Predicting Fuel Consumption and Travel Time Of Motor Transport Vehicles

ROY B. SAWHILL, and JOSEPH C. FIREY, Respectively, Associate Professor of Civil Engineering and Professor of Mechanical Engineering, College of Engineering, University of Washington

Extensive data on fuel consumption and travel time of heavier trucks have been collected by research engineers at the University of Washington during the past two years under research contracts with the Bureau of Public Roads. Additional field measurements were supplied and the total information used to assist in identifying the factors to be considered in developing a formula for predicting fuel consumption or travel time. In the development of these equations the first approach was to investigate a theoretical work and energy method for making the prediction. By making a comparison of the theoretical values of fuel consumption and travel time with the actual measured values, it was possible to understand the factors involved and then to make an empirical mathematical fit of the data to an equation. The prediction of fuel consumption depends on the vehicle characteristics of gross vehicle weight and brake horsepower at wide-open throttle as well as the road characteristics of the distance traversed, the length of downhill distance, and the amount of rise in the highway profile. The prediction of travel time likewise depends on these vehicle and road characteristics in the cases of relatively rolling or mountainous terrain. However, in relatively flat topography and free-moving traffic the travel time is a function of the properly posted speed limit.

The formulas presented in this paper will be beneficial for future highway programming and planning purposes in evaluating benefits to be derived from various alternate highway locations. In addition, this information can be used for determining the economics of hauling commodities in large trucks on one route vs another, for commercial operation or construction purposes.

• THE MEASUREMENT of fuel consumption and travel time is not a new endeavor — literature is available dating back to shortly after the advent of the automobile. The major reasons for continued measurement of fuel consumption and travel time are to keep abreast of modifications in the vehicle performances and to improve the preciseness of instrumentation for making necessary measurements.

The measurement of these two characteristics is not as prevalent for the heavier-weight commercial vehicle as for passenger cars. The first major contribution to evaluating the gasoline consumption of trucks was performed (1) by the Oregon State Highway Department in the late 1930's. The Oregon study was comprehensive regarding the measurement of fuel consumption relative to surface type and alignment of the highway. It was, however, more complete in analyzing passenger car operation and

was somewhat limited in the amount of information collected on the commercial vehicle.

Not until 1948 was a study concentrating on the fuel consumption and travel time of the heavier weight vehicles undertaken. The results of this study, conducted under the direction of Saal, have been published (2). The study is considered one of the first steps forward in putting the fuel consumption and travel time of the commercial vehicles into a form intended to predict or evaluate the travel time and the fuel consumption of gasoline-powered vehicles in traversing a section of highway. This report is believed to be the first of its kind to utilize the parameters of rise and fall of the highway profile in making the predictions.

In 1958, under the sponsorship of the Bureau of Public Roads, fuel consumption and travel time studies were performed by two agencies throughout the United States for the measurement of fuel consumption and travel time of commercial vehicles in normal operation (3). Information was collected on the fuel consumption and travel time of these commercial vehicles operating over conditions of varied roadway types and traffic volume characteristics. The rise and fall of the highway profile was evaluated for the routes by use of altimeters. The route over which the commercial vehicles operated was subdivided into sections of sufficient length to obtain a large enough quantity for accurate measurement of the fuel consumption while the change in roadway or traffic volume conditions was also kept in mind. This series of tests stimulated engineers at the University of Washington to measuring fuel consumption and travel time of commercial vehicles; and this was the agency that collected the much-needed data on the fuel consumption of diesel powered vehicles. With the development of such a fuel meter by the University of Washington engineers, a subsequent study was performed in the summer of 1959 that evaluated the fuel consumption and travel time of gasoline- and diesel-powered vehicles in operating under a variety of conditions of speed, grade, load, surface, and traffic operating conditions (4).

During 1959 and 1960 one of the research test truck drivers became interested in the rise and fall concept of predicting fuel consumption and travel time. As a research assistant, this graduate student (5) evaluated a new concept of the rise and fall consideration that would eliminate one or two steps necessary in the use of the data presented in HRB Bulletin 9A. This thesis led to the more thorough investigation and measurement of fuel consumption and travel time for a range of values of rise and fall.

During the summer of 1960 and 1961 the University of Washington conducted additional fuel consumption studies that in part evaluated the more precise measurement of the fuel consumption of diesel- and gasoline-powered vehicles in traversing a wide range of rise and fall sections of four-lane divided highway relatively free of traffic interference.

There is a definite need for the evaluation of the operating characteristics of commercial vehicles particularly of fuel consumption and travel time requirements in negotiating the various highway profiles. The highway engineer has been only partly cognizant of the limitations of these vehicles in the design of highways. Evidence indicates that the most beneficial solution to the economics of motor-vehicle transportation is a compromise between vehicle and highway design. The highway engineer should design future highways with consideration to the operating characteristics of existing late model commercial vehicles. Such vehicles, unlike passenger cars, represent a major investment that cannot be amortized over a short period of time.

One of the primary purposes of the present study was to collect reliable information on up-to-date motor transport vehicles operating over a variety of highway profile conditions. From this data the study may possibly be expanded to include nonexisting vehicle types relative to weight and horsepower as well as percent of highway grades that are not now presently allowed under interstate or Federal highway construction standards.

Most highway engineers are becoming acutely aware of the need to evaluate the benefits derived by a highway relocation or improvement and to substantiate this by factual information for purposes of design, budget, and programming, as well as for public acceptance.

The previous studies of this type have been extremely well conceived and conducted. However, as in the case of HRB Bulletin 9A, the vehicles used for testing were some years older than those used for the present study. The level of control of the previous studies is not precisely known, but it is doubtful that the accuracy of measurements exceeded that of the University of Washington study. Fuel was measured to the nearest 5 ml and travel time to the nearest 0.01 min. HRB Bulletin 9A was a contribution to the evaluation of these two benefits derived from highway improvements. The method of analysis was an attempt to evaluate the fuel consumption and also the travel time by the manipulation of the apparently obvious parameters of rise and fall of the highway profile. However, no attempt is made in the report to rationalize the method of interpolating the data for arriving at a solution to the amount of fuel or travel time consumed in traversing a section of highway.

One contribution by the University study has been the inclusion of fuel consumption of diesel-powered vehicles in addition to that of gasoline-powered vehicles. The study also attempts to rationalize the method of predicting the fuel consumption and travel time and to verify or revise the concept published in HRB Bulletin 9A regarding the relation of fuel consumption to vehicle weight, as well as travel time as a function of weight to horsepower.

DATA COLLECTION

The measurement of fuel was undertaken by using the same method as in previous studies by the University (4). The system of burettes was slightly modified by the installation of a small-diameter standpipe tube beside each of the burettes. Behind each tube was mounted a graduated scale allowing greater precision as well as allowing a reading to be taken with the vehicle in motion. The day tank installation for metering diesel fuel was also improved by providing a more continuous flow of fuel to the day tank and also by reducing the slight error introduced by the operation of the vehicle on steep grades.

The measurement of time for the enroute tests as well as all other tests was made with stop watches calibrated to 0.01 min.

TEST SECTION AND VEHICLE

The test section utilized for the series of tests reported in this study is a portion of US 10 between Seattle and Cle Elum over the Snoqualmie Pass Highway. This same section was used in the study of 1958, which established control points for various types of highway or traffic conditions. Some of the same check points were used in this subsequent study, and additional check points were selected where deemed necessary to provide sufficient fuel consumed to obtain a reliable measure of the quantity used. In all cases the section of highway was four-laned and in general divided. Few of the sections operated at a traffic volume in excess of their practical capacity; and in cases where the driver observed infringement on his freedom of operation the observer would identify the particular section.

Table 1 gives geometric characteristics of the test section under study. The determination of the distance between check points was ascertained from actual construction plans and verified by the use of a calibrated fifth-wheel odometer, accurate to within $\pm 1/2$ percent. The elevations used for each check point was likewise determined from the actual construction plans.

The thesis that was the forerunner of this report considered diesel-powered tractors with semitrailers for fuel consumption and travel time to indicate a method of approach or the manipulation of the parameters for arriving at a more rapid evaluation of the fuel consumption and travel time. The test vehicles used for the study were a gasoline- and diesel-powered three-axled tractor with two-axle semitrailers, operated during the summer of 1960 and a gasoline- and diesel-powered two-axle tractor pulling a single-axle semitrailer and a two-axle full trailer operated during the summer of 1961. The test units used in 1961 and the diesel used in 1960 are shown in Figure 1.

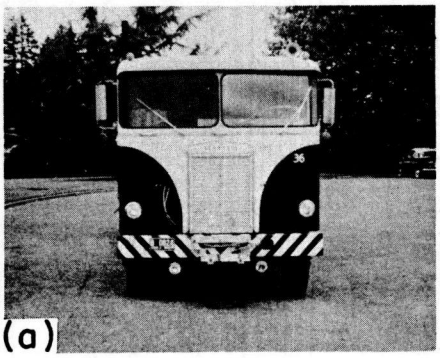
TABLE 1

TEST SECTION DESCRIPTIVE DATA

Check Point	Distance (ft)	Rise[a] PVI	Rise[a] POVC	Fall[a] PVI	Fall[a] POVC
Overpass SSH 2-D to Light at Issaquah	19,346	35.57	37.17	159.36	159.36
to East Fork Issaquah Creek	16,648	403.48	399.09	0	0
to North Bend signal light	55,482	653.37	616.68	694.31	656.45
to Edgewick Road	21,379	224.82	223.47	5.21	3.80
Marker east of Weigh Station to Middle crossing, Snoq. River	25,629	620.27	653.70	24.20	20.77
to Ollallie Creek	47,140	678.74	678.17	0.95	0.29
to Marker at West Summit	18,844	947.22	946.74	0	0
Marker at East Summit to Hyak Creek Bridge	12,899	0	0	393.44	391.40
to West end of snow shed	15,201	41.15	35.36	55.33	49.61
to Stampede Pass Overpass	26,236	20.50	14.01	148.38	144.22
to U-turn sign	25,001	281.69	273.94	52.90	45.53
to Easton	21,168	24.00	23.60	487.57	487.17
to U-turn sign	21,690	513.62	506.22	33.00	27.40
to Stampede Pass Under Crossing	25,038	52.48	44.50	280.85	271.11
to West End Snow Shed	26,352	199.20	186.42	57.20	55.96
to Hyak Creek Bridge[b]	16,152 (15,201)	82.19 (55.33)	69.63 (49.61)	66.69 (41.15)	49.52 (35.36)
Hyak Creek Bridge to Marker at East Summit	12,139	442.94	442.94	0	0
Marker at West Summit to Ollallie Creek	18,844	0	0	941.06	941.06
to Middle crossing Snoq. River	47,346	53.30	36.40	771.53	733.41
to Edgewick Road	28,200	35.54	21.30	663.11	651.69
to Signal light North Bend	21,009	0.30	0.13	212.70	221.56
to East Fork Issaquah Creek	55,488	694.31	656.45	653.38	616.68
to Light at Issaquah	16,590	0	0	403.48	399.09
to Overpass SSH 2-D	19,309	159.36	159.36	35.57	37.17

[a]PVI—elevations were determined from highway profiles using intersection of grades; POVC—elevations were determined by using actual elevations of highway directly under intersection of grade lines.

[b]This section varied for summer of 1960; correct data for period given in parentheses.



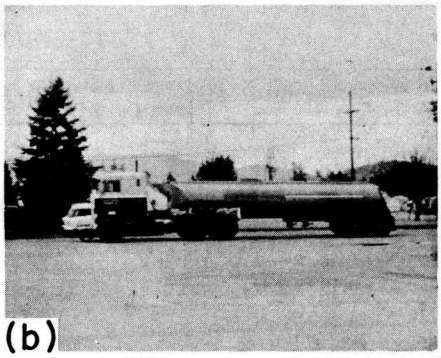
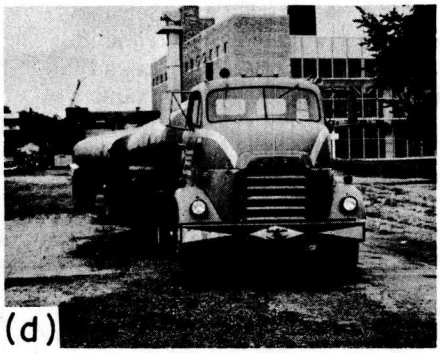
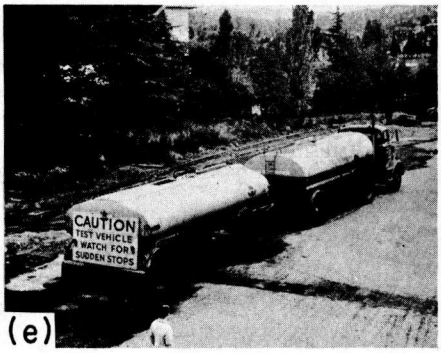


Figure 1. Visual description of three of the four test units used for precise measurement of fuel and travel time: (a) and (b) test unit 20-B (3-S2 diesel), summer 1960; (c) test unit 30-AB (2-S1-2 diesel), summer 1961; (d) and (e) test unit 31-AB (2-S1-2 gasoline), summer 1961.





The initial data, collected during the summer of 1960, was given preliminary evaluation before the other two test vehicles were operated during the summer of 1961. The latter study provided additional data, because it was found advantageous to increase the number of different gross vehicle weights from three to five. The characteristics of the vehicle and the various loading conditions are given in Table 2.

In addition, data were utilized from other previous studies to evaluate the procedure developed in the estimation of fuel consumption and travel time. Field data from the 1948 study conducted by Carl Saal was supplied to the University of Washington research group, and it was subjected to the same analysis as the detailed field data obtained for this study to verify or modify the methods developed in this report.

TABLE 2

TEST VEHICLE DESCRIPTIVE DATA

Characteristic	Test Vehicle			
	20 B	22 B	30 AB	31 AB
Axle class. of comb.	3-S2	3-S2	2-S1-2	2-S1-2
Power unit vehicle (tractor):				
Year of manufac.	1958	1955	1955	1956
Body type[a]	--	--	--	--
Frontal area of power unit (sq ft)			57.0	41.0
Wheelbase (ft):				
Axle 1 to 2		15.8	9.8	10.7
Axle 2 to 3		4.0		
Engine				
Fuel	Diesel	Gasoline	Diesel	Gasoline
No. of cylinders	6	6	6	6
Displacement (cu in.)	743	501	743	503
Mfgrs. net hp at rpm	200 at 2,100	184 at 2,600	220 at 2,100	214 at 3,200
Rear axle gear ratio	5.54	6.686	6.51/4.93	8.87/6.50
Transmission ratio:				
Main 1st	10.45	8.08	5.19	5.71
2nd	8.38	4.67	2.28	3.02
3rd	6.52	2.62	1.72	1.78
4th	5.23	1.38	1.00	1.34
5th	4.09[b]	1.00		1.00
Aux. 1st		1.29		
2nd		0.84		
3rd				
Tire size, power unit	11 × 24.5	10.0 × 20	11 × 24.5	10.3 × 20
First trailer:				
Type	Semi	Semi	Semi	Semi
Body type	Tanker	Tanker	Tanker	Tanker
Frontal area	Less than tanker	Less than tanker	Less than tanker	Less than tanker
Wheelbase (ft):				
Kingpin to axle	22.3	22.3	15.2	15.2
Axle 1 to 2	3.8	3.8		
Second trailer:				
Type			Full	Full
Body type			Tanker	Tanker
Frontal area			Less than tractor	Less than tractor
Wheelbase, axle 1 to 2 (ft)			19.5	19.5
Combination, over-all length (bumper to bumper) (ft)		47.8	61.2	62.1
Gross weight, empty (lb)	26,960	27,900	27,000	25,340

[a]None on tractors.
[b]Vehicle 20 B had 12 gear transmissions; gears 6 through 12 were 3.28, 2.55, 2.05, 1.59, 1.88, 1.00, and 0.80.

NOMENCLATURE

The following nomenclature is used:

HP = engine horsepower output;
HHV = fuel higher heating value, Btu per gallon;
n = engine thermal efficiency;

Samples taken from a continuous mixer at standard mix temperatures showed about the same amount of hardening as batch plants.

Mixes.—The results of three different mixes made at Plant F are shown in Figure 6. There is no significant difference in the hardening obtained with the different mixes. Data from other plants indicate no definite effect on hardening of mix composition. Another example is shown in Figure 7.

Asphalts.—The asphalts used in this project were from three different sources but thin film oven tests, viscosities, and other properties varied little. Table 8 gives some typical test results that were supplied by the producers for their 85-100 penetration grade asphalts, and Figure 1 shows typical viscosity-temperature relationships as supplied by the same producers.

There appears to be some difference in viscosity values at 275 F between the table values and the curves. This is brought about by variations in the asphalt from time to time as the tables or charts were compiled. Tests made on the viscosity of the asphalts indicate the curves in Figure 1 represent the material used in the mixes of this project.

Table 9 gives the results of the thin film oven tests compared with hardening obtained in the plant mixes at 325 F. This temperature probably approaches the maximum for acceptable operations in construction. The retained penetrations of the laboratory tests and of the field mixing are in excellent agreement.

The thin film oven tests and other laboratory tests of the asphalts do not vary greatly and it would not be expected that there would be any marked difference in the behavior of the asphalts when mixed in the field. The effect of asphalt type on hardening was somewhat difficult to evaluate because it was impossible to separate this variable completely from the effect of plants and aggregates. However, there appeared to be no great difference in hardening that could be attributed to type of asphalt. Had asphalts

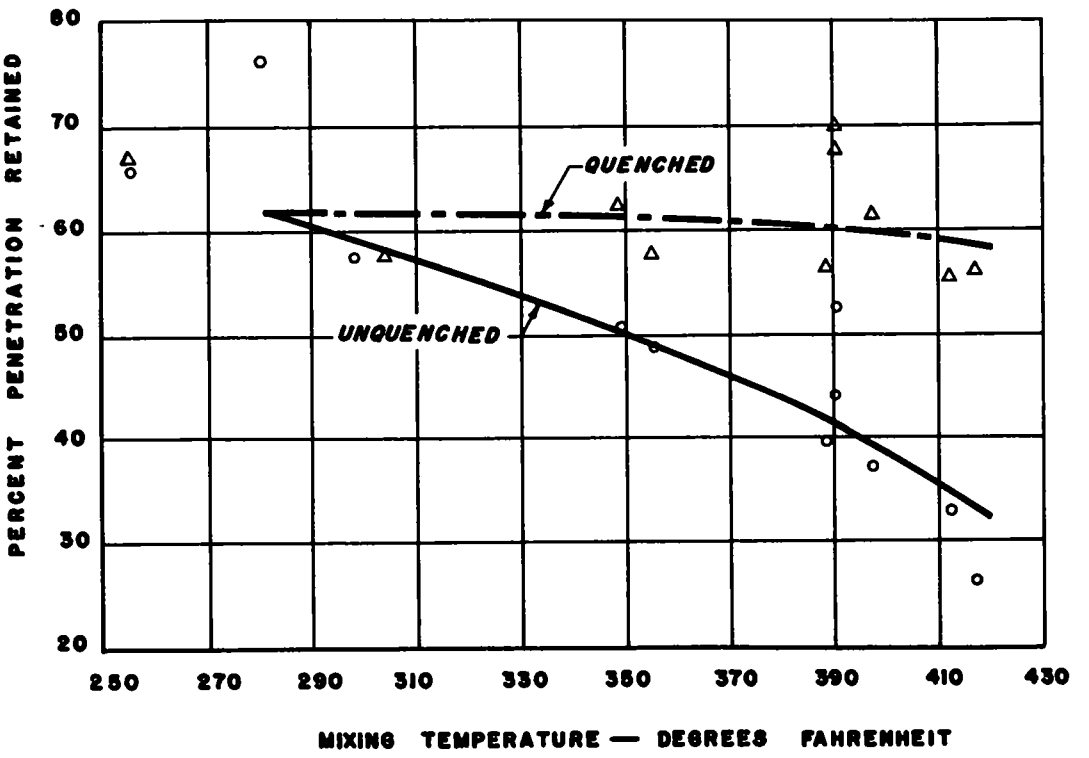


Figure 8. Comparison of percent penetration retained for all quenched and unquenched samples.

less resistant to hardening been used, it is quite likely that greater hardening would have occurred in the plant.

Rate of Cooling. —In measuring hardening in the mixer, a problem arose as to the proper procedure to use in cooling samples. Some investigators (19) have found that samples cooled quickly showed less penetration loss than those cooled slowly. This behavior was borne out by the present investigation. A study of Figures 8 and 9 shows this effect quite clearly.

The quenched samples show little change in hardening when the temperature was increased from about 300 to 400 F. Because large changes took place in the slowly cooled samples, indications are that the hardening is both a time- and temperature-controlled phenomenon. The mixes made at about 300 F show less difference between quenched and unquenched samples than do the mixes made at higher temperatures. This would mean that the hardening occurring after mixing is not serious with mixing temperatures normally used. Moreover, under present day practice, it is difficult to see what could be done about the situation to prevent such hardening. The finding is interesting from the theoretical aspect in that it shows appreciable hardening occurring long after the violent agitation of the mixture has ceased.

Some attempts were made to follow trucks enroute from the plant to the paver and take samples at intervals during the hauling period. Such results indicate some hardening enroute but results were spotty and it was difficult to draw conclusions.

None of the off-specification batches were laid or compacted, so taking road samples was impossible. Others (1, 11) found no difference between samples taken at the plant and those taken from the newly laid pavement. On this project, slowly cooled samples taken at the plant gave results similar to samples taken at the paving machine, so it is assumed that the slowly cooled samples approached the values that would have been obtained if paving samples had been available.

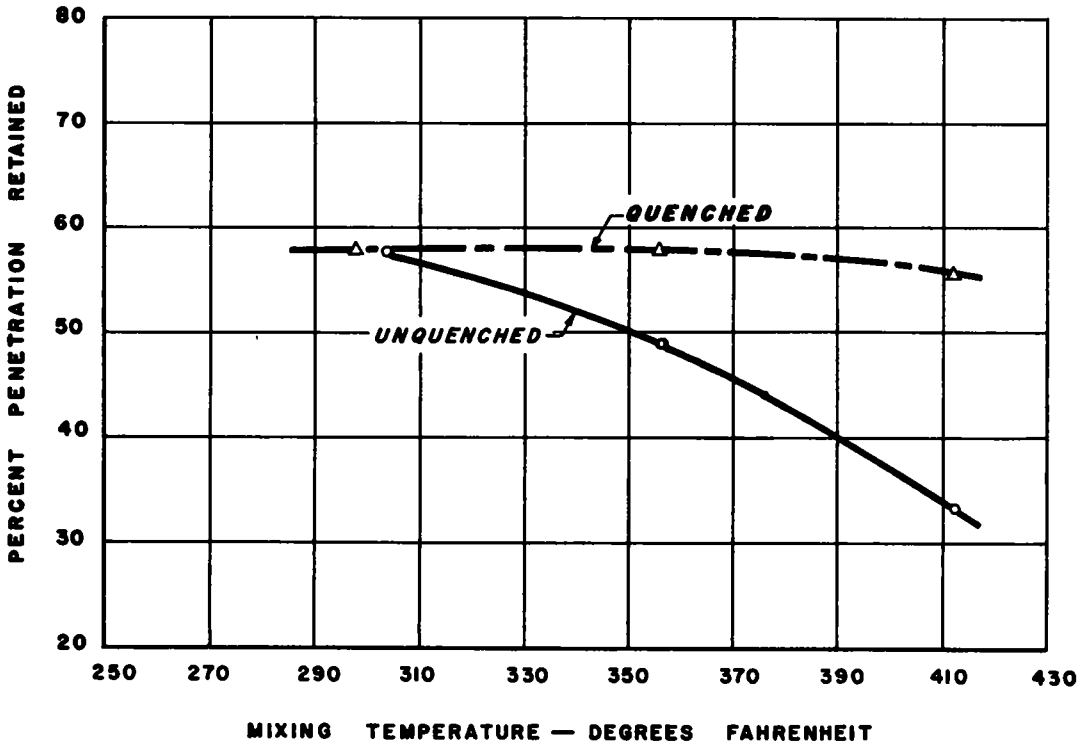


Figure 9. Comparison of percent penetration retained for quenched and unquenched samples within Group XVII.

Grade resistance can be calculated from the potential energy relation,

$$(PE) = \left(\frac{GVW}{37,500}\right) G_i \frac{d_i}{52.8} \tag{6}$$

in which (PE) is the potential energy acquired by a truck of weight GVW when traversing a highway section of grade G_i and length d_i expressed in horsepower-hours. The highway percent grade, G, is here taken positive on upgrades and negative on downgrades. To assist in the subsequent evaluation of energy dissipated at the brakes, grade energy is best evaluated separately for the uphill and downhill portions of a highway. For uphill sections:

$$\int_o^T (PHP)_u \, dT = \left(\frac{GVW}{37,500}\right) \sum_i G_i \frac{d_i}{52.8}$$

$G_i \, d_i = R_i$ = rise of the section i in feet

$$\int_o^T (PHP)_u \, dT = \frac{GVW}{1.98 \times 10^6} \sum R_i \tag{7a}$$

Similarly, for downhill sections:

$G_j \, d_j = F_j$ = fall of the section j in feet

$$\int_o^T (PHP)_d \, dT = \frac{GVW}{1.98 \times 10^6} \sum F_j \tag{7b}$$

The total grade energy then becomes

$$\int_o^T (PHP) \, dT = \frac{GVW}{1.98 \times 10^6} \sum R - \frac{GVW}{1.98 \times 10^6} \sum F \tag{7c}$$

Eq. 8 for truck kinetic energy is obtained from Beakey (1) and includes an approximate correction for rotational kinetic energy:

$$(KE) = \left(\frac{GVW}{29.6 \times 10^6}\right)\left(1 + 152 \frac{W + 1}{GVW}\right) \frac{(mph)^2}{2} = K\,(mph)^2 \tag{8}$$

in which (KE) is the kinetic energy acquired by a truck of weight GVW when the speed is increased from zero to (mph) expressed in horsepower-hours. Because in loading and subsequently unloading cargo a truck must be stopped, the net change of truck kinetic energy is always zero on any useful run, even though wide variations of kinetic energy may occur during the run. Hence,

$$\int_o^T (AHP) \, dT = 0 \tag{9}$$

Nevertheless, changes of truck kinetic energy must be evaluated because in coming to a stop at the end of a run and in making stops during a run the energy dissipated at the brakes is most readily evaluated as being equal to a portion of the resulting loss of vehicle kinetic energy.

As discussed elsewhere (4), engine friction horsepower can be approximated by Eq. 10, provided the usable range of engine RPM is not too wide.

$$FHP = bN_E \tag{10a}$$

$$\int (FHP) \, dT = bN_E \, dT = \frac{b(M)}{60} \tag{10b}$$

The total number of engine revolutions, M, made while running over a section of highway can be approximated as the product of average engine rpm and the time taken to traverse the section.

$$M_d = N_{EA} \, T_d \, (60) \tag{11}$$

The time taken to traverse a section of highway of length d can be calculated as

$$T_d = \frac{d}{mph_d} = \frac{d}{52.8\ mph_d} \tag{12}$$

in which (mph_d) is the average truck speed over the section.

The engine friction energy term now becomes

$$\int_o^d (FHP)\ dT = \frac{bN_{EA}}{52.8} \frac{d}{(mph_d)} = f \frac{d}{(mph_d)} \tag{13}$$

The energy dissipated at the brakes is clearly indeterminate because the driver has a choice in the extent to which he may use the brakes, and widely varying traffic conditions may dictate in part the extent to which the brakes are used. An estimate of the energy dissipated at the brakes can, nevertheless, be made by use of the following assumptions:

1. The brakes are used only when stopping or on downhill sections.
2. On downhill runs, the truck potential energy is fully utilized to overcome engine friction, rolling resistance, and brake resistance only. Stated otherwise, the brakes are assumed to be used on downhill to keep truck speed constant.
3. When the brakes are being applied, the throttle is closed.

The horsepower balance for a downhill run then becomes

$$IHP_i = FHP + RHP + PHP + AHP + HPB_F \tag{14}$$

in which IHP_i is the indicated power developed by the engine at closed throttle. Over the downhill distance d_F, the work and energy balance becomes

$$\int_F (IHP_i)\ dT = \int_F (FHP)\ dT + \int_F (RHP)\ dT + \int_F (PHP)\ dT + \int_F (AHP)\ dT + \int_F (HPB_F)\ dT \tag{15a}$$

in which HPB_F is the power dissipated at the brakes during downhill running. Rearranging.

$$\int_F (HPB_F)\ dT = \int_F (IHP_i)\ dT - \int_F (FHP)\ dT - \int_F (RHP)\ dT - \int_F (PHP)\ dT - \int_F (AHP)\ dT \tag{15b}$$

The indicated work done by the engine at closed throttle downhill running is small. It can be adequately approximated by use of the fuel consumption relation.

$$(\text{Gal used downhill}) = \frac{2,545}{(nI)(HHV)} \int_F (IHP_i)\ dT = (Gal_F) \tag{16a}$$

$$\int_F (IHP_i)\ dT = \frac{(n)(HHV)(Gal_F)}{2,545} \tag{16b}$$

The total gallons of fuel used on downhill runs can be estimated as the product of the engine idle fuel flow rate, ghp_i, and the time spent on downhill runs, T_F.

$$(Gal_F) = (ghp_i)\ T_F \tag{17}$$

The time spent on downhill can be calculated as

$$T_F = \frac{d_F}{52.8\ mph_F} \tag{18}$$

in which mph_F is the average truck speed during downhill running that would normally be the legal or safe operating speed limit.

$$\int_F (IHP_i)\ dT = \frac{(nI)(HHV)(ghp_i)d_F}{(2,545)(mph_F)(52.8)} = e \frac{d_F}{(mph_F)} \tag{19a}$$

The remaining terms in the relation for downhill braking energy are evaluated as explained previously with the following results:

$$\int_F (FHP)\, dT = f \frac{d_F}{(mph_F)} \tag{19b}$$

$$\int_F (RHP)\, dT = a \frac{d_F}{52.8} \tag{19c}$$

$$\int_F (PHP)\, dT = - \frac{GVW}{1.98 \times 10^6} \sum F \tag{19d}$$

$$\int_F (AHP)\, dT = 0 \tag{19e}$$

After collecting all terms, the energy dissipated at the brakes during downhill running is evaluated as

$$(HPB_F)\, dT = e \frac{d_F}{(mph_F)} - f \frac{d_F}{(mph_F)} - \frac{ad_F}{52.8} + \frac{GVW}{1.98 \times 10^6} \sum F \tag{20}$$

The horsepower balance when the brakes are being applied to stop the truck is

$$IHP_i = FHP + RHP + PHP + AHP + HPB_B \tag{21}$$

Over the braking distance d_B, the work and energy balance becomes

$$\int_B (IHP_i)\, dT = \int_B (FHP)\, dT + \int_B (RHP)\, dT + \int_B (PHP)\, dT + \int_B (AHP)\, dT + \int_B (HPB_B)\, dT \tag{22a}$$

By rearranging terms,

$$\int_B (HPB_B)\, dT = \int_B (IHP_i)\, dT - \int_B (FHP)\, dT - \int_B (RHP)\, dT - \int_B (PHP)\, dT - \int_B (AHP)\, dT \tag{22b}$$

The time spent braking the truck to a stop is estimated as

$$T_B = \frac{2d_B}{52.8\ mph_t} \tag{23a}$$

in which mph_t is the average truck speed at the start of braking. The various terms are evaluated as before with the following results:

$$\int_B (IHP_i)\, dT = e \frac{2d_B}{mph_t} \tag{23b}$$

$$\int_B (FHP)\, dT = f \frac{2d_B}{mph_t} \tag{23c}$$

$$\int_B (RHP)\, dT = \frac{ad_B}{52.8} \tag{23d}$$

$$\int_B (PHP)\, dT = \frac{GVW}{1.98 \times 10^6} \sum R_B - \frac{GVW}{1.98 \times 10^6} \sum F_B \tag{23e}$$

$$\int_B (AHP)\, dT = S\, K\, (mph_t)^2 \tag{23f}$$

in which S is the total number of stops made from an average truck speed of (mph_t). By collecting all terms the energy dissipated at the brakes during stops is evaluated.

$$\int_B (HPB_B)\, dT = e\,\frac{2d_B}{(mph_t)} - f\,\frac{2d_B}{(mph_t)} - \frac{ad_B}{52.8} - \frac{GVW}{1.98 \times 10^6}\left(\sum R_B - \sum F_B\right) + S\,K\,(mph_t)^2 \tag{24}$$

Some simplification results if it is assumed that, on an average, as many stops are made going uphill as are made going downhill and that the net truck potential energy change during stops is zero.

$$\int_B (HPB_B)\, dT = e\,\frac{2d_B}{(mph_t)} - f\,\frac{2d_B}{(mph_t)} - \frac{ad_B}{52.8} + S\,K\,(mph_t)^2 \tag{25}$$

Each of the original five integral terms in the work and energy balance relation has now been evaluated. When these are collected together, the following equations result for gasoline-powered trucks,

$$\int_D (IHP)\, dT = \frac{a(D - d_F - d_B)}{52.8} + \frac{GVW}{1.98 \times 10^6}\sum R + f\left(\frac{D}{mph_D} - \frac{d_F}{mph_F} - \frac{2d_B}{mph_t}\right) + e\left(\frac{2d_B}{mph_F}\right) + e\left(\frac{d_F}{mph_F} + \frac{2d_B}{mph_t}\right) + S\,K\,(mph_t)^2 \tag{26a}$$

and for diesel-powered trucks,

$$\int_D (BHP)\, dT = \frac{a(D - d_F - d_B)}{52.8} + \frac{GVW}{1.98 \times 10^6}\sum R + (e - f)\left(\frac{d_F}{mph_F} + \frac{2d_B}{mph_t}\right) + S\,K\,(mph_t)^2 \tag{26b}$$

The fuel consumption relations now become for gasoline-powered trucks,

$$Gal = \frac{2{,}545\,a}{(nI)(HHV)(52.8)}(D - d_F - d_B) + \frac{2{,}545\,(GVW)}{(nI)(HHV)(1.98 \times 10^6)}R + \frac{2{,}545\,f}{(nI)(HHV)}\left(\frac{D}{mph_D} - \frac{d_F}{mph_F} - \frac{2d_B}{mph_t}\right) + \frac{2{,}545\,e}{(nI)(HHV)}\left(\frac{d_F}{mph_F} + \frac{2d_B}{mph_t}\right) + \frac{2{,}545\,S\,K\,(mph_t)^2}{(nI)(HHV)} \tag{27a}$$

and for diesel-powered trucks,

$$Gal = \frac{2{,}545\,a}{(nB)(HHV)(52.8)}(D - d_F - d_B) + \frac{2{,}545\,(GVW)}{(nB)(HHV)(1.98 \times 10^6)}\sum R + \frac{2{,}545\,(e-f)}{(nB)(HHV)}\left(\frac{d_F}{mph_F} + \frac{2d_B}{mph_t}\right) + \frac{2{,}545\,S\,K\,(mph_t)^2}{(nB)(HHV)} \tag{27b}$$

These equations relate total fuel consumption to the properties of the vehicle and the geometry of the highway. In using them, the following truck properties must be known:

a $= \frac{RHP}{mph}$ = rolling resistance factor;

nI = average engine indicated thermal efficiency for gasoline engines;

nB = average engine brake thermal efficiency for diesel engines;
HHV = higher heating value of fuel in Btu per gallon;
GVW = gross vehicle weight, pounds;
f = engine friction factor;
e = engine idle factor; and
K = truck kinetic energy factor.

Methods of measuring these truck properties are described elsewhere (4). The following properties of the highway must also be known:

D = total length in hundreds of feet;
d_F = length of downhill highway in hundreds of feet; and
$\sum R$ = sum of rises of the highway in feet.

These highway properties may be determined from highway surveys or plans.

The following additional needed quantities are influenced by both the truck and the highway as well as by traffic conditions:

d_B = total braking distance to stops in hundreds of feet;
(mph_t) = average truck speed at start of braking to a stop;
S = number of stops made;
mph_D = average truck speed over the highway; and
mph_F = average truck speed on downhill sections.

In general, these quantities are not readily determinable. For existing highways and trucks these could be measured experimentally. For planned highways and new truck designs they can only be estimated. The methods described by Crumbley (5) can be used to estimate the average truck speed over the highway. The average truck speed on downhill sections is presumably the legal speed limit or the safe operating speed limit. Especially difficult to estimate are the quantities involved in braking to a stop, because these depend primarily on traffic conditions. In the experiments described herein only one stop was made on a test run, and the energy lost in braking to a stop could be ignored.

THEORETICAL TRAVEL TIME ANALYSIS

Although the methods described by Crumbley (5) can be used to estimate the travel time of trucks over a highway, they become time consuming for highways of appreciable length. For longer highways an approximate method of estimating the travel time has been developed, described here.

Large transport trucks have low engine power relative to their weight. As a result their normal operation on a highway can be approximated as follows:

1. On level and nearly level as well as on downhill roads the truck travels at the legal speed limit.
2. On all other sections of highway, the engine is at wide-open throttle.

The travel time at the legal speed limit is calculated as

$$T_L = \frac{d_L}{52.8\ mph_L} \tag{28a}$$

in which d_L is the total length of level, nearly level, and downhill highway traveled at the speed limit (mph_L). Where several different legal speed limits apply, the relation becomes

$$T_L = \frac{d_{50}}{52.8(50)} + \frac{d_{45}}{52.8(45)} + \frac{d_{40}}{52.8(40)} + \text{etc.} \tag{28b}$$

To determine the sections of a highway on which the truck can operate at the legal speed limit, the chart of maximum sustained speed vs grade (6) can be utilized. If maximum sustained speed exceeds the legal speed limit, the truck is presumed to be at the speed limit. If maximum sustained speed is less than or equal to the legal speed limit, the engine is presumed to be at wide-open throttle.

At wide-open throttle the time rate of fuel consumption (gallons per hour) is approximately constant because truck engines operate within a narrow range of usable engine rpm. The following relation for the time rate of fuel consumption at wide-open throttle is obtained by rearranging the engine thermal efficiency equation.

$$\text{Gal per hour at WOT} = \text{ghpw} = \frac{2,545(\text{HPW})}{(\text{n})(\text{HHV})} \tag{29}$$

The wide-open throttle engine power output, HPW, should be evaluated for the average engine RPM when at wide-open throttle.

The travel time on the wide-open throttle sections of the highway, T_W, can be calculated as the ratio of gallons of fuel used on these sections to the rate of fuel consumption at wide-open throttle.

$$T_W = \frac{\text{Gal at WOT}}{\text{gphw}} \tag{30}$$

The gallons of fuel used at wide-open throttle can be estimated by the methods of the preceding section.

The total travel time over a highway is the sum of the travel time at legal speed limit and the travel time at wide-open throttle. Ignored in this treatment of truck travel time are the following:

1. On level and downhill highway sections, a truck may run at less than the legal speed limit due to traffic conditions or the limits of safe operation.
2. The effect of stops and slowdowns due to traffic is not included.
3. Truck drivers often exceed the posted legal speed limits.

The influence of these factors is difficult to estimate. The travel time calculated by the methods described here can be considered as a "standard" travel time or a "minimum legal" travel time. Actual travel times may be greater or less than this "standard" travel time, depending on the effects of the foregoing factors.

COMPARISON OF THEORETICAL AND MEASURED FUEL CONSUMPTION AND TRAVEL TIME

Fuel consumptions and travel times calculated by the preceding theoretical method were found to agree reasonably well with the measured values for the test trucks. The comparison of theoretical and measured fuel consumption is shown on Figures 2 and 3. The comparison of theoretical and measured travel time is shown on Figure 4. These comparisons show a sufficiently good correlation to justify the assumptions made and the general form of the resulting theoretical fuel consumption and travel time relations.

Perhaps the greatest single source of error in the theoretical calculated results is the assumption of constant thermal efficiency of the engine. Dynamometer tests of engines as well as the truck road test data (4) clearly show engine thermal efficiency to vary over a moderate range of values. At idle (closed throttle), as on downhill runs the brake thermal efficiency of a diesel engine is clearly zero rather than the constant value used in the foregoing theoretical calculation; and this error led to negative calculated values of fuel consumption on downhill runs. On the other hand, failure to use this simplifying assumption leads to a very complex calculation procedure.

The negative fuel consumption values for diesel-powered trucks were eliminated and the correlation of theoretical to measured values improved by making the following assumptions:

1. At closed throttle and idle, the brake thermal efficiency of a diesel engine is zero.
2. At all other conditions the brake thermal efficiency of a diesel engine is constant.

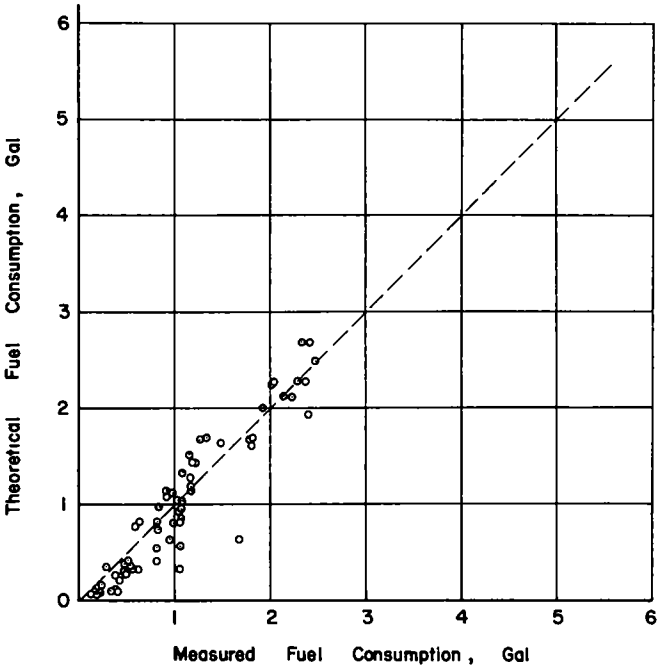


Figure 2. Comparison of theoretical calculated fuel consumption with measured fuel consumption of diesel-powered trucks.

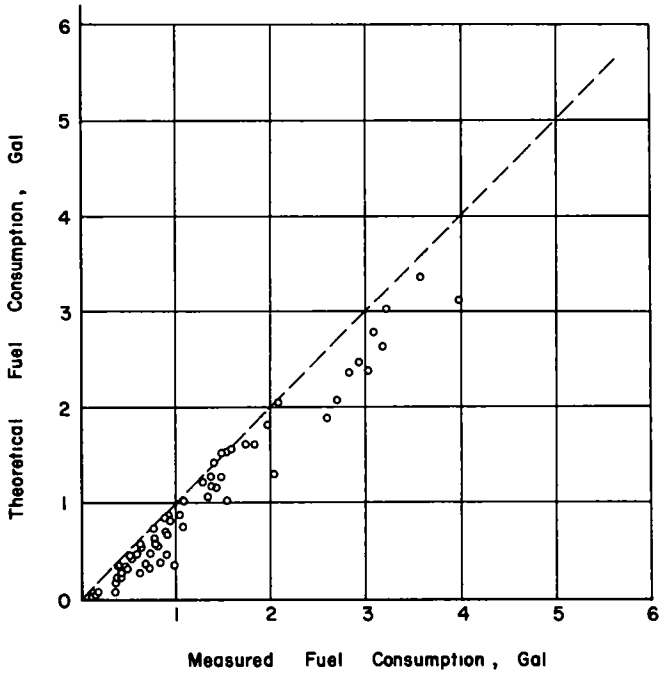


Figure 3. Comparison of theoretical calculated fuel consumption with measured fuel consumption of gasoline-powered trucks.

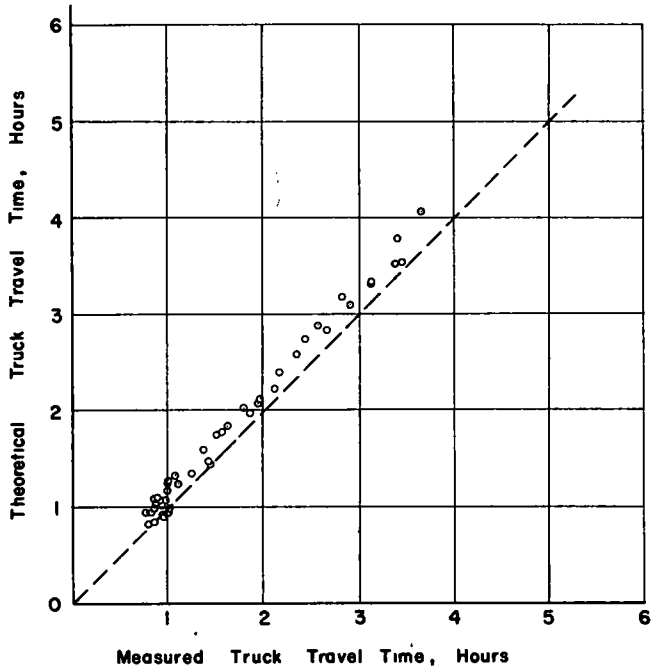


Figure 4. Comparison of theoretical calculated travel time and measured truck travel time.

With these assumptions the fuel consumption relation for diesel-powered trucks became

$$Gal = \frac{2,545\ a}{(nB)(HHV)}(D - d_F - d_B) + \frac{2,545\,(GVW)}{(nB)(HHV)(375)}\ R +$$

$$(gph_i)\left(\frac{d_F}{mph_F} + \frac{2d_B}{mph_t}\right) + \frac{2,545\ S\ K\ (mph_t)^2}{(nB)(HHV)} \tag{31}$$

TABLE 3

TEST VEHICLE GROSS WEIGHTS

Test Vehicle	Loading Condition (lb)				
	1	2	3	4	5
3-S2 diesel (20B)	33,000		55,000	66,000	
3-S2 gas (22B)	33,000		55,000	66,000	
2-S1-2 diesel (30AB)	33,000	44,000	55,000	66,000	76,000
2-S1-2 gas (31AB)	32,100	42,600	53,500	64,000	76,000
2-S1 diesel (30A)[a]	18,000	33,000			
2-S1 gas (31A)[b]	16,300	33,000			

[a]Same as 30AB but trailer B dropped.
[b]Same as 31AB but trailer B dropped.

An alternate method of analyzing the results of this investigation is to assume the form of the fuel consumption and travel time equations to be that resulting from the theoretical analysis, but to determine the truck properties constants empirically so that a best fit is obtained to the measured data.

MATHEMATICAL FIT OF EMPIRICAL DATA

To develop an improved truck fuel consumption equation the experimental fuel consumption measurements were fitted to an equation of the same form as the theoretical equation. The vehicle factors were adjusted to fit the data to

$$Gal = K_0 + K_1 (D - d_F) + K_2 \sum R + K_3 d_F \tag{32}$$

The factors K_0, K_1, K_2, and K_3 are the empirical vehicle factors; the highway factors of rise and distance remained unchanged. Values of the empirical vehicle factors were calculated by applying a multivariant regression analysis to the experimental data through the use of an IBM 709 computing machine.

The regression analysis was applied to each test truck at each test weight. Observation showed that the factors K_0 and K_1 were nearly independent of vehicle weight: factor K_2 varied directly with vehicle weight, and factor K_3 varied nearly directly with maximum engine power output (or probably engine displacement and rpm). Eq. 32 was accordingly rewritten:

$$Gal = K_0 + K_1 (D - d_F) + S_2 (GVW) \sum R + S_3 (BHPW) d_F \tag{33}$$

Average values of these empirical vehicle factors, K_0, K_1, S_2, and S_3 were then determined for gasoline- and for diesel-powered trucks with the following results: For gasoline-powered trucks,

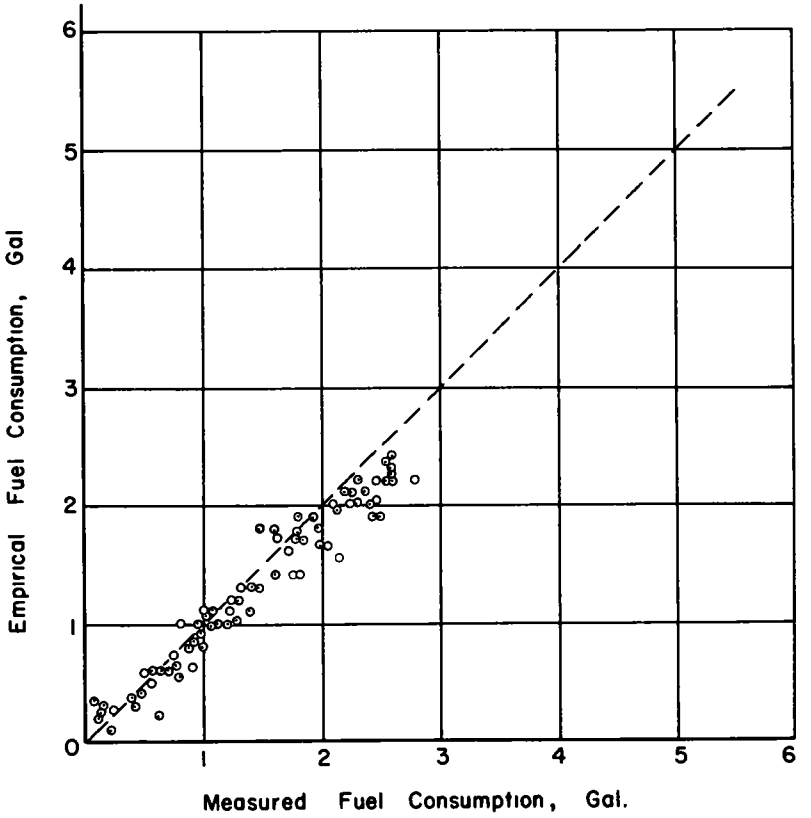


Figure 5. Comparison of empirical calculated fuel consumption with measured fuel consumption of diesel-powered trucks.

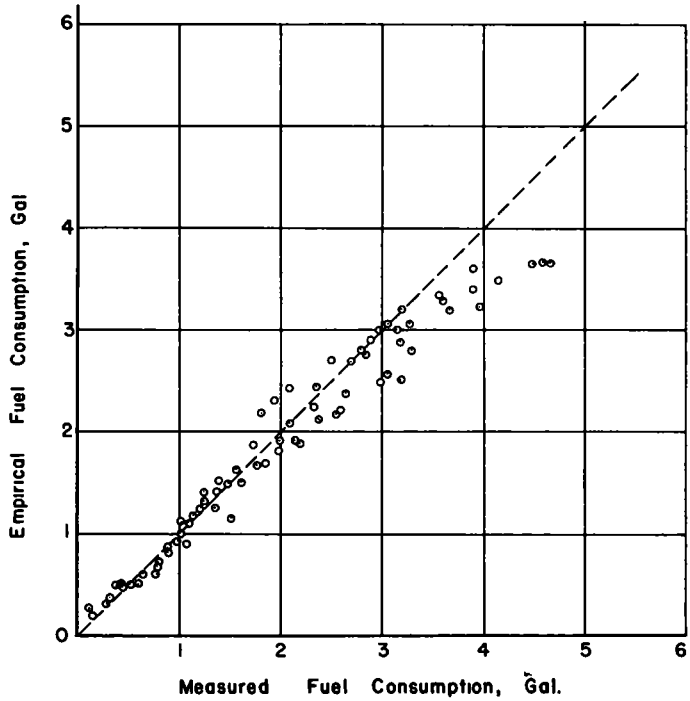


Figure 6. Comparison of empirical calculated fuel consumption with measured fuel consumption of gasoline-powered trucks.

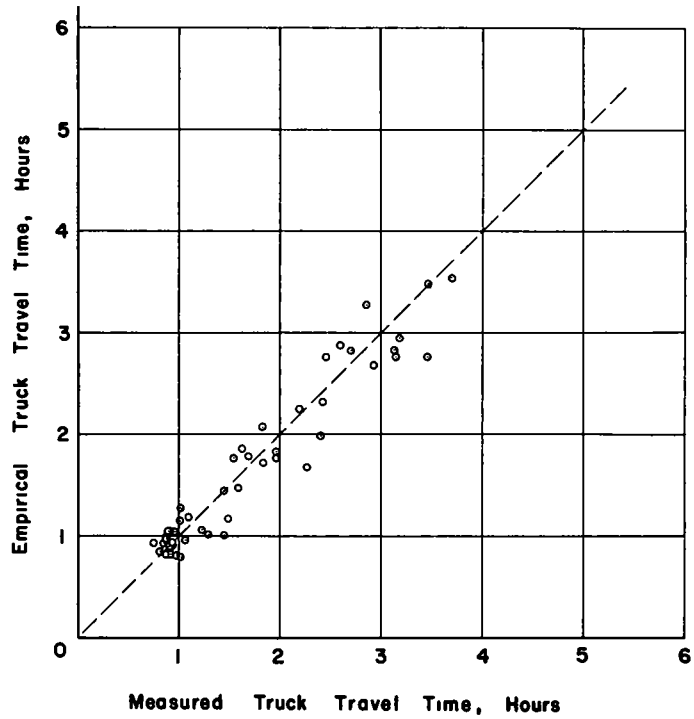


Figure 7. Comparison of empirical calculated travel time and measured truck travel time.

$$Gal = 0.0249 + 0.00314\,(D - d_F) + (41.7 \times 10^{-9})(GVW)\sum R + (1.005 \times 10^{-5})(BHPW)\,d_F \tag{34a}$$

For diesel-powered trucks,

$$Gal = (0.0058) + 0.0026(D - d_F) + (22.0 \times 10^{-9})(GVW)\sum R + (1.047 \times 10^{-5})(BHPW)\,d_F \tag{34b}$$

The degree to which these empirical fuel consumption equations fit the experimental data is shown in Figure 5 for gasoline-powered trucks and in Figure 6 for diesel-powered trucks. The fit is seen to be distinctly better than that obtained with the theoretical fuel consumption equations.

Table 4 compares the numerical values of the empirical vehicle factors to the corresponding theoretical vehicle factors.

TABLE 4

COMPARISON OF THEORETICAL AND EMPIRICAL VALUES OF VEHICLE FACTORS

Vehicle Factor	Vehicle Type	Value	
		Empirical	Theoretical
K_0	Diesel	0.0058	0
	Gasoline	0.0249	0
K_1	Diesel	0.0026	0.0016 to 0.0023
	Gasoline	0.00314	0.0021 to 0.0030
S_2	Diesel	22.0×10^{-9}	33.2×10^{-9}
	Gasoline	41.7×10^{-9}	35.8×10^{-9}
S_3	Diesel	1.047×10^{-5}	0.28×10^{-5}
	Gasoline	1.005×10^{-5}	0.31×10^{-5}

The empirical values agree well with the theoretical values, indicating that the basic form of the fuel consumption equation is probably satisfactory.

To develop an improved truck travel time equation, the theoretical equation was used, but the gallons of fuel used during wide-open throttle running were calculated by means of Eqs. 32, 33, and 34. A comparison of these empirically calculated travel times to the measured travel times, which appears in Figure 7, shows an improvement in correlation.

LIMITATIONS

The truck fuel consumption and travel time relations presented are probably usable only within the following ranges of truck and highway properties:

1. GVW between 25,000 and 75,000 lb.
2. $\frac{GVW}{BHPW}$ between 150 and 400.
3. Grades up to 8 percent.
4. Geared transmissions with friction clutches.
5. Hard surfaced highways (e.g., concrete and asphalt).
6. Naturally aspirated engines.

Most naturally aspirated truck engines develop nearly constant torque at wide-open throttle over the usable engine-speed range. The wide-open throttle torque of supercharged engines may, however, vary markedly with engine speed and, for this reason, the equations presented may not apply to such trucks.

Hydraulic couplings and torque converters do not hold a fixed ratio between vehicle speed and engine speed in any one gear setting. Hence the fuel consumption and travel time relations developed herein may not apply to trucks equipped with hydraulic couplings or torque converters.

Gravel- or dirt-surfaced roads greatly increase truck rolling resistance and hence increase fuel consumption and travel time compared to asphalt- or concrete-surfaced roads. Thus the equations presented are not applicable to gravel- or dirt-surfaced roads.

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