Fuel Consumption Related to Roadway Characteristics

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In 1979, the Federal Highway Administration contracted the Texas Research and Development Foundation to prepare an updated set of vehicle operating cost tables for use in the Highway Performance Monitoring Program. Included in this research was a reinvestigation of the interrelations between roadway characteristics and fuel consumption, which required the performance of a set of experiments to investigate the effect of grade, curvature and surface type, and pavement condition on fuel consumption. These experiments were conducted in 1980 and 1981 by using a set of eight vehicles, which ranged from a small economy car to a 2-S2 semitruck. The tests were conducted while the vehicles were idling, accelerating, decelerating, and traveling at constant speed. The idle fuel-consumption test showed that new vehicles consumed fuel at a higher rate than previously had been published. Acceleration and deceleration models were generated, which allowed a direct analysis of speed-change cycles for all driving situations. A new set of constant- speed fuel-consumption tables as a function of grade were generated and are presented in this paper. It was found during this research that pavement condition did not affect fuel economy over the range of conditions normally encountered in the United States. This resulted from testing on asphalt concrete pavements with a range in serviceability of 1.8-4.2 and testing on concrete and surface-treated pavements. This is a very significant finding in the economic and energy analysis of highway transportation systems, since it removes the fuel-based incentive for providing smooth pavements on highways.

Existing literature (1,2) shows a strong relation between vehicle operating cost and the roadway characteristics of grade, curvature, and roughness. Due to the dramatic increase in vehicle operating costs in the past decade, states that use these as inputs to the process of planning the construction, reconstruction, and maintenance of roadways found vehicle operating costs were a major influence on the selection process. In 1979, the Federal Highway Administration (FHWA) sponsored the Texas Research and Development Foundation to perform research on the relations between vehicle operating costs and roadway characteristics. This research included fuel-consumption measurements and a detailed analysis of oil consumption, tire wear, maintenance and repair, depreciation, accident rates, and vehicle emissions (3).

TEST VEHICLES

The fuel-consumption tests were performed with eight vehicles with characteristics representative of the general vehicle population, as described in Table 1. Four automobiles were included in the fleet: an economy car, two midsized cars, and a large luxury car.

The test fleet included two midsized cars so that the variance of the two identical automobiles could be used in the statistical analysis for significance factors. However, since the statistical tests on the effect of surface type showed no significance when tested with the repeat variance on tests, it was not necessary to use the variance between the repeat vehicles.

Four trucks were also tested: a pickup, a two-axle single-unit truck (2A-SU), a three-axle single-unit truck (3A-SU), and a four-axle semi (2-S2). All trucks had a minimum of 20 000 miles at the start of the test. All tests with the trucks, except the pickup, were run in the loaded condition. A load was selected that was typical for the model of truck being tested. In some cases, the typical weight for the truck tested was not representative of the vehicle class weight. In order to have a common vehicle weight basis for the operating cost tables, it was necessary to extrapolate the fuel-consumption data to different weight classes.

It was also necessary to extrapolate the fuel-consumption data collected with the 2-S2 to estimate fuel consumption for the six-axle semi (3-S2). Data from previous studies were used to make this extrapolation. Although extrapolating data is not a desirable situation, steps were taken to minimize the amount of extrapolation. This included the use of a test weight for the 2-S2 vehicle that was only 6500 lb less than the typical loaded weight for a 3-S2.

TEST SECTIONS

Test sections were selected to be homogenous with respect to grade, surface type, and roughness. The test section properties are summarized in Table 2. Grades were determined from as-constructed plan sheets on file at the Texas State Department of Highways and Public Transportation. Roughness was measured by Austin Testing Engineers by using a Maysmeter calibrated against the Texas calibration sections in the Austin, Texas, area.

A total of 12 test sections were used during the experiments. Tests to determine the effect of curvature were performed on a large parking lot with the economy car, the large car, and the pickup. The parking-lot owners prohibited further testing, fearing the test would damage the pavement. No other acceptable area was found to continue these tests with the other vehicles.

After the tests had been completed with three of the vehicles, two sections with more desirable characteristics were located. Test sections used with each vehicle are shown in Table 2. Section 10 was used to replace section 6, since the serviceability index of section 10 was closer to the middle of the range of serviceability. Section 11 replaced section 7, since the new section had a surface treatment in relatively good condition and would allow a direct comparison of the influence of surface type on fuel consumption.

EQUIPMENT

A Fluidyne 1214F fuel meter (4), a Lamar System fifth wheel (from Lamar Instruments, Redondo Beach, California), and two digital recorders were selected from the available hardware. The digital recorders were mounted in a black box, which also contained counters for the distance and fuel measurements, a crystal clock, and a microprocessor for data management. The recording unit had 12 thumbwheels that could be used to identify the test run and select the sample time interval. After initial testing, a sampling interval of 2 s was selected. An inverter was used to power the recording unit.

The fifth wheel had a design resolution of 50 counts/ft. However, careful tests of the distance measurements indicated that only 36 counts/ft were recorded. Furthermore, the number of counts per foot seemed to vary with speed and the tire-surface interaction. A gas spring of the type used on hatch-back doors of automobiles was mounted on a fabricated bracket to try to eliminate wheel bounce problems, but this did not correct the problem. Thus, the distance data were not as reliable as desired.

For the constant-speed tests, the vehicle speedometer was used to determine speed. Radar was used

Table 1. Test fleet characteristics.

Characteristic	1980 Ford Escort	1980[a] Ford Fairmont	1979 Oldsmobile Delta 88	1980 Ford Pickup	2A-SU GMC	3A-SU GMC (Brigadier)	2-S2 Freightliner
Road weight (lb)	2412	3006	4350	3678	17 120	35 870	56 000
Curb weight (lb)	2112	2706	4050	3378	10 720	15 760	24 680
Engine displacement (in^3)	98	200	350	350	366	426	855
No. of cylinders	4	6	8	8	8	6	6
Fuel type	Unleaded	Unleaded	Unleaded	Unleaded	Leaded	Diesel	Diesel
Frontal area (ft^2)	20.7	22.1	29.2	31.0	38.7	57.3	95.7
Transmission	Manual	Automatic	Automatic	Automatic	Manual	Manual	Manual
No. of forward gears	4	3	3	3	5	8	9
Body style	Station wagon	Sedan	Sedan	Box	Van	Dump	Flatbed
Options							
Air conditioning	Yes	Yes	Yes	Yes	No	Yes	Yes
Power steering	No	Yes	Yes	Yes	No	Yes	Yes
Power brakes	No	Yes	Yes	Yes	No	Yes	Yes
Steel-belted radials	Yes	Yes	Yes	Yes	No	No	No
Fuel consumption[b] (miles/gal)							
City cycle	28	18	-	16	NA	NA	NA
Highway cycle	44	24	-	18	NA	NA	NA
Combined	32	20	16	17	NA	NA	NA
Test vehicle number	1	2	4	5	6	7	8
Vehicle category	Small car	Medium car	Large car	Pickup truck	2A-SU truck	3A-SU truck	2-S2 semi

Note: NA = not applicable.
[a]Two vehicles with these characteristics were used. [b]Fuel-consumption data from U.S. Environmental Protection Agency (EPA).

Table 2. Test section characteristics.

Location	Section No.	Surface Type[a]	Grade (%)	Length (mile)	Serviceability Index	Vehicles Tested[b]
US-281	1	AC	2.6	0.5	4.2	All
SH-71	2	AC	0	0.4	4.4	All
US-281	3	AC	5.6	0.4	4.5	All
FM-2222	4	AC	11	0.4	4.0	All
Old Highway 20	5	AC	~0	0.8	1.5	All
FM-973	6	AC	~0	0.8	3.8	1, 3, 4
FM-973	7	AC	~0	0.5	3.7	1, 3, 4
Burger Center	8	AC	~0	-[c]	1.5	1, 3, 4
I-10	9	PCC	~0	2.1	3.4	All
Littig Road	10	AC	~0	0.5	3.2	2, 5, 6, 7, 8
Hays County	11	ST	~0	0.6	3.5	2, 5, 6, 7, 8
CC-229	12	Gravel	~0	0.6	1.8	All

[a]Surface types are as follows: AC = asphalt concrete, PCC = portland cement concrete, and ST = surface treatment.
[b]See vehicle numbers in Table 1.
[c]Constant-speed-cycle tests.

to test the accuracy of the speedometer. Data from the fifth wheel were reliable enough to establish that the test was performed at constant speed. By reviewing these distance measurements, it was possible to eliminate test runs when there was a speed change.

In the acceleration and deceleration tests, it was necessary to use the distance data from the fifth wheel. In this case, the best estimate between distance recordings and actual distance traveled was used to establish the relation between speed and fuel consumption during acceleration and deceleration. Thus, these relations have an inherent source of unquantified error. Although this is an undesirable situation, it could not be avoided or altered with the resources available. Due to the lack of any better data source, the fuel-consumption relations for acceleration and deceleration seemed reasonable and were useful on this project.

A wood box was fabricated to hold the fuel meter. The meter was mounted to the front bumper of the vehicles with a bicycle rack, as shown in Figure 1. Quick-connects were used to attach the fuel lines so that the fuel meter could be removed when not in use. Mounting the fuel meter on the front bumper disrupts the aerodynamic design of the vehicle and hence alters fuel consumption. However, this was a constant factor in all tests, so it did not influence the effects investigated in this research.

METHODOLOGY

The first test performed after the fuel meter was installed in a vehicle was to measure idle fuel consumption. With gasoline vehicles, an exhaust analyzer was used to measure hydrocarbons and nitric oxide. This measure showed that all the vehicles were properly tuned.

The vehicles were driven a minimum of 12 miles to the test section. The equipment was installed, and the vehicle was idled for a minimum of 3 min while air temperature and wind were measured. Acceleration, deceleration, and coast-down tests were then performed. Finally, the constant-speed tests were performed.

Constant-speed tests were performed in the sequence 10, 30, 50, 70, 20, 40, and 60 mph in each direction. The sequence was repeated three times. Occasionally, traffic would require aborting a test before the end of the section. These occurrences were noted in a field book and were subsequently screened during data processing.

Vehicles with automatic transmissions were tested in Drive. The driver used his or her discretion for selecting the gear for manual shift vehicles. The gear used was always recorded in the log book.

By using the automatic data-recording box, one technician could both drive and operate the equipment for all vehicles except the two heaviest

Figure 1. Fuel meter mounted on vehicle.

trucks. Professional truck drivers were hired to operate these trucks while the technician operated the equipment.

RESULTS OF FUEL-CONSUMPTION EXPERIMENTS

Experiments were performed to determine the effect of speed, grade, pavement type, and roughness on fuel consumption at constant speed. In addition, fuel consumption was measured during idling, acceleration, and deceleration.

Fuel Consumption While Idling

Average fuel consumption per minute was calculated from the idling tests performed before each test session on the various sections. These values were converted to gallons per hour and are summarized in the table below (note, fuel consumption for the 3-S2 is assumed):

Vehicle	Fuel Consumption (gal/h)
Small cars	0.271
Medium cars	0.563
Large cars	0.563
Pickups	0.756
2A-SU	1.198
3A-SU	0.398
2-S2	0.470
3-S2	0.470

The fuel-consumption rates while idling, especially for automobiles, are substantially higher than the values reported by Winfrey (2). This is attributed to emission reduction equipment on the automobiles. Modern cars have a much higher idling speed than the vehicles used for the idling consumption rates reported by Winfrey.

Fuel Consumption During Acceleration and Deceleration

Fuel consumption was measured as the vehicles accelerated from a stop to 70 mph or the top speed of the vehicle and then decelerated back to a stop. These tests were started with the third vehicle, so no acceleration and deceleration data were collected for the heavy car and pickup truck.

The typical graphs of the raw data for a medium-class car during acceleration and deceleration tests are shown in Figures 2 and 3, respectively. The fuel-consumption tests during acceleration start with a low number of distance counts per time interval, or speed; as the number of counts per foot increases, the fuel consumption per unit time increases. Fuel consumption during deceleration (Figure 3) starts at a high speed, i.e., many distance counts per time interval, and then reduces to zero. The variance in Figures 2 and 3 is the result of repeated tests.

Acceleration Fuel-Consumption Models

Careful review of the acceleration data showed a linear relation between fuel consumption and speed in all cases. Due to time constraints, it was decided to generate these equations by visual inspection of the data. For the automobiles and pickup truck, linear equations, passing through the origin, did a good job of modeling the data. However, this type of model was not adequate for the trucks because it underestimated the fuel consumption at low speeds and overestimated consumption at high speeds. For trucks, a maximum fuel-flow rate during acceleration was identified at approximately 45 mph. In addition, a minimum fuel-flow rate was identified at low speeds. These equations are summarized in Table 3. The fuel-rate equations were integrated with respect to speed to obtain equations for estimating fuel consumption during acceleration.

The procedure used to generate the acceleration portion of fuel consumption for speed-change cycles was to calculate the volume of fuel required for each 5-mph increase in speed and then sum the appropriate values for acceleration phases of more than 5 mph. An example of this calculation procedure is shown in Table 4.

Acceleration Rate Models

A nonuniform model was used for calculating time and distance during acceleration (5). In the nonuniform acceleration model, the acceleration varies as a linear function of speed; that is,

$$ACCEL = A - B(V) \quad (1)$$

where

ACCEL = acceleration at velocity V (ft/s^2),
A,B = constants, and
V = speed (ft/s).

By using this formulation, the time to change from speed V_o to V_1 is

$$t = \{\ln[A - B(V_1)] - \ln[A - B(V_o)]\}/-B \quad (2)$$

where t equals time (s).

The distance traveled in feet (X) over the time interval t from initial speed V_o can be expressed as follows:

$$X = (A/B)t - (A/B^2)(1 - e^{-Bt}) + (V_o/B)(1 - e^{-Bt}) \quad (3)$$

Thus, to quantify this model, only the two coefficients A and B need to be determined. Due to the formulation of this model, A represents the maximum acceleration and A/B is the maximum speed attainable. The values of A and B selected as representative of the vehicle classes used in this report are given below:

Vehicle	Coefficient A	Coefficient B
Automobile		
Small	7.2	0.060
Medium	8.60	0.076
Large	7.9	0.055
Truck		
Pickup	7.9	0.08
2A-SU	2.8	0.026
3A-SU	1.8	0.016
2-S2	1.8	0.016
3-S2	1.8	0.016

Figure 2. Fuel consumption of medium car during acceleration (raw data).

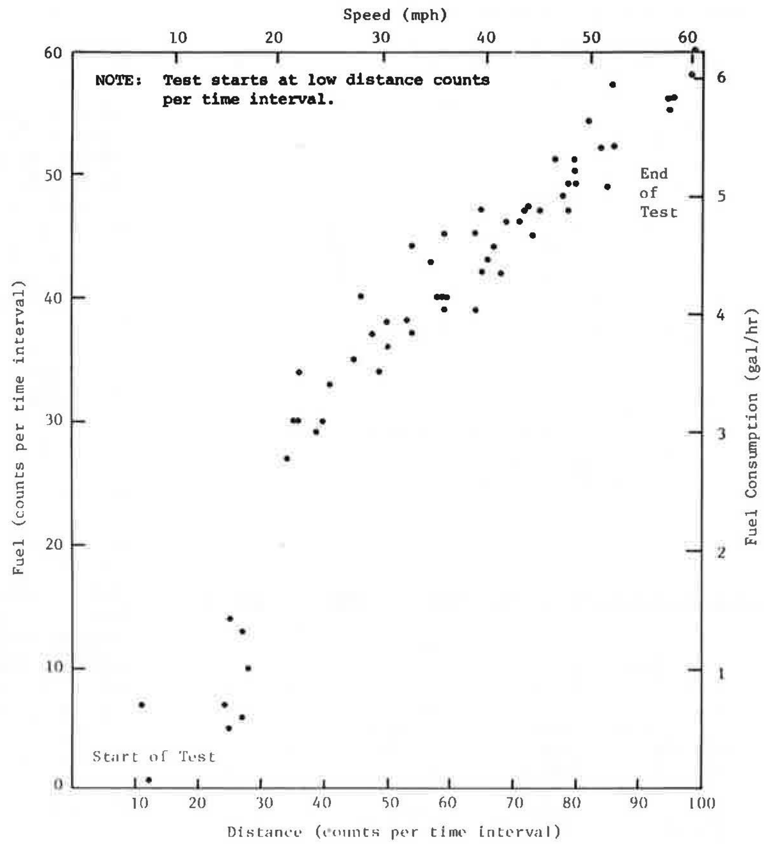

Figure 3. Fuel consumption of medium car during deceleration (raw data).

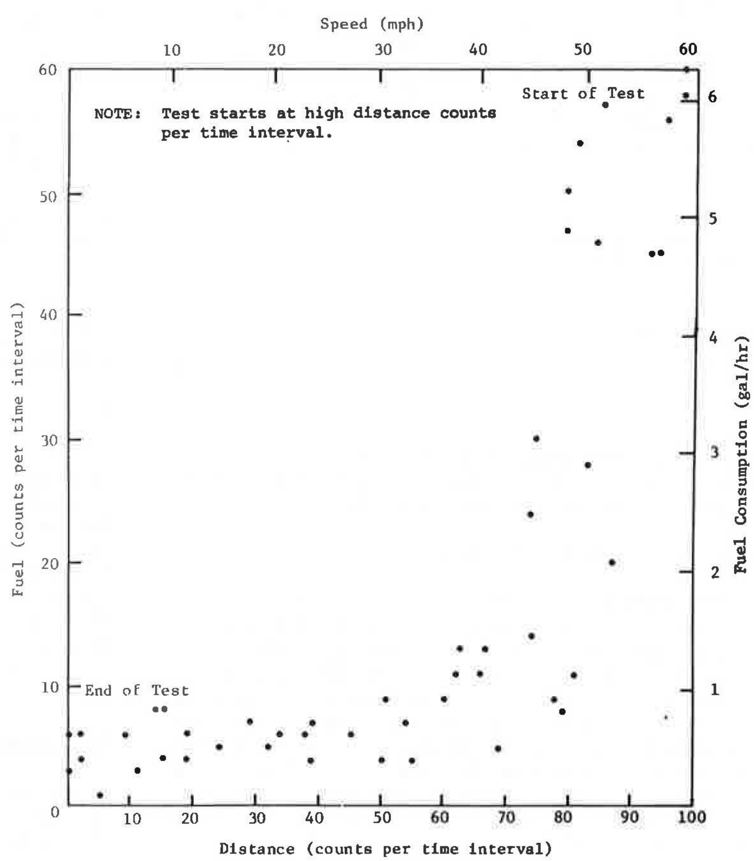

Table 3. Acceleration fuel-consumption models.

Vehicle	Coefficient A	Coefficient B	Maximum Speed (mph)	Maximum Fuel Rate (gal/h)
Small car	0.0	0.062	-	-
Medium car	0.0	0.102	-	-
Large car[a]	0.0	0.136	-	-
Pickup[a]	0.0	0.136	-	-
2A-SU	1.34	0.260	45	13.0
3A-SU	2.07	0.263	45	13.9
2-S2	6.20	0.180	45	14.6
3-S2[a]	6.80	0.240	45	17.6

Note: FR = A + BV; if V < max speed, FT = At + Bs; if V > max speed, FT = (FR max)t

where

FR = fuel rate (gal/h),
V = speed (mph),
FT = total fuel for acceleration (gal) obtained by integrating the equation for fuel rate,
t = time for acceleration (h), and
s = distance for acceleration (mile).

[a]Assumed.

Table 4. Example of fuel-consumption calculations for acceleration, large car.

Start Speed (mph)	Time for Acceleration: 5 mph (h) (t)[a]	Distance for Acceleration: 5 mph (mile) (s)[b]	Fuel for 5-mph Acceleration[c] (gal)	Cumulative Fuel (gal)
0	0.000 26	0.000 66	0.000 09	0.000 09
5	0.000 28	0.002 11	0.000 29	0.000 38
10	0.000 29	0.003 68	0.000 50	0.000 88
15	0.000 31	0.005 39	0.000 75	0.001 63
20	0.000 34	0.007 57	0.001 03	0.002 66
25	0.000 36	0.009 86	0.001 34	0.004 00
30	0.000 39	0.012 56	0.001 71	0.005 71
35	0.000 42	0.015 75	0.002 13	0.007 84
40	0.000 45	0.019 38	0.002 64	0.010 48
45	0.000 50	0.023 77	0.003 24	0.013 72
50	0.000 55	0.029 19	0.003 97	0.017 69
55	0.000 63	0.035 97	0.004 89	0.022 58
60	0.000 71	0.044 66	0.006 07	0.028 65
65	0.000 83	0.056 12	0.007 63	0.036 28

[a] $t = \{\ln[A - B(V_1C)] - \ln[A - B(V_oC)]\}/3600(-B)$

[b] $s = [(A/B)t - (A/B^2)(1 - e^{-Bt}) + (V_oC/B)(1 - e^{-Bt})]/5280$

where

A = 7.9,
B = 0.055,
C = 1.467,
V_o = initial speed (mph), and
V_1 = end speed (mph).

[c] FT = At + Bs

where

FT = total fuel (gal),
A = 0.0, and
B = 0.136.

The acceleration rates used in this project for automobiles are compared with the rates recommended by St. John and Kobett (6) in Figure 4.

Deceleration Fuel-Consumption Models

The fuel-consumption tests during deceleration showed that, for the automobiles, there was about a 6-s lag between the time the driver started deceleration and when the fuel consumption reached a steady-state condition. This may be attributed to dash pots (or vacuum-actuated switches) that are used on modern carburetors to keep the throttle from closing rapidly to reduce hydrocarbons. After this phase, fuel consumption during deceleration reached a steady-state condition. The two phases are clearly shown in Figure 3.

A two-step function was used to model the fuel data for deceleration. One step covers the transition phase of deceleration while the throttle is closing, as shown in Figure 3. Even though the data on this figure indicate that the fuel consumption during the transition phase is a function of speed, such a conclusion based on these data would be incorrect. The throttle is regulated such that it closes at a constant time rate that is not dependent on speed. It should be noted that the fuel supply to a diesel motor is completely shut off, as shown on Figure 5, whenever there is negative horsepower, such as during deceleration or on negative grades.

The models generated by analyzing the plots of the fuel data during deceleration are given in Table 5. In using these models to generate the speed-change fuel-consumption tables, the transition phase model was used for the first 6 s for automobiles and the first 3 s for trucks. The remainder of the time during deceleration was modeled with the steady-state models.

Deceleration Rate Models

A uniform deceleration model was chosen for braking for two primary reasons. First, sliding friction is theoretically independent of the relative speed of the surfaces in contact. The second reason is more pragmatical, in that it is difficult to quantify a typical braking pattern for the population of vehicles on the road. Much of the existing research in the area has quantified braking performance into levels of constant deceleration. The constant deceleration model may be expressed as follows:

$$D = dV/dt \tag{4}$$

where D equals deceleration (ft/s²) and dV/dt equals change in speed with time. The time to change from speed V_o to V_1 is

$$t = (V_o - V_1)/D \tag{5}$$

where

t = time (s),
V_o = initial speed (ft/s), and
V_1 = final speed (ft/s).

The distance traveled in feet (X) for changing from speed V_o to V_1 is

$$X = [1/(2D)](V_o^2 - V_1^2) \tag{6}$$

The distance traveled over time interval t from the initial speed V_o is

$$X = V_o t - (1/2)Dt^2 \tag{7}$$

In the above formulations, the deceleration has been expressed as a positive (+) quantity, i.e., negative acceleration equals positive deceleration. Based on information reported by Claffey (1) on normal deceleration rates used by drivers in traffic, a two-level deceleration model was used. For decelerations at speeds less than 30 mph, a 5.0-mph/s (7.33-ft/s²) rate was used. For initial speeds greater than 30 mph, a 3.3-mph/s (4.84-ft/s²) rate was used. These rates were used for all vehicle classes.

Fuel Consumption at Constant Speed

Three parameters were studied in the constant-speed fuel-consumption experiments: the effects of speed, grade, and pavement type and surface condition. The major emphasis in the fuel consumption was placed on the constant-speed experiments.

Figure 4. Comparison of acceleration rates of St. John and Kobett to rates developed in this study for cars.

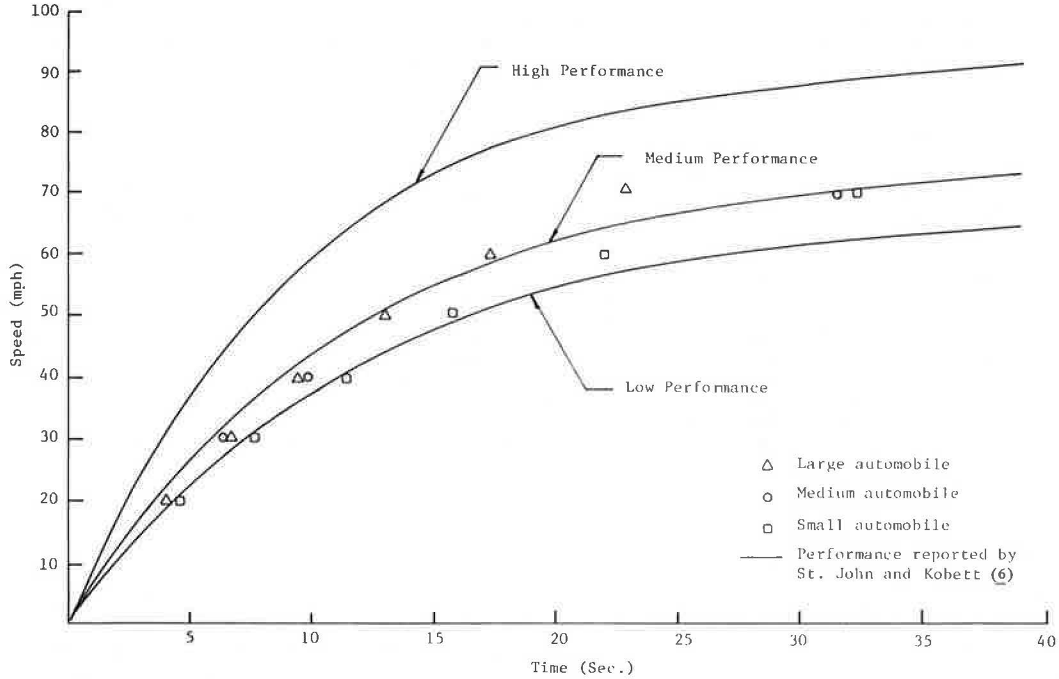

Figure 5. Fuel consumption of diesel motor during deceleration.

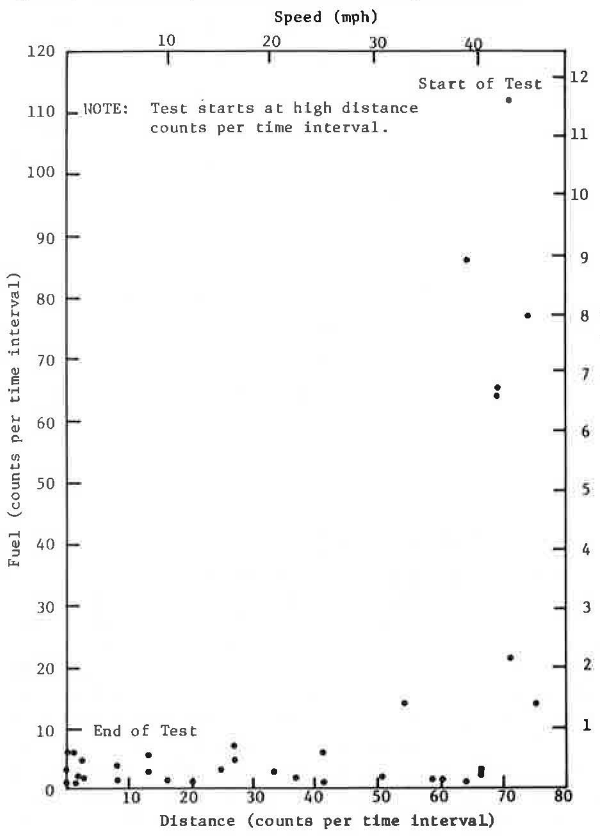

Table 5. Deceleration fuel-consumption model.

	Coefficient			Coefficient	
Item	C_1	C_2	Item	C_1	C_2
Small car	0.52	2.07	2A-SU	1.45	7.23
Medium car	0.72	3.62	3A-SU	0	7.23
Large car	0.93[a]	4.13[a]	2-S2	0	7.23
Pickup	0.93[a]	4.13[a]	3-S2	0	7.23[a]

Note: $f = [C_2 t_2 + C_1 (t - t_2)]/3600$

where

f = fuel consumption (gal);
C_2 = fuel consumption during initial deceleration;
t_2 = time of initial deceleration (s): for automobiles and pickups t_2 = min (6,t), and for other trucks t_2 = min (3, t);
C_1 = fuel consumption during stable deceleration, and
t = time of deceleration.

If $(t - t_2) < 0$, $(t - t_2) = 0$.

[a]Assumed.

Due to the fact that the fuel experiments with the 2A-SU and the 2-S2 were not tested at the typical vehicle weights, it was necessary to adjust the measured fuel consumption to typical fuel-consumption rates for the vehicle population. In addition, it was necessary to extrapolate the data from the 2-S2 experimental vehicle to the 3-S2. The best source of data for making these adjustments was developed by France (7) in a direct study of truck fuel economy on a dynomometer.

France tested several trucks at different test weights. One of these vehicles had the same type of motor as the 2-S2 used in this research. Graphs of fuel economy versus weight at each speed were plotted from France's data. These plots were then entered with the test weight and the desired typical weight for this research to determine fuel consumption at these weights for each speed. The ratio of the fuel consumption at the typical weight to the fuel consumption at the test weight was multiplied by the fuel consumption measured in this research to obtain the fuel consumption for the typical vehicles. The data used for these calculations are summarized in Table 6.

Effect of Speed and Grade on Fuel Consumption

Plots of fuel consumption versus grade and speed were generated from the data. These graphs were

Table 6. Fuel adjustment factors and consumption rates for 2A-SU, 2-S2, and 3-S2.

Item	Fuel-Adjustment Factors and Consumption Rates by Speed (mph)													
	5	10	15	20	25	30	35	40	45	50	55	60	65	70
2A-SU fuel consumption (gal/1000 miles)														
Estimated at 12 kips[a]	435	244	141	145		111		114			152			
Estimated at 17.1 kips[a]	444	256	152	156		121		127			172			
Ratio (12 kips/17.1 kips)	0.98	0.95	0.93	0.93	0.92	0.92	0.90	0.89	0.88	0.88	0.88	0.87	0.87	0.87
Measured at 17.1 kips	217	217	180	132	132	122	126	129	140	151	159	166	172	178
Adjusted to 12 kips	212	207	167	122	122	112	113	115	123	133	139	144	150	163
Semitruck fuel consumption (gal/1000 miles)														
Estimated at 62.5 kips[a]	408	353	227	204		196		210			250			
Estimated at 56.0 kips[a]	408	353	227	204		192		204			238			
Estimated at 40.0 kips[a]	404	350	225	202		186		188			209			
Ratio (62.5 kips/56.0 kips)	1.00	1.00	1.00	1.00	1.01	1.02	1.03	1.03	1.04	1.05	1.05	1.06	1.07	1.08
Ratio (40.0 kips/56.0 kips)	0.99	0.99	0.99	0.99	0.98	0.97	0.94	0.92	0.91	0.89	0.88	0.87	0.87	0.87
Measured at 56.0 kips	470	370	287	205	202	200	197	195	192	190	192	195	197	200
Adjusted to 62.5 kips (3-S2)	470	370	287	205	204	204	202	201	199	199	202	207	210	215
Adjusted to 40.0 kips (2-S2)	465	367	284	203	198	193	186	180	174	169	168	170	171	173

[a] Estimated from data collected by France (7).

Figure 6. Constant-speed fuel consumption (gal/1000 miles): small car.

GRADE %	SPEED mph 5	10	15	20	25	30	35	40	45	50	55	60	65	70
8	87.00	85.00	65.00	52.50	46.80	41.00	44.30	47.50	47.50	47.50	52.30	57.00	61.80	66.50
7	85.00	83.00	52.50	48.00	42.50	37.00	39.80	41.50	42.00	42.50	46.30	50.00	55.50	61.00
6	83.00	81.00	50.50	47.00	42.00	36.00	37.00	38.00	39.00	40.00	43.00	46.00	51.00	56.00
5	82.00	79.00	51.50	46.00	41.50	35.00	36.00	37.00	37.80	38.50	41.00	43.50	47.80	52.00
4	80.00	78.00	57.50	44.00	40.00	34.00	35.30	36.50	36.80	37.00	39.50	42.00	45.20	48.30
3	77.00	76.00	61.00	43.00	39.80	33.50	34.50	35.50	35.80	36.00	38.00	40.00	42.50	45.00
2	75.00	73.00	59.50	42.00	38.00	32.00	32.50	33.00	33.00	33.00	35.00	37.00	39.50	42.00
1	70.00	70.00	55.50	41.00	34.50	28.00	29.00	30.00	28.30	27.50	30.00	32.50	35.50	38.50
0	67.00	64.00	50.00	36.00	29.50	27.00	24.80	24.00	24.80	25.00	25.50	28.00	31.50	35.00
-1	57.00	57.00	42.00	27.00	23.00	19.00	21.00	23.00	21.50	20.00	22.30	24.50	27.80	31.00
-2	49.00	49.00	35.00	22.00	19.00	16.00	18.50	21.00	19.00	17.00	19.00	21.30	23.50	26.00
-3	43.00	43.00	32.00	20.00	17.50	15.00	17.30	19.50	17.50	15.50	17.30	19.00	21.50	24.00
-4	38.00	38.00	29.00	20.00	17.40	14.80	16.90	19.00	16.50	14.00	15.80	17.50	20.30	23.00
-5	35.00	35.00	27.50	20.00	17.00	14.50	16.50	18.50	15.30	12.00	14.30	16.50	19.30	22.00
-6	34.50	34.50	26.80	19.00	16.50	14.00	15.80	17.50	14.50	11.50	13.50	15.50	18.30	21.00
-7	34.50	34.50	26.00	17.50	15.50	13.50	15.20	17.00	13.80	10.50	12.30	14.00	16.50	19.00
-8	35.00	35.00	25.50	16.00	14.50	13.00	14.50	16.00	12.50	9.00	11.00	13.00	15.50	18.00

then used to generate fuel-consumption tables for each grade level as given. Figures 6-13 give the typical fuel consumption for the eight vehicle classes.

Effect of Pavement Type and Condition on Fuel Consumption

Measurements were taken on PCC, AC, ST, and gravel sections to determine if surface type had an influence on fuel consumption. Three AC sections were used to test for the influence of surface condition on fuel consumption. Student's t-test values were computed for each of the individual combinations of speed and section to determine if there were any significant differences on fuel consumption. In general, there were no statistically significant differences at the 95 percent level between the fuel consumption on the paved sections. Fuel consumption on the unpaved section was slightly higher then the fuel consumption on the paved sections.

Estimation of Fuel Consumption on Curves

Unfortunately, it was not possible to measure fuel consumption as a function of curvature. Previous researchers have shown a definite correlation between degree of curvature and fuel consumption for small radius curves (1,2). However, this relation is generally not significant for the curves encountered on rural roads, which was the primary concern in this research. Therefore, the effect of curvature on fuel consumption was approximated by using horsepower calculations. The procedure used to estimate fuel consumption on curves was as follows:

1. Compute the horsepower (h_c) required to transverse the curve at a constant speed,
2. Determine the grade that could be climbed with h_c at the same constant speed, and
3. Use interpolation to determine the fuel consumption at the grade level determined in step 2 from Figures 6-13 for the vehicle type.

Figure 7. Constant-speed fuel consumption (gal/1000 miles): medium car.

GRADE %	SPEED mph 5	10	15	20	25	30	35	40	45	50	55	60	65	70
8	91.00	91.00	83.30	75.00	76.00	77.00	82.00	86.50	90.00	93.50	102.00	110.00	112.00	113.00
7	82.00	82.00	75.50	68.50	68.30	68.00	71.80	75.50	80.00	84.00	93.50	103.00	104.00	106.00
6	77.50	77.50	70.80	64.00	63.00	62.00	65.30	68.50	73.00	77.30	87.00	96.00	97.80	99.50
5	74.00	74.00	67.50	61.00	59.80	58.50	61.30	64.00	68.50	72.50	80.30	87.50	91.50	95.50
4	73.00	73.00	66.50	60.00	57.80	55.50	58.30	60.50	64.50	68.00	73.00	77.50	84.80	92.00
3	71.50	71.50	64.50	57.50	55.50	53.50	56.30	58.80	61.00	63.00	66.00	68.50	78.30	87.50
2	68.00	68.00	60.80	53.50	52.30	50.50	53.00	55.50	56.80	58.00	60.50	62.50	72.50	82.50
1	61.50	61.50	54.30	47.00	46.30	45.00	46.00	46.50	49.30	51.50	54.50	57.00	64.50	72.00
0	55.40	55.40	47.30	38.70	38.00	37.30	37.60	38.00	40.50	43.00	47.90	52.80	57.60	62.70
-1	52.00	52.00	41.80	31.00	30.30	29.50	31.80	33.50	34.80	36.00	41.00	45.50	51.00	56.00
-2	50.80	50.80	39.70	28.00	25.80	22.50	26.30	29.50	30.30	31.00	34.80	38.50	45.00	51.50
-3	51.30	51.30	38.90	26.90	23.70	20.50	23.30	25.50	26.50	27.80	31.50	35.00	41.30	47.30
-4	52.00	52.00	39.90	27.30	24.00	20.30	20.70	21.00	23.00	25.00	28.80	32.00	37.50	42.50
-5	53.00	53.00	40.00	27.30	23.80	20.00	19.30	18.50	20.50	22.80	26.00	29.50	34.50	39.00
-6	53.50	53.50	40.60	27.30	23.50	19.80	18.00	16.30	18.90	21.00	29.00	27.00	30.80	34.00
-7	54.30	54.30	40.70	27.30	23.80	19.50	17.30	15.00	17.30	19.00	21.30	23.50	26.80	30.00
-8	54.50	54.50	41.20	27.30	23.00	19.30	16.80	14.30	15.40	16.50	18.30	20.00	22.80	25.50

Figure 8. Constant-speed fuel consumption (gal/1000 miles): large car.

GRADE %	SPEED mph 5	10	15	20	25	30	35	40	45	50	55	60	65	70
8	84.00	84.00	82.30	80.50	81.30	82.00	86.00	90.00	111.00	131.00	131.00	131.00	161.00	190.00
7	83.50	83.50	81.50	79.50	78.80	78.00	81.50	85.00	97.50	110.00	113.00	115.00	133.00	150.00
6	83.00	83.00	80.80	78.50	76.30	74.00	77.30	80.50	86.30	92.00	96.00	100.00	113.00	125.00
5	82.20	82.20	79.60	77.00	74.00	71.00	73.30	75.50	78.50	81.50	85.80	90.00	97.50	105.00
4	81.30	81.30	77.90	74.50	70.30	66.00	68.30	70.50	71.00	71.50	75.80	80.00	85.50	91.00
3	79.80	79.80	75.70	71.50	65.80	60.00	62.30	64.50	64.20	63.80	67.80	71.80	76.60	81.30
2	77.00	77.00	71.50	66.00	59.00	52.00	55.30	58.50	58.00	57.50	61.30	65.00	70.00	75.00
1	70.00	70.00	64.00	58.00	51.80	45.50	48.80	52.00	52.50	53.00	56.00	59.00	64.20	69.40
0	59.00	59.00	51.10	43.20	41.80	40.30	42.30	44.30	46.50	48.70	52.50	56.30	61.60	66.90
-1	56.50	56.50	45.00	33.50	35.00	36.50	37.80	39.00	42.50	46.00	50.00	54.00	60.00	66.00
-2	54.80	54.80	42.90	31.00	32.00	33.00	33.50	34.00	38.50	43.00	47.50	52.00	58.00	64.00
-3	54.00	54.00	41.30	28.50	29.30	30.00	29.50	29.00	34.30	39.50	44.30	49.00	55.40	61.80
-4	53.50	53.50	40.70	27.80	27.20	26.50	25.50	24.50	30.30	36.00	40.30	44.50	50.80	57.00
-5	53.00	53.00	40.00	27.20	25.00	23.00	21.60	20.20	26.00	31.80	34.40	37.00	42.30	47.50
-6	52.50	52.50	39.80	27.00	23.50	20.00	18.00	16.00	22.00	28.00	27.50	27.00	29.50	32.00
-7	52.50	52.50	39.50	26.50	22.00	17.50	13.90	10.20	16.60	23.00	22.50	22.00	23.50	25.00
-8	52.50	52.50	39.50	26.50	20.50	14.50	11.30	8.50	13.30	18.00	18.00	18.00	19.00	20.00

COMPARISON WITH PREVIOUS RESEARCH

There have been four prior studies on the effect of roadway characteristics on fuel consumption (1,8-10). The effect of grade and speed were investigated by Claffey (1) and Zaniewski and others (8) with results similar to the findings of this research. Because the findings of this research are for the current vehicle fleet and essentially agree with prior results, it is recommended that the current results be used in future economic analyses.

The findings of this research relative to the effect of pavement roughness are in direct conflict with the findings of Claffey and Zaniewski, where pavement roughness was found to influence fuel consumption by as much as 30 and 10 percent, respectively. However, the rough paved sections in each of these studies were badly broken, potholed, and patched and thus are not representative of realistic operating conditions in the United States. Use of these data require interpolation between the extreme conditions of pavement roughness. In Kenya (9), no effect of pavement roughness on fuel consumption was found, reportedly because the range of roughness was too small.

Ross (10) studied the fuel consumption of three automobiles at 55 mph on five bituminous test sections with a range in roughness of 0.9 to 4.4 on the serviceability index (SI) scale. Ross reported that, for a practical range of roughness (1.5-4.5

Figure 9. Constant-speed fuel consumption (gal/1000 miles): pickup truck.

GRADE %	SPEED mph 5	10	15	20	25	30	35	40	45	50	55	60	65	70
8	137.00	137.00	129.00	120.00	111.00	101.00	109.00	116.00	132.00	147.00	155.00	162.00	170.00	178.00
7	127.00	127.00	108.00	108.00	100.00	92.00	97.50	103.00	119.00	135.00	144.00	152.00	162.00	172.00
6	118.00	118.00	109.00	100.00	93.50	87.00	90.00	93.00	108.00	123.00	133.00	143.00	155.00	166.00
5	112.00	112.00	104.00	95.00	89.50	84.00	85.80	87.50	99.80	112.00	124.00	135.00	145.00	155.00
4	107.00	107.00	97.50	88.00	85.50	83.00	83.50	84.00	93.00	102.00	114.00	125.00	137.00	148.00
3	103.00	103.00	92.50	82.00	81.50	81.00	81.00	81.00	86.00	91.00	103.00	114.00	128.00	142.00
2	97.00	97.00	85.00	73.00	75.00	77.00	77.00	77.00	79.50	82.00	91.00	100.00	116.00	131.00
1	86.00	86.00	75.00	64.00	66.50	69.00	69.50	70.00	71.30	72.50	78.80	85.00	98.00	111.00
0	77.90	77.90	64.80	51.60	52.30	53.00	54.00	55.00	59.70	64.40	67.50	70.60	81.90	93.20
-1	72.00	72.00	55.00	38.00	37.80	37.50	39.30	41.00	47.00	53.00	56.50	60.00	66.50	73.00
-2	70.00	70.00	52.30	34.50	33.30	32.00	33.00	34.00	37.50	41.00	44.50	48.00	51.50	57.00
-3	68.00	68.00	51.30	34.50	31.30	28.00	29.00	30.00	33.00	36.00	39.50	43.00	47.50	52.00
-4	68.00	68.00	52.00	36.00	31.50	27.00	27.50	28.00	30.50	33.00	36.50	40.00	45.00	50.00
-5	68.50	68.50	52.80	37.00	31.50	26.00	26.80	27.50	29.80	32.00	35.00	38.00	44.00	50.00
-6	70.00	70.00	54.20	38.30	32.20	26.00	26.60	27.00	28.50	30.00	33.50	37.00	42.00	47.00
-7	71.00	71.00	54.80	38.50	32.30	26.00	26.00	26.00	26.80	27.50	30.80	34.00	38.00	42.00
-8	72.50	72.50	55.50	38.50	32.30	26.00	25.50	25.00	25.00	25.00	28.00	31.00	32.50	34.00

Figure 10. Constant-speed fuel consumption (gal/1000 miles): 2A-SU.

GRADE %	SPEED mph 5	10	15	20	25	30	35	40	45	50	55	60	65	70
8	416.00	406.00	330.00	263.00	247.00	231.00	238.00	248.00	223.00	203.00	202.00	201.00	204.00	216.00
7	389.00	380.00	306.00	242.00	230.00	219.00	228.00	240.00	217.00	197.00	198.00	198.00	201.00	214.00
6	362.00	354.00	288.00	230.00	220.00	212.00	221.00	232.00	211.00	194.00	194.00	194.00	198.00	211.00
5	343.00	335.00	228.00	222.00	213.00	206.00	210.00	218.00	201.00	188.00	179.00	189.00	194.00	206.00
4	324.00	317.00	263.00	215.00	206.00	198.00	200.00	204.00	192.00	182.00	176.00	182.00	187.00	200.00
3	305.00	298.00	249.00	206.00	197.00	189.00	187.00	187.00	179.00	174.00	171.00	174.00	180.00	192.00
2	281.00	275.00	230.00	192.00	182.00	173.00	170.00	169.00	165.00	163.00	163.00	166.00	171.00	184.00
1	249.00	243.00	202.00	166.00	151.00	138.00	141.00	146.00	151.00	150.00	153.00	156.00	161.00	174.00
0	212.00	207.00	167.00	132.00	121.00	112.00	113.00	115.00	123.00	133.00	139.00	144.00	150.00	163.00
-1	150.00	147.00	126.00	108.00	101.00	94.60	86.10	79.30	93.10	108.00	120.00	130.00	135.00	147.00
-2	121.00	118.00	109.00	101.00	91.20	82.60	73.10	65.10	73.80	83.70	99.70	115.00	122.00	135.00
-3	121.00	118.00	107.00	97.80	86.60	76.20	65.90	57.10	64.10	72.20	88.30	103.00	110.00	121.00
-4	124.00	121.00	109.00	98.80	84.80	71.60	60.50	50.80	58.00	66.10	79.10	92.00	98.50	110.00
-5	127.00	124.00	110.00	99.70	83.00	67.00	56.50	47.20	53.20	59.90	71.70	83.30	90.70	102.00
-6	130.00	127.00	112.00	101.00	81.10	62.40	53.40	45.50	50.10	55.50	66.40	76.30	83.70	94.30
-7	131.00	128.00	112.00	98.80	78.40	58.80	50.20	42.80	45.70	49.30	60.30	70.30	79.40	91.60
-8	133.00	130.00	110.00	94.20	74.30	55.10	47.50	41.00	42.60	44.90	56.80	67.70	75.90	87.90

SI), fuel consumption is 1.5 percent higher on the rough section. In developing this conclusion, Ross used very strict criteria for eliminating outlaying data, and hence the variance of the data used in the analysis was much smaller than would be anticipated in the real world. Ross found that the measured fuel consumption on a section with an SI of 2.1 was less than the fuel consumption on sections with SIs of 4.4 and 3.6 for all three vehicles. Because of these apparent anomalous measures, these data were removed from the final analysis. Considering the fact that Ross eliminated so much data from the final analysis and still only found a very minor influence of roughness on fuel consumption, it is believed that an analysis of the complete data base would support the findings that roughness does not have a measurable effect on real-world fuel economy.

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Figure 11. Constant-speed fuel consumption (gal/1000 miles): 3A-SU.

GRADE %	SPEED mph 5	10	15	20	25	30	35	40	45	50	55	60	65	70
8	885.00	705.00	525.00	344.00	351.00	357.00	360.00	363.00	378.00	393.00	392.00	390.00	399.00	407.00
7	789.00	640.00	491.00	342.00	348.00	353.00	357.00	360.00	373.00	386.00	384.00	382.00	389.00	397.00
6	694.00	576.00	458.00	340.00	344.00	347.00	351.00	354.00	365.00	375.00	374.00	372.00	379.00	386.00
5	596.00	510.00	424.00	338.00	339.00	339.00	342.00	345.00	353.00	361.00	360.00	359.00	366.00	372.00
4	505.00	448.00	391.00	333.00	331.00	328.00	331.00	333.00	339.00	344.00	344.00	343.00	349.00	355.00
3	412.00	383.00	354.00	324.00	318.00	312.00	314.00	315.00	318.00	320.00	321.00	322.00	328.00	333.00
2	330.00	323.00	316.00	308.00	297.00	285.00	282.00	278.00	278.00	278.00	287.00	295.00	300.00	304.00
1	274.00	270.00	272.00	273.00	254.00	235.00	230.00	225.00	225.00	225.00	238.00	250.00	255.00	260.00
0	236.00	217.00	198.00	179.00	168.00	156.00	153.00	149.00	149.00	149.00	153.00	156.00	163.00	169.00
-1	196.00	159.00	122.00	85.00	79.00	73.00	68.00	62.00	72.00	82.00	79.00	75.00	75.00	79.00
-2	153.00	119.00	85.00	50.00	45.00	40.00	30.00	24.00	30.00	37.00	37.00	37.00	37.00	38.00
-3	126.00	96.00	66.00	36.00	32.00	28.00	16.50	15.00	18.50	22.00	25.00	28.00	28.00	30.00
-4	110.00	82.00	54.50	27.00	23.50	20.00	15.50	11.00	15.00	19.00	21.80	24.60	25.00	26.00
-5	94.00	70.00	46.00	22.00	18.50	15.00	11.50	8.00	13.00	18.00	19.80	21.50	22.00	23.00
-6	78.00	58.00	38.00	18.00	14.50	11.00	9.00	7.00	12.00	17.00	17.80	18.50	19.00	20.00
-7	64.50	48.00	31.50	15.00	11.00	7.00	6.50	6.00	11.00	16.00	15.60	15.10	15.00	16.00
-8	46.50	35.00	23.50	12.00	8.50	5.00	5.00	5.00	10.00	15.00	13.70	12.30	12.00	14.00

Figure 12. Constant-speed fuel consumption (gal/1000 miles): 2-S2.

GRADE %	SPEED mph 5	10	15	20	25	30	35	40	45	50	55	60	65	70
8	742.00	655.00	564.00	475.00	477.00	478.00	406.00	337.00	296.00	258.00	286.00	318.00	373.00	428.00
7	683.00	605.00	524.00	446.00	448.00	449.00	384.00	323.00	281.00	240.00	271.00	305.00	353.00	402.00
6	643.00	575.00	500.00	426.00	426.00	425.00	370.00	318.00	276.00	236.00	267.00	301.00	340.00	381.00
5	604.00	546.00	529.00	416.00	402.00	415.00	365.00	318.00	276.00	236.00	267.00	301.00	336.00	372.00
4	594.00	531.00	467.00	406.00	404.00	410.00	364.00	318.00	276.00	236.00	267.00	301.00	334.00	368.00
3	574.00	516.00	455.00	396.00	399.00	400.00	359.00	318.00	276.00	236.00	267.00	301.00	330.00	359.00
2	534.00	481.00	423.00	366.00	372.00	376.00	340.00	305.00	263.00	222.00	254.00	288.00	312.00	337.00
1	505.00	436.00	366.00	297.00	309.00	318.00	274.00	231.00	206.00	182.00	199.00	218.00	252.00	285.00
0	465.00	367.00	284.00	203.00	198.00	193.00	186.00	180.00	174.00	169.00	168.00	170.00	171.00	173.00
-1	346.00	258.00	178.00	102.00	100.00	96.50	93.50	89.50	87.00	111.00	111.00	113.00	129.00	130.00
-2	228.00	129.00	74.20	0.00	0.00	0.00	0.00	0.00	0.00	53.40	54.30	56.70	86.80	86.50
-3	98.90	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	43.40	43.30
-4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
-5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
-6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
-7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
-8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Discussion

Paul Claffey

My comments on Zaniewski's work refer specifically to the conclusion expressed in the abstract of his paper, that the highway pavement and its condition do not affect fuel economy over the range of conditions normally encountered in the United States. Certainly, many miles of road surface in this country, whether of concrete, asphalt, or stabilized gravel, have characteristics compatible with good motor vehicle fuel economy. Nevertheless, there are still hundreds of miles of primary roads with surfaces that have a deleterious effect on fuel economy. It has been found, from large-scale studies of motor vehicle fuel consumption relative to road surface conditions for all types of vehicles (especially large trucks), that fuel economy drops sharply for operation on road surfaces that (a) allow wheel slippage (loose surface material), (b) force tire indentations (exposed imbedded stones and/or a spalled surface condition), and/or (c) provide a coarse-sandpaper kind of surface (certain stone surface treatments). For example, a fully loaded 2-S2 tractor-semitrailer truck combination traveling at 50 mph will use more than 50 percent more fuel on a badly spalled concrete road surface as compared with operation over a smooth high-type road surface. I have observed many miles of such

Figure 13. Constant-speed fuel consumption (gal/1000 miles): 3-S2.

GRADE %	SPEED mph 5	10	15	20	25	30	35	40	45	50	55	60	65	70
8	756.00	679.00	599.00	523.00	553.00	588.00	528.00	463.00	426.00	389.00	424.00	445.00	460.00	490.00
7	694.00	627.00	557.00	489.00	518.00	551.00	498.00	443.00	402.00	360.00	399.00	424.00	432.00	456.00
6	655.00	593.00	531.00	467.00	491.00	520.00	478.00	434.00	393.00	350.00	388.00	413.00	411.00	426.00
5	615.00	563.00	562.00	455.00	462.00	505.00	468.00	431.00	389.00	347.00	384.00	407.00	400.00	410.00
4	604.00	547.00	495.00	443.00	462.00	496.00	463.00	426.00	384.00	342.00	378.00	400.00	390.00	396.00
3	581.00	531.00	481.00	430.00	453.00	480.00	451.00	420.00	378.00	335.00	370.00	390.00	375.00	377.00
2	543.00	494.00	444.00	395.00	418.00	444.00	419.00	392.00	350.00	306.00	340.00	361.00	342.00	340.00
1	512.00	447.00	381.00	315.00	339.00	365.00	325.00	285.00	261.00	239.00	252.00	258.00	260.00	271.00
0	470.00	370.00	287.00	205.00	204.00	204.00	202.00	201.00	199.00	199.00	202.00	207.00	210.00	215.00
-1	0.00	0.00	0.00	0.00	0.00	34.10	49.90	58.20	63.80	89.90	91.70	90.90	93.80	89.10
-2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	12.10	24.20
-3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
-4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
-5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
-6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
-7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
-8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

spalled concrete road surface in the United States, including mileage on the Interstate system.

The road surfaces used in the test operations reported on by Zaniewski are described in Table 2. They are identified as AC, PCC, ST, or gravel without any indication of the looseness of surface material, the amount of exposure of imbedded stone, or the roughness characteristics of the surface stone. Because fuel consumed by the test vehicles was about the same for all of the test sections, each probably had a firm, smooth surface without exposed surface stone. The SI (given in Table 2 for each test road section) is no help. It could vary over the range shown (from less than 1.0 to more than 4.0) because of surface undulations, even though the road surface is about the same as far as vehicle fuel consumption is concerned. A road with a low SI does not necessarily cause excess fuel to be consumed by vehicles that use the road.

Zaniewski refers to the work of Ross (10). In the Ross study, passenger car fuel consumption was measured for operation on each of a series of level, straight road sections that have relatively smooth undulating surfaces. The SI was 0.9 for the road in the poorest condition and 4.4 for the road in the best condition (similar to the test roads used by Zaniewski). Ross found, as did Zaniewski, that the fuel consumption per unit distance for each test car was about the same for each of the roads in his study.

I had occasion to observe the test roads used in the Ross study, and it was obvious why fuel economy was about the same for each road. None of the test sections had loose surface material, exposed imbedded stones, or coarse-sandpaper roughness. Despite the wide range of SI represented in the study roads, the surfaces were all pretty much alike relative to fuel consumption.

There are many sections of primary road in this country as well as in other countries where surface conditions cause excessive fuel consumption. It would be most unwise to conclude from studies conducted only on roads with surfaces conducive to good fuel economy that the highway pavement and its condition do not affect fuel economy.

Author's Closure

The points made by Claffey concerning alternative measures of road surface characteristics that may influence the fuel consumption of vehicles are well taken and probably correct. The generalized statement made in the abstract of the paper, "pavement condition does not affect fuel consumption over the range of conditions normally encountered in the United States", should have explicitly referred to pavement condition as defined by the SI.

This is a very significant finding, in that many states use either the SI or an alternative measure of roughness to quantify the condition of roadways. These states were erronously using previous research, which indicated that fuel consumption on a good pavement surface was less than fuel consumption on a bad pavement, to compute the economic and energy benefits of improving the SI, or roughness, of a road.

The three types of surface condition measures identified by Claffey as affecting fuel consumption are all candidates for further research into the influence of surface characteristics on fuel economy. Specifically, any future research should include not only the measurement of fuel, but engineering measures of the condition of the road surface with respect to looseness and microtexture. In order to be useful to highway engineers, terms like "badly spalled concrete" and "smooth high pace type" road surfaces must be replaced with reproducable measures of the extent of spalling. Unwise conclusions concerning the interrelations between pavement condition and fuel consumption can only be avoided by measuring both the dependent and independent variables in the relations. The research performed by Ross (10) and myself has clarified and resolved the situation with respect to one very important measure of road surface condition.

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Impact of Two-Way Left-Turn Lanes on Fuel Consumption

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Two-way left-turn lanes (TWLTLs) serve to eliminate conflict between midblock left turns and through traffic moving in the same direction. The purpose of this study was to evaluate the potential fuel savings generated by TWLTLs through reduced stops and delays. In the first part of the paper, the results of two earlier studies are examined and related to fuel efficiency and fuel savings. In the second part, the results of a simulation study are presented. The simulation study estimated annual fuel savings generated by the introduction of TWLTLs on sections of two-way two-lane and two-way four-lane arterials under various combinations of driveway density, average daily traffic, and left-turn frequency. The magnitude of the benefits to be derived from TWLTLs obviously depends on the magnitude of the existing midblock left-turn conflicts. On two-lane roadways, potential fuel savings can be substantial even at relatively low volumes. Fuel savings on four-lane roadways compared favorably with fuel savings estimated to result from another energy conservation method, the right-turn-on-red policy.

Urban streets must serve two distinct and conflicting functions, namely, the movement of traffic and the provision of access to abutting properties. The operating characteristics of a given street are largely determined by the compromises involved in serving these two functions. Those streets that are designated to favor one of these functions present relatively little problem to the transportation engineer. For example, freeways serve well the movement function, and local streets provide easy access to all properties. Most arterials, however, serve both movement and access. Even arterials, which were originally intended to serve the movement function, eventually attracted commercial, industrial, or high-density residential developments, i.e., the high accessibility resulted in an increased intensity of land use. The nature and the intensity of these developments often created left-turn demands to driveway entrances between intersections that led to conflicts between left turners and through traffic.

In many cases, the conventional median with left-turn pockets is a good solution. There are instances, however, when the need for access to abutting properties from both directions is there, but the pattern of location of the driveways makes left-turn pockets impractical. The prohibition of left turns would eliminate the conflict between through traffic and turning traffic, but it seriously limits the accessibility of the properties and would therefore be often unacceptable. Median two-way left-turn lanes (TWLTLs) may offer a solution.

A TWLTL is a single lane identified by pavement markings and signs and reserved for the exclusive use of left-turning traffic from either direction. Left turns can be made from any point along the median lane.

The major function of this lane is to provide a deceleration and waiting lane for left turns to minor traffic generators (major traffic generators are better served by one-way left-turn pockets), including abutting properties and minor streets. Secondary functions include the separation of opposing traffic flows, an acceleration lane for vehicles turning left into the arterials from minor streets and driveways, an emergency lane in case of temporary lane closures due to maintenance or accidents, and a lane for use by emergency vehicles, especially during peak hours.

A TWLTL can simultaneously improve access to land use and increase the speed of through traffic by eliminating the conflict between left-turning vehicles and through traffic moving in the same direction. Left-turning vehicles can wait in safety for appropriate gaps in the opposing through traffic.

Initial concerns with the potential hazard of head-on collisions between left-turning vehicles that enter from the opposite direction have been proved unfounded (1,2). Several studies have shown TWLTLs to be beneficial by reducing both left-turn-related accidents and delays. Guidelines have been published regarding the application and design of TWLTLs (3,4). One of the more specific guidelines states (5):

> The two-way left-turn lane is operationally warranted on arterial highways that have average daily traffic (ADT) volumes higher than 10 000 and traffic speeds faster than 48 km/h (30 mph). The number of driveways should exceed 60 in 1.6