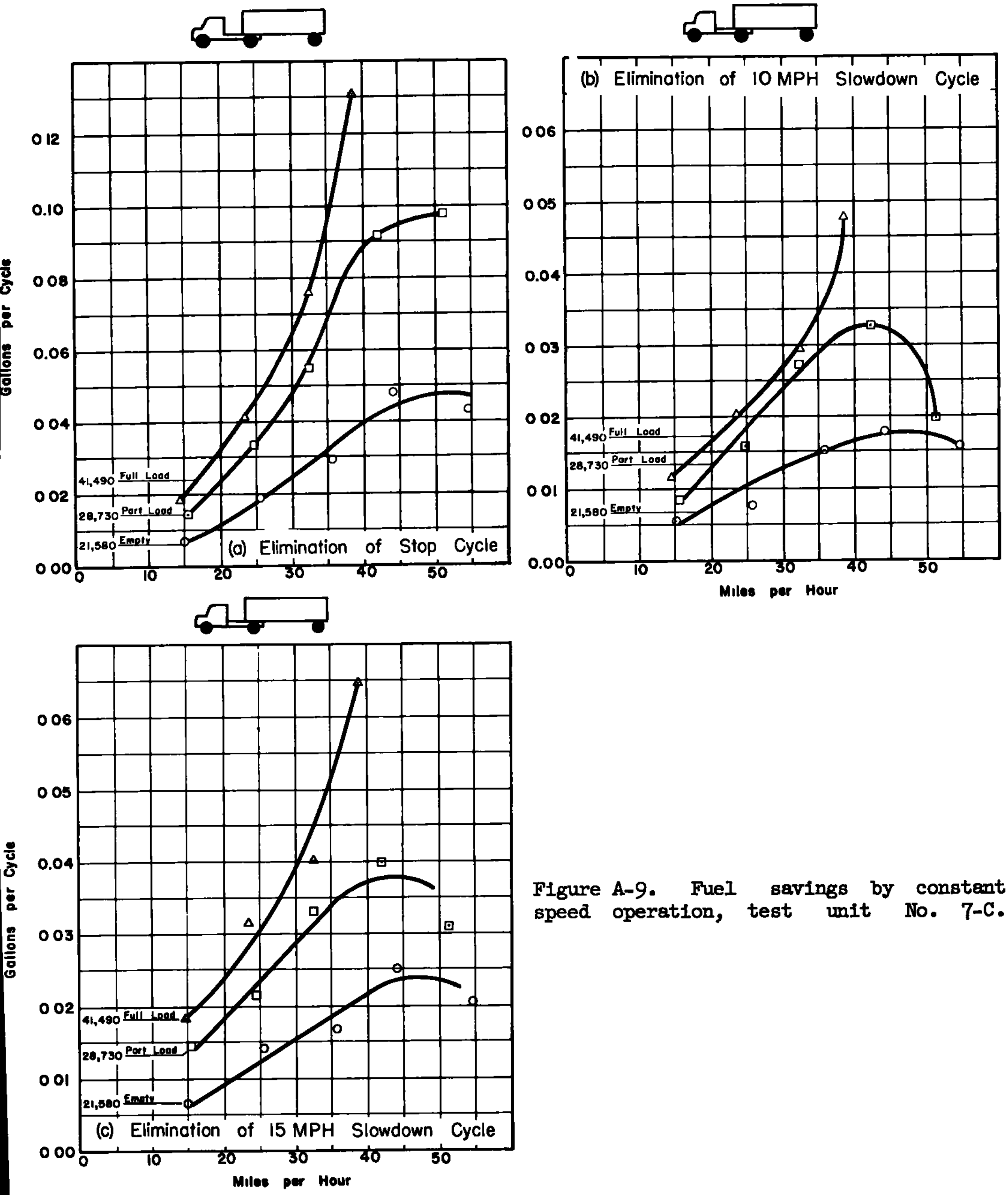


Figure A-9. Fuel savings by constant speed operation, test unit No. 7-C.

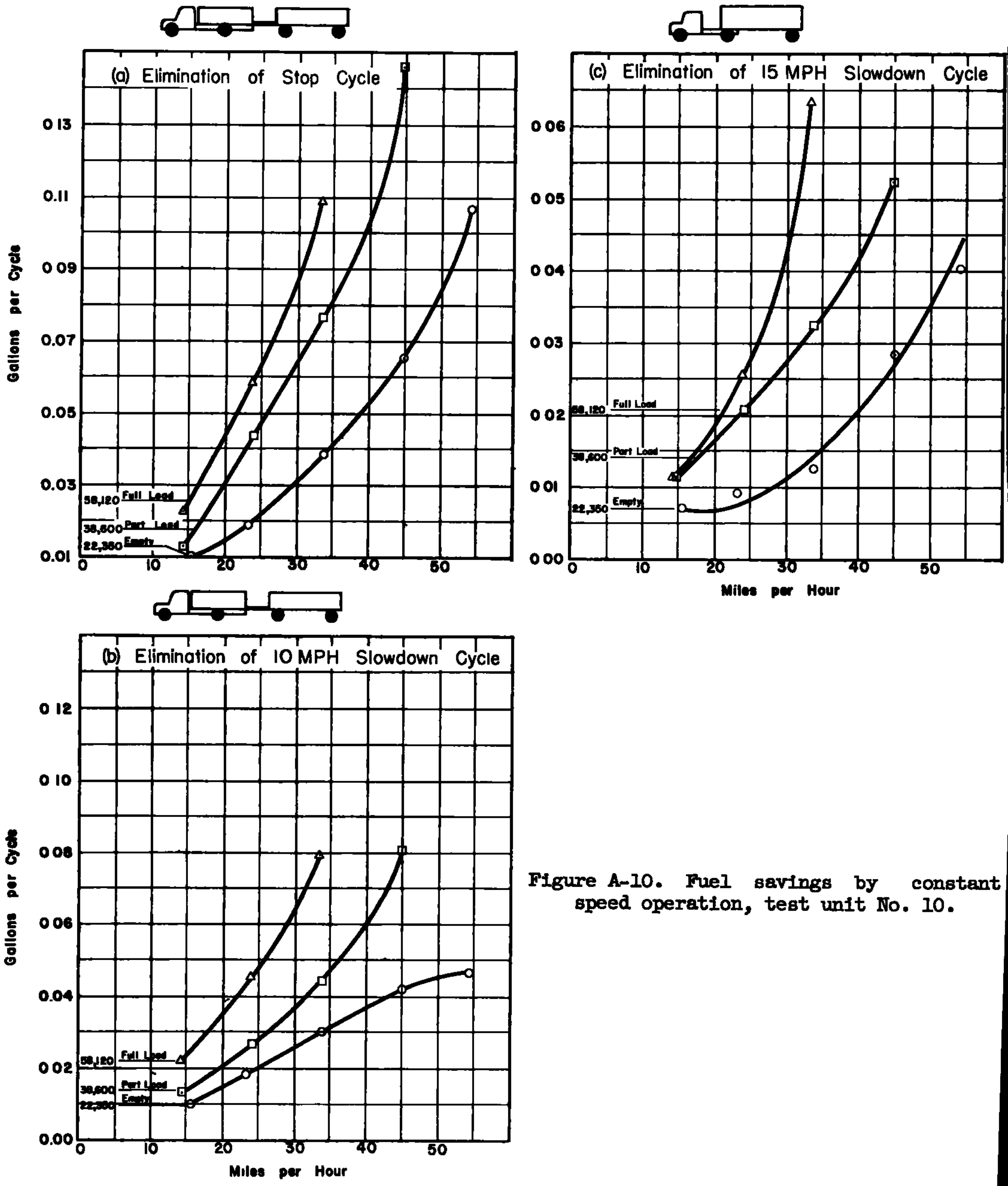


Figure A-10. Fuel savings by constant speed operation, test unit No. 10.

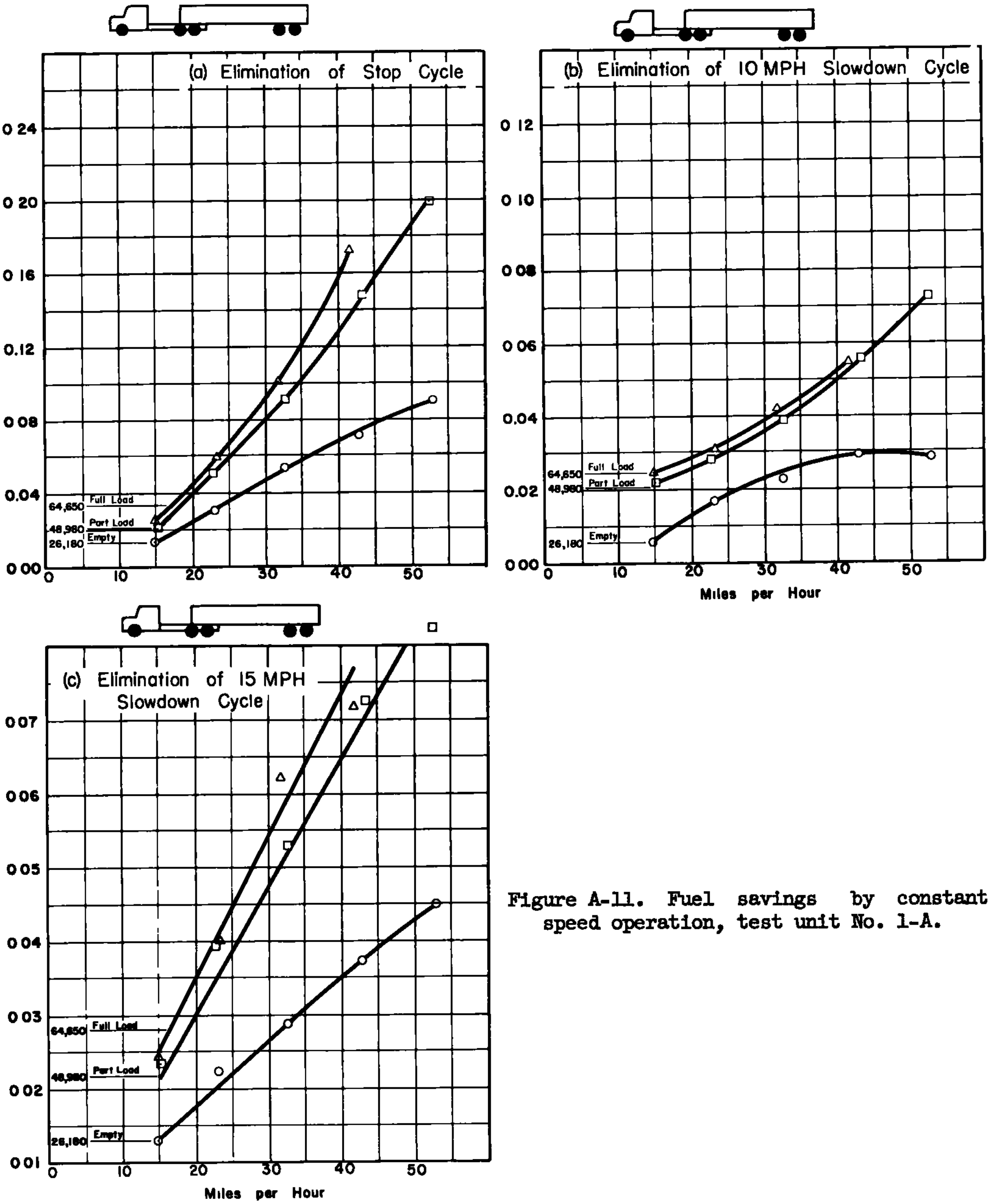


Figure A-11. Fuel savings by constant speed operation, test unit No. 1-A.

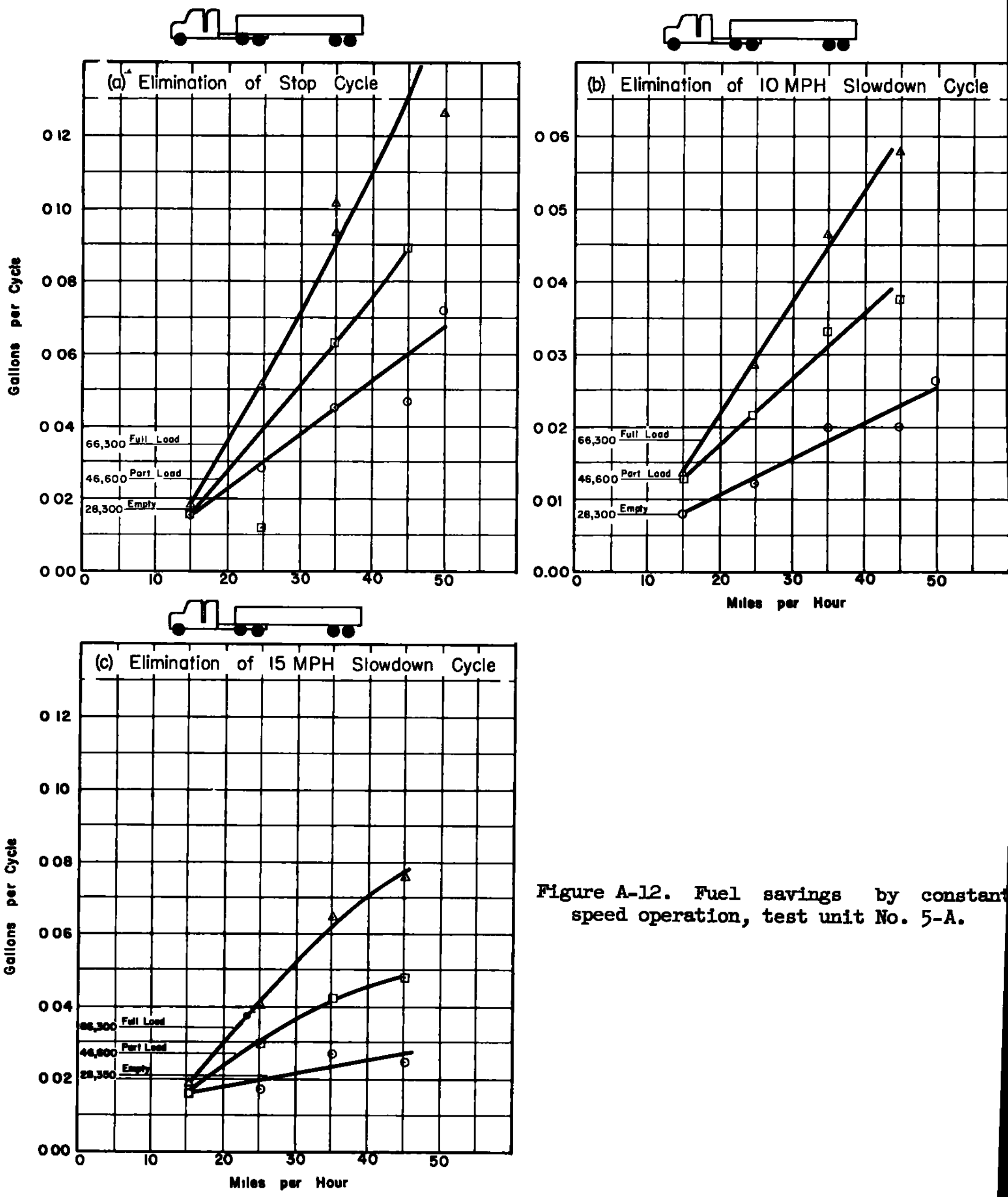


Figure A-12. Fuel savings by constant speed operation, test unit No. 5-A.

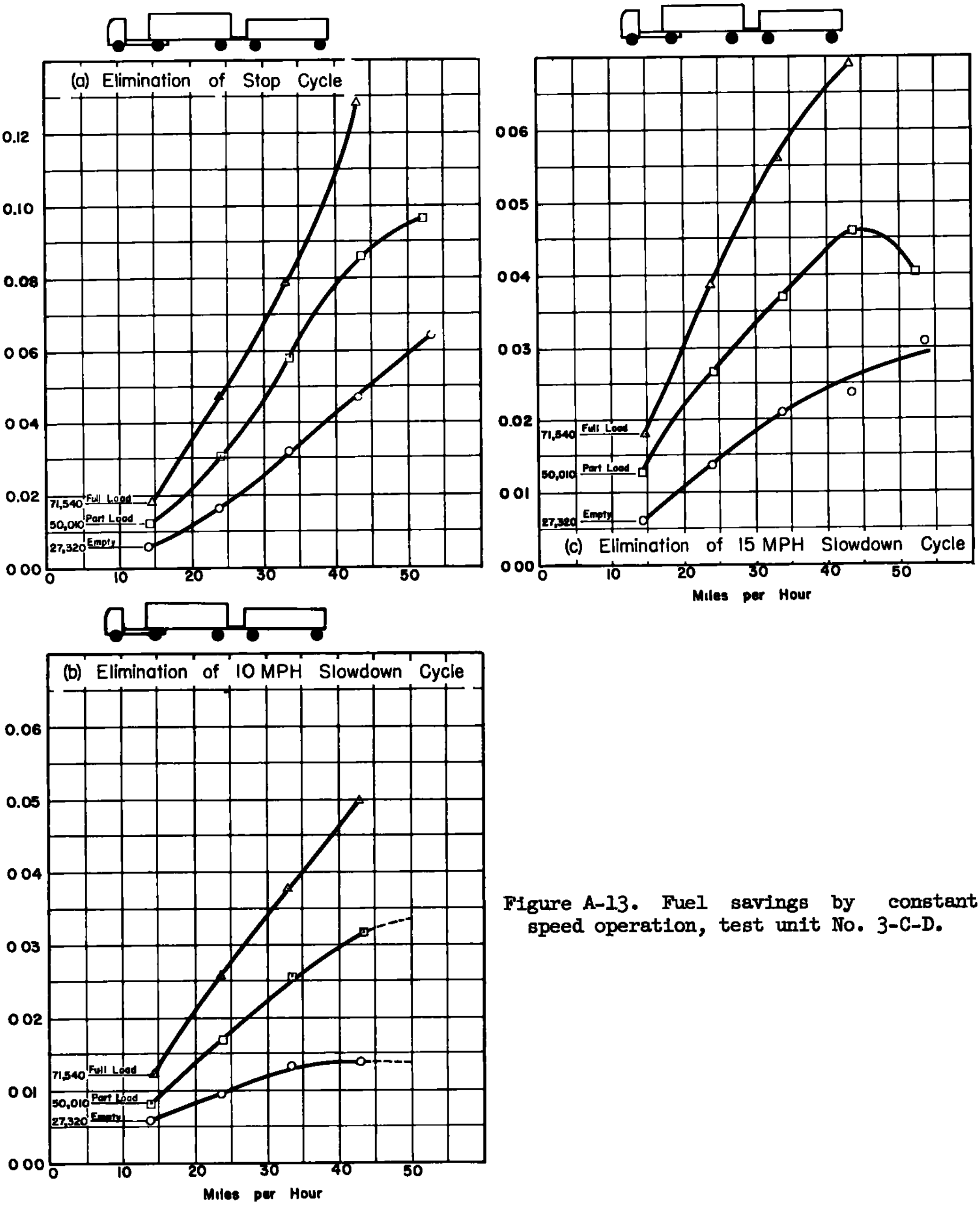


Figure A-13. Fuel savings by constant speed operation, test unit No. 3-C-D.

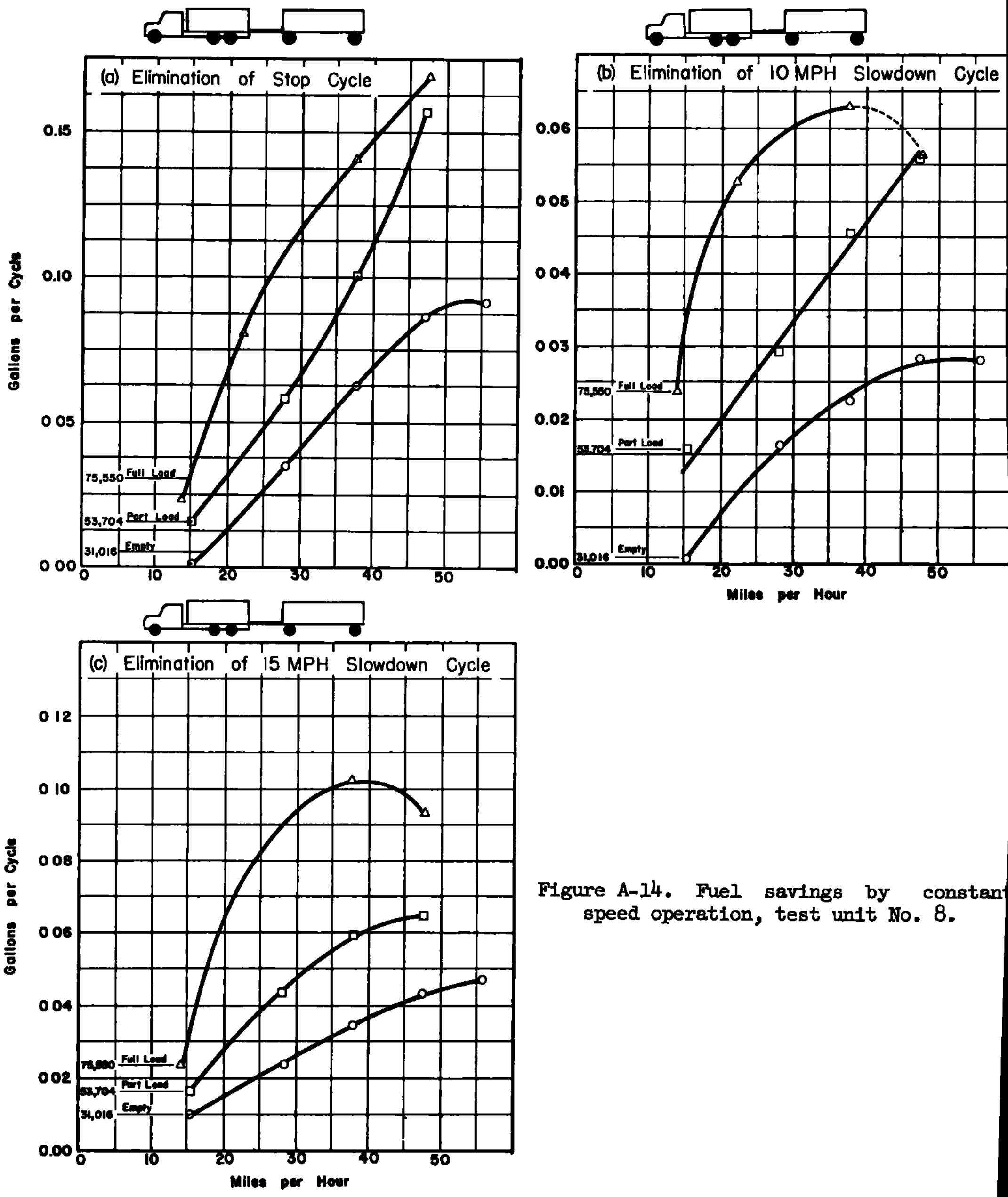


Figure A-14. Fuel savings by constan
speed operation, test unit No. 8.

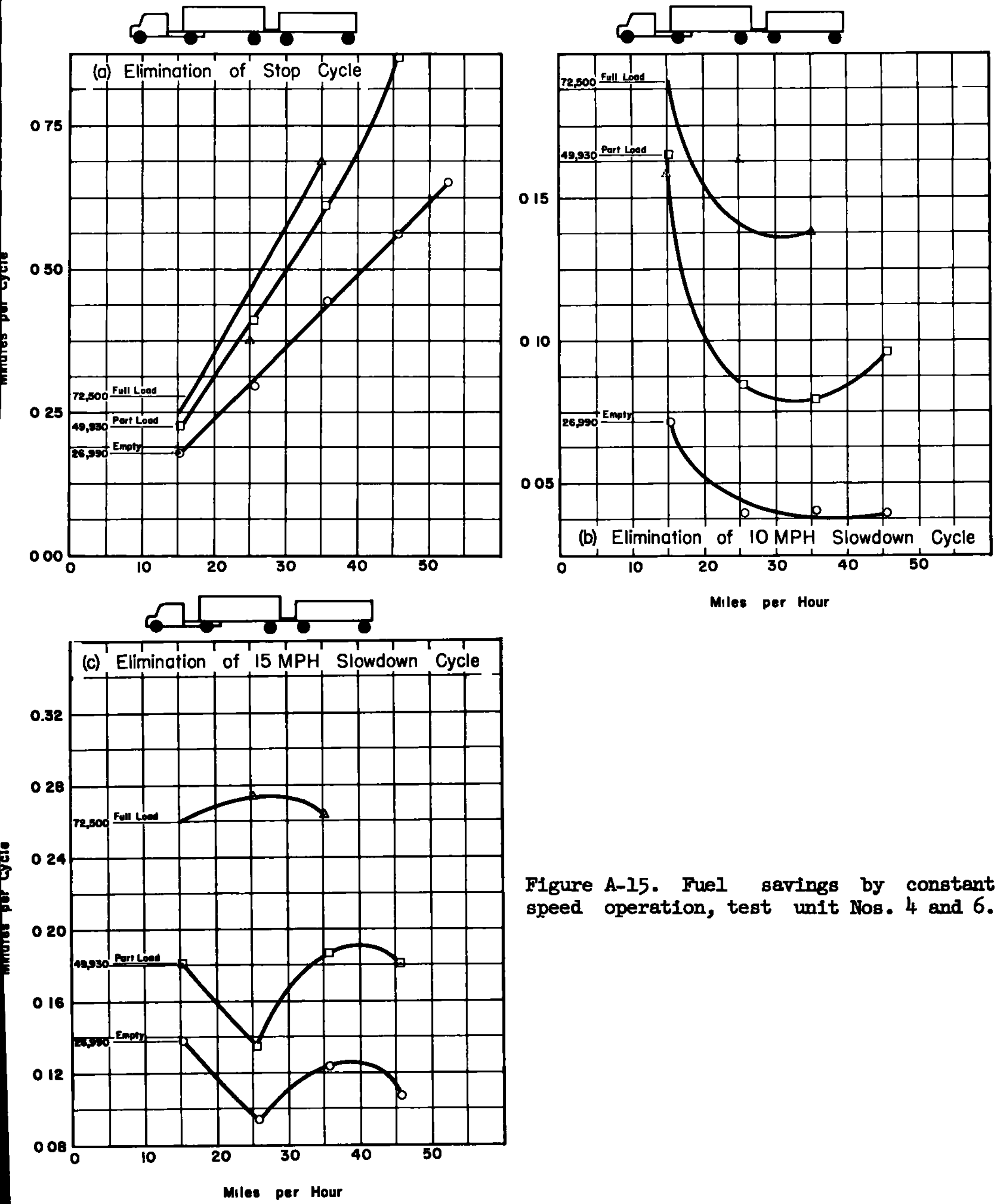


Figure A-15. Fuel savings by constant speed operation, test unit Nos. 4 and 6.

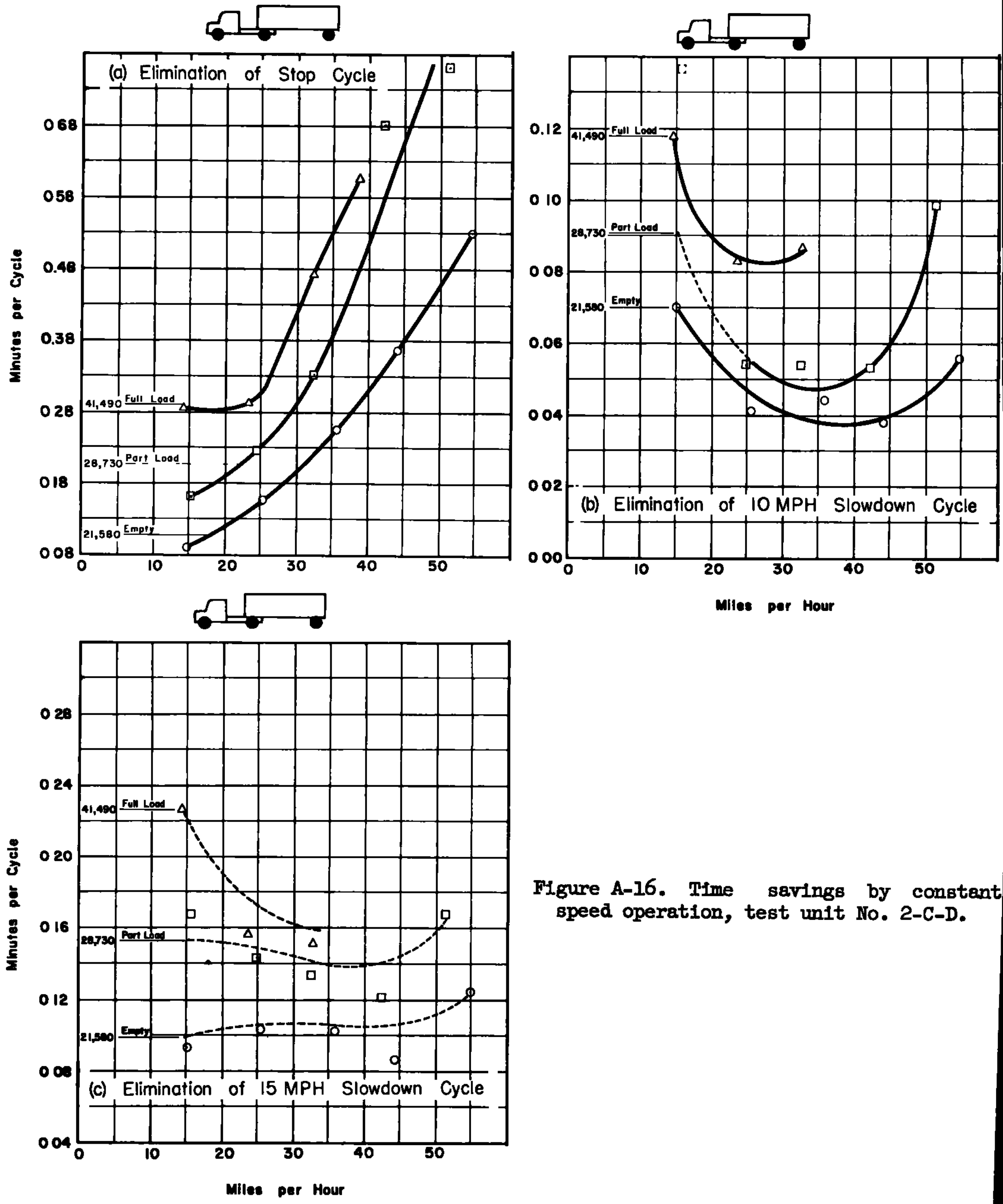


Figure A-16. Time savings by constant speed operation, test unit No. 2-C-D.

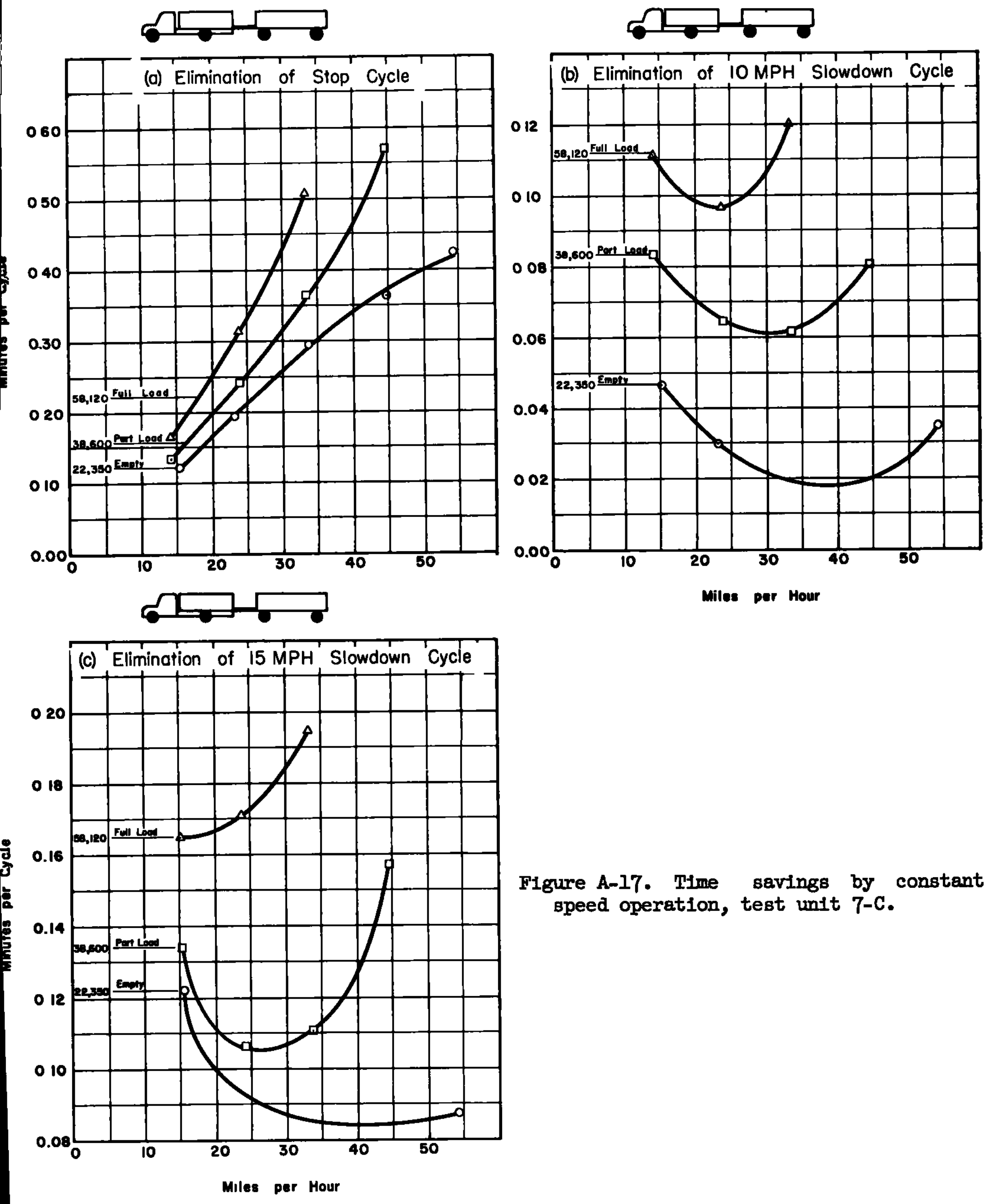
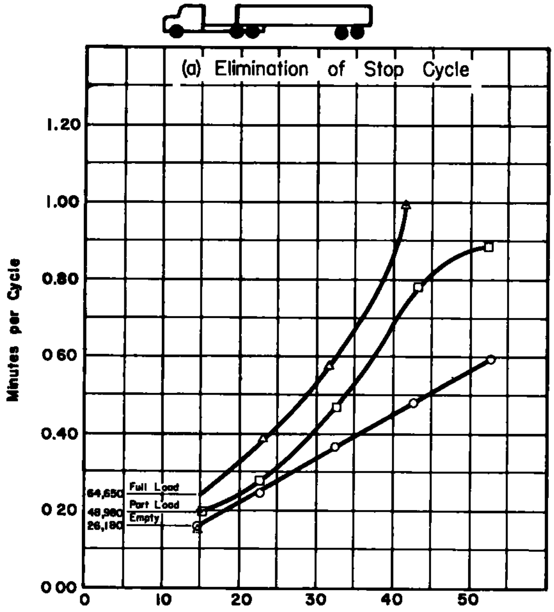
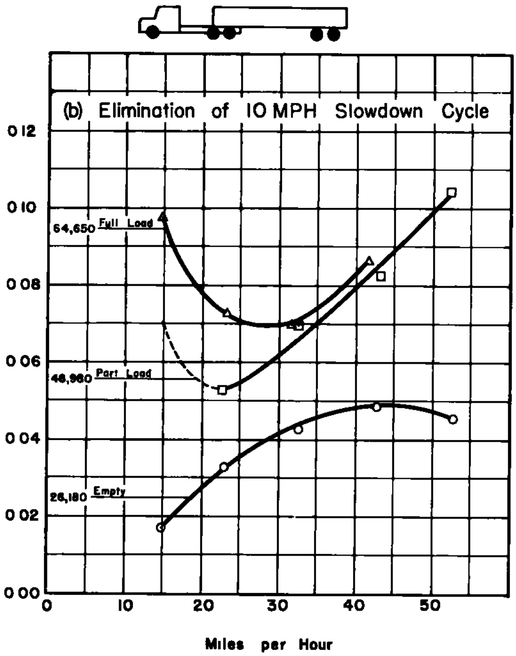


Figure A-17. Time savings by constant speed operation, test unit 7-C.





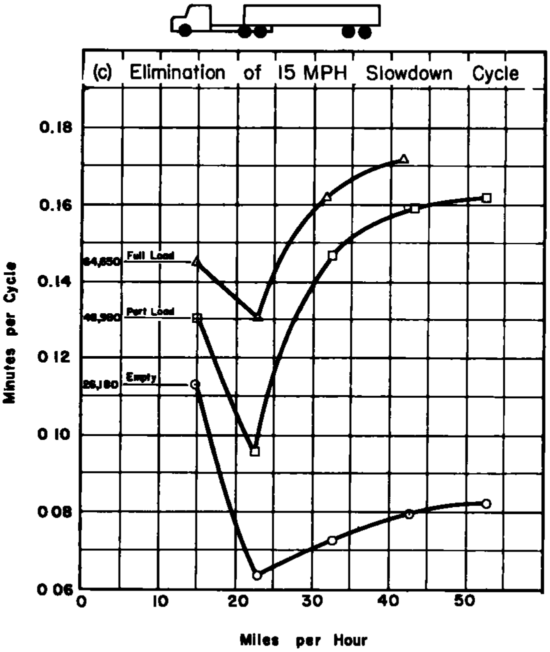


Figure A-18. Time savings by constant speed operation, test unit No. 10.

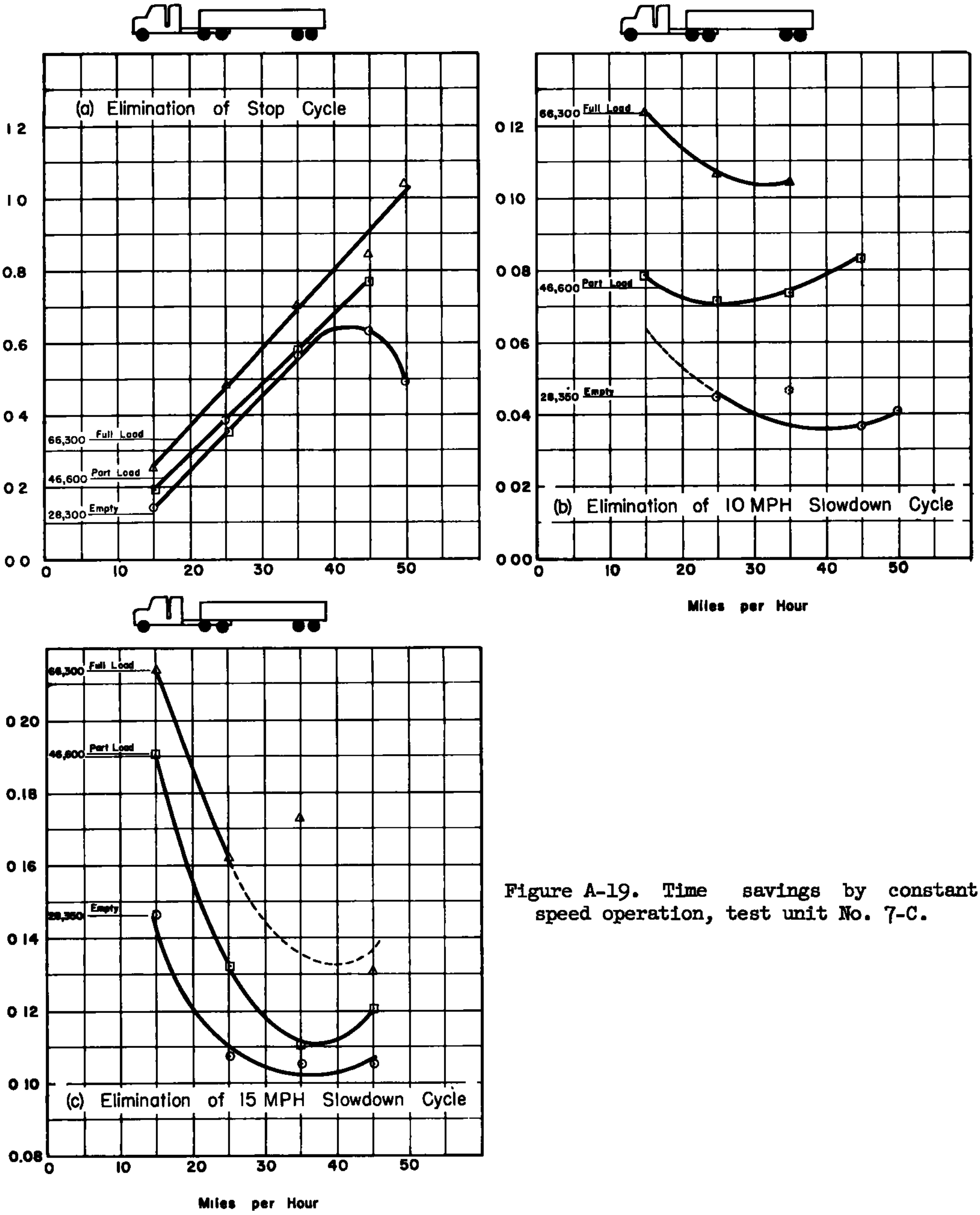


Figure A-19. Time savings by constant speed operation, test unit No. 7-C.

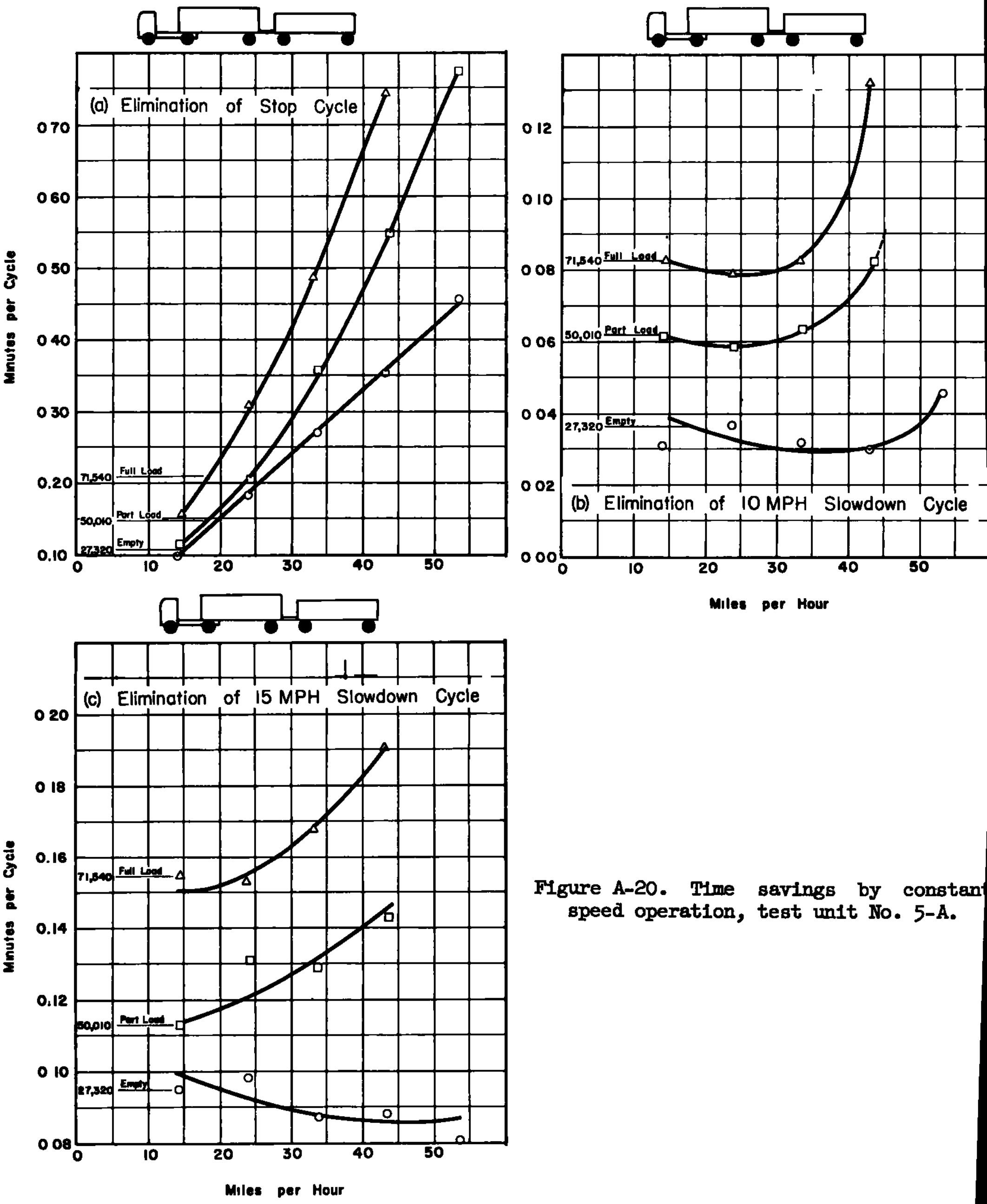
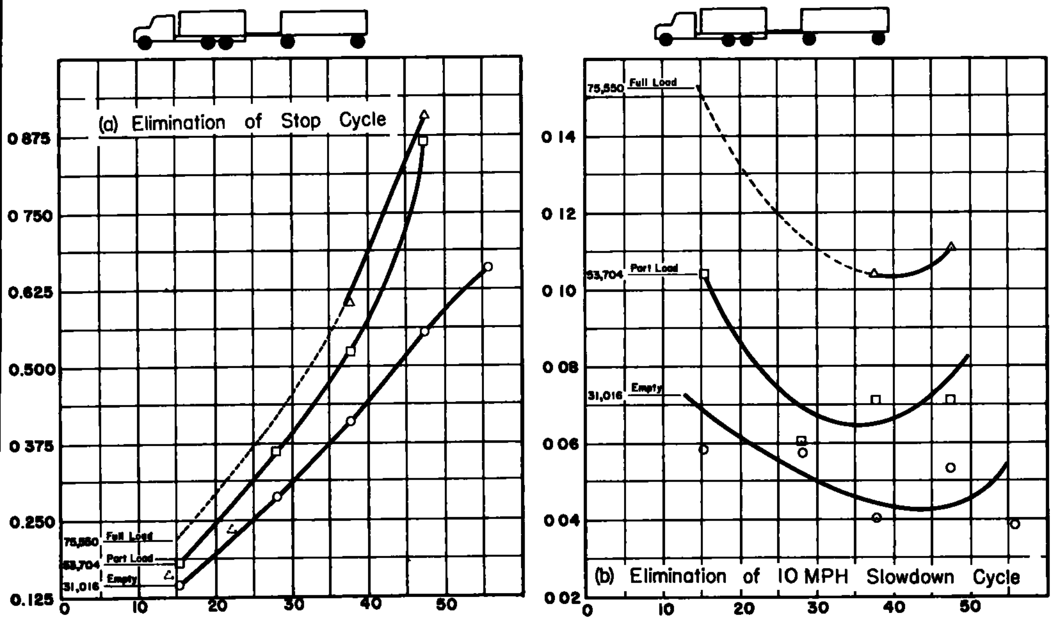


Figure A-20. Time savings by constan
speed operation, test unit No. 5-A.



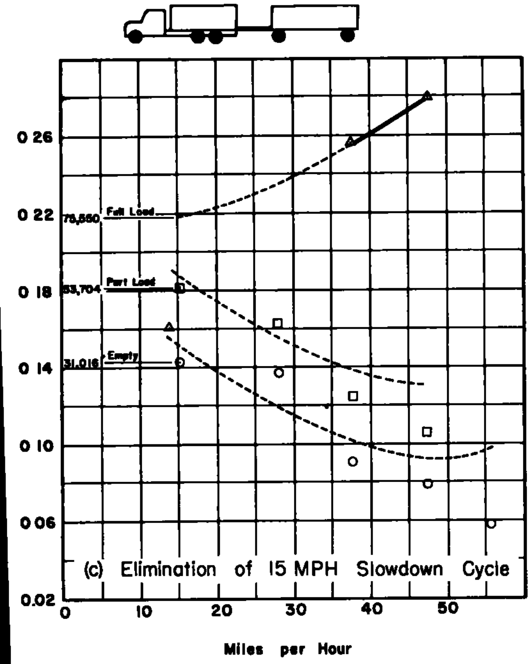


Figure A-21. Time savings by constant speed operation, test unit No. 3-C-D.

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