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Technical Report

Quantitative Effects of Acceleration Rate on Fuel Consumption

by

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NOTICE

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Introduction

One factor which has a significant effect on vehicle fuel consumption is the rate at which the vehicle is accelerated. Quantitative and qualitative studies have shown that more rapid and/or more frequent accelerations result in increased fuel consumption.1/ The EPA has conducted a study to quantify the effects of operating a vehicle at different acceleration rates.

The test involved accelerating the vehicle at a constant acceleration rate to a speed of 55 mph, and maintaining the 55 mph speed until total distance traveled equaled one mile. Conceptually, this may be viewed as entering a freeway system with different acceleration rates. The acceleration rates varied in increments of one from 1 to 5 mph/sec. Fuel consumption was measured with a Fluidyne flow metering system.

Discussion/Procedure

The test was conducted on a Clayton twin roll dynamometer. The dynamometer rolls were coupled with a motorcycle chain to prevent tire slippage at the higher acceleration rates. The vehicle was a 1979 Nova, 250 CID, 1 bbl, with an automatic transmission.

The vehicle was first warmed to stable operating conditions by being driven over 2 HFET driving cycles. The fuel consumption tests were conducted starting the flow meter with the engine running, allowing five seconds of idle and then accelerating at the desired constant rate until the vehicle reached 55 mph. A 55 mph cruise was then maintained until a distance of one mile was travelled from the initial start.

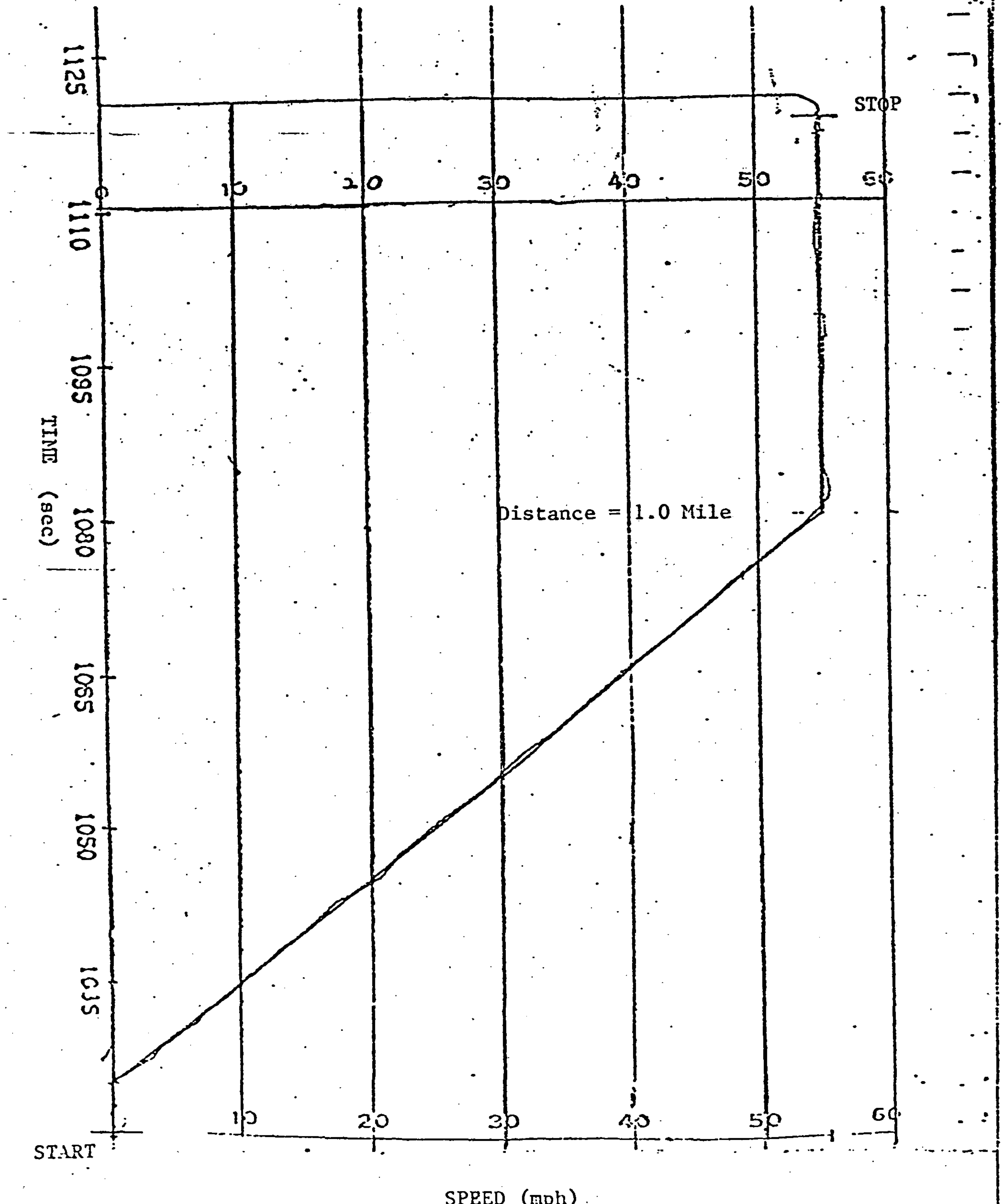
The acceleration rate and cruise speeds were accurately followed by using a "drivers aid" strip chart on which the desired acceleration ramps and cruise speed had been previously drawn. At the higher acceleration rates, if the vehicle could not match the acceleration trace, the accelerator pedal was depressed fully until the 55 mph cruise mode was reached.

Five repeat tests were conducted for each acceleration rate. The order of the tests were randomized to minimize any systematic fuel consumption effects which might have occurred because of increasing tire or lubricant temperatures. An example strip chart recording for a 1.0 mph/sec. acceleration trial is shown in Figure 1.

The data from the 20 test trials were corrected for actual distance travelled and fuel temperature to yield a fuel consumption figure in terms of cc/mile. The distance travelled was based on the dynamometer roll revolutions recorded during each test. An SAE fuel temperature correction for Group 3 test fuel was used to correct fuel volume measurements.2/ All data are tabulated in Appendix A.

Figure I

Speed Time Trace For A
1.0 mph/sec Acceleration Trial



Results

Fuel consumption increased approximately linearly with increasing acceleration rate. The results are summarized in Table 1 and plotted in Figure II. A linear regression line fit to the data yielded a correlation coefficient of .93, and, as illustrated in Figure 2, nearly passes through the standard deviation limits of all the acceleration trials.

Fuel consumption increased by 10.4 percent between acceleration rates of 1 mph/sec and 4 mph/sec. An apparent exception to the trend of increased fuel consuption with increased acceleration rate occurred when vehicle acceleration rate changed from 4 mph/sec to 5 mph/sec. Here, fuel consumption decreased. This apparent decrease in fuel consumption is most likely explained by the difficulty the vehicle encountered in achieving these constant acceleration rates. The acceleration rates of 3.0, 4.0, and 5.0 mph/sec exceeded the maximum vehicle acceleration capability at the higher speeds of 30 to 45 mph. The vehicle speed-time traces were particularly similar for the acceleration rates of 4.0 and 5.0 mph/sec. Driver comments indicated that the accelerator pedal was fully depressed for approximately 80 percent of the 4.0 mph/sec acceleration and virtually 100 percent of the 5.0 mph/sec acceleration. Therefore, the actual vehicle accelerations for these two test acceleration modes differed very little. The standard deviation values of fuel consumption for the 4.0 and 5.0 mph/sec trials overlapped, indicating little significance in a difference in fuel consumption between the tests for these two acceleration modes.

It is interesting to note the greatest increase in fuel consumption for any 1 mph/sec increment occurred when the acceleration rate changed from 3.0 to 4.0 mph/sec. The increase was probably caused by an anonmalous delay in the speed at which the transmission 1st - 2nd gear shift occurred when the acceleration rate changed from 3.0 to 4.0 mph/sec. This transmission effect was discussed in an earlier EPA technical report involving the same vehicle.3/ The report predicted a significant increase in fuel consumption when the vehicle acceleration rate exceeded the maximum acceleration rate on EPA test cycles, 3.3 mph/sec.

A model to calculate the energy demand on the vehicle for each different acceleration trial was derived, and actual fuel energy expended was compared to the theoretical energy demand. The derivation, calculations, and results are discussed in detail in Attachment I. The results are summarized in Table 2.

The energy model indicates that most of the increase in fuel consumption with increased acceleration rates occurs because of the increased energy demand. For acceleration rates between 1 and 3 mph/sec, the energy demand increased by about 6 percent as did the fuel consumption. Only when the acceleration exceeded 3 mph/sec did the fuel consumption increase more rapidly than the energy demand.

Table 1

Rate of Acceleration (mph/sec)	No. of Trials	Average Fuel Consumption (cc/mile)	Standard Deviation (cc/mile)
1.0	4	259.4	4.83
2.0	4	270.9	1.39
3.0	4	274.1	2.87
4.0	4	286.4	6.88
5.0	4	282.4	6.79

Figure II

Fuel Consumption vs. Acceleration Rate

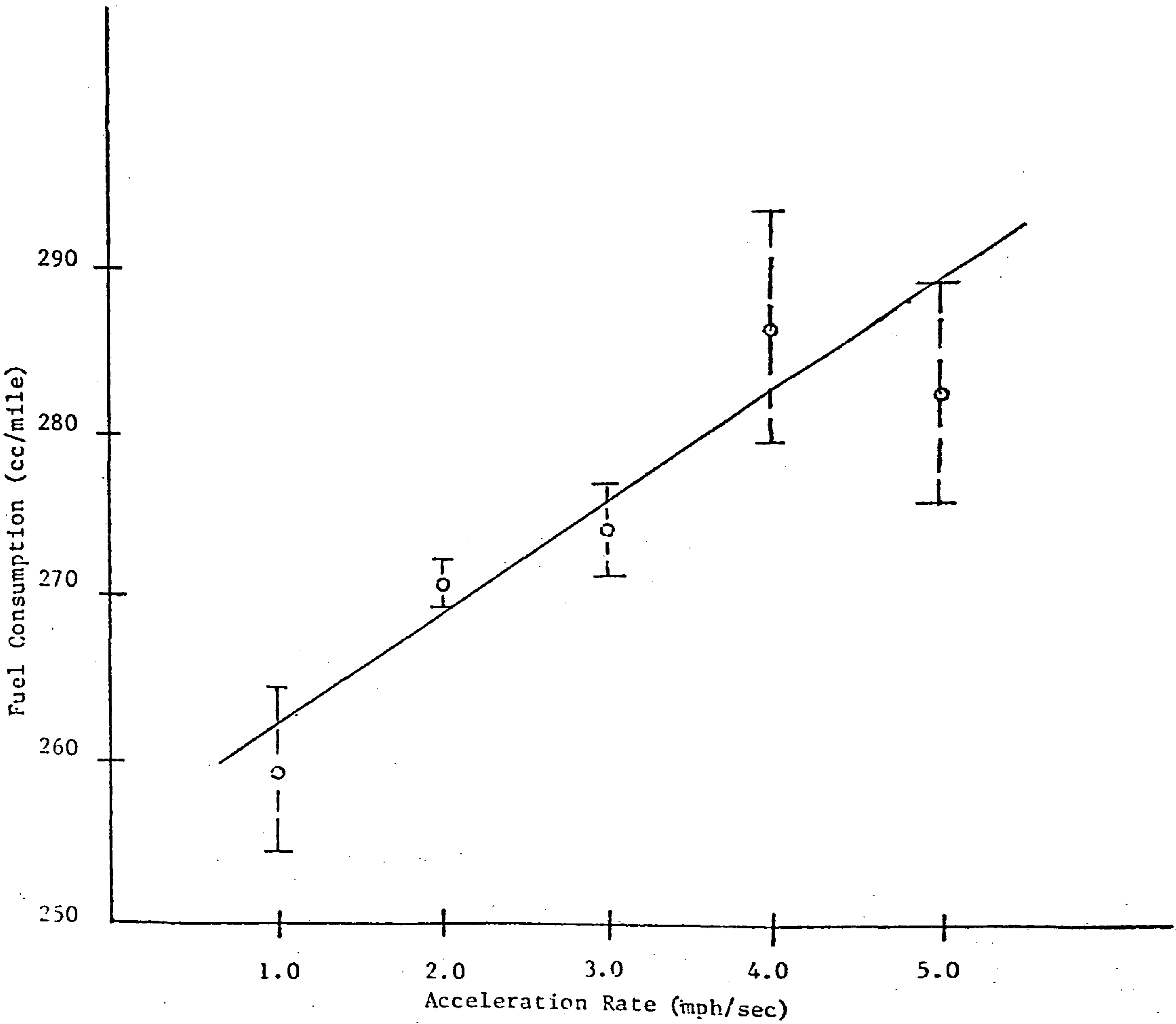


Table 2

Trial Acceleration Rate	Theoretical Energy Demand	Fuel Energy Expended	% Eff. $\frac{\text{Energy Demand}}{\text{Energy Expended}}$
1 mph/sec	1.479×10^6J	8.307×10^6J	17.8
2 mph/sec	1.550×10^6J	8.657×10^6J	17.9
3 mph/sec	1.573×10^6J	8.778×10^6J	17.9
4 mph/sec	1.582×10^6J	9.171×10^6J	17.3

Note: The theoretical energy demand assumes the vehicle accurately followed the acceleration-cruise trace. This was reasonably true for acceleration rates up to 4 mph/sec. The 5 mph/sec acceleration significantly exceeded the vehicle acceleration capability, therefore the theoretical energy demand for this acceleration was not included in the table.

This may also be expressed in terms of a simple energy efficiency ratio (theoretical energy demand/fuel energy consumed). The efficiency remained almost constant for all tests except for a notable decrease at the 4.0 mph/sec acceleration. The decrease may be explained by the transmission effect discussed earlier.

The increase in energy demand with an increase in acceleration rate is shown in the model to be a function of the increased time the vehicle is operated at the 55 mph cruise speed. Since the aerodynamic drag force, simulated by the dyno power absorber, is proportional to the square of vehicle speed, more power is absorbed when the vehicle is accelerated to the cruise speed quickly.

Conclusions

The test vehicle for this experiment exhibited an increase in fuel consumption with an increase in acceleration rate. Fuel consumption increased by 10.4 percent when the acceleration rate increased from 1.0 mph/sec to 4.0 mph/sec.

Computation of the energy demand indicates that most of the effect occurs because the increased acceleration rates result in more vehicle operation at the cruise speed inducing more dyno power absorber work on the vehicle.

However, the maximum fuel consumption effect occured when the acceleration rate changed from 3.0 to 4.0 mph/sec. This result probably occurred because of an anomaly in transmission shift characteristics of this vehicle when the acceleration rate exceeded the maximum acceleration rates of the EPA test cycles.

References

1/ "Passenger Car Fuel Economy: EPA and Road - A Report to the Congress," Draft, U.S. Environmental Protection Agency, April 1980.

2/ "Fuel Economy Measurement Road Test Procedure - Cold Start and Warm-Up Fuel Economy," SAE J1256, Society of Automotive Engineers, Warrendale, PA, May 1979.

3/ "The Effect of Acceleration Rate on Automatic Transmission Shift-Speeds for Two 1979 Novas," R. Jones, EPA Technical Report, January 1980.

Appendix A

Fuel Consumption Data

Vehicle: 1979 Nova, silver

Date: 3/1/80

Dyno Cell: D207, rolls coupled, d = 8.65 in.

Barometric Pressure: 29.48 in. Hg

Temperature: WB = 62.5 DB = 74.0

Inertia Weight: 3750 lb. AHP = 12.9 IHP = 10.4

Test Tires: Bridgestone bias

Data

Trial Acceleration Rate (mph/sec)	Roll Revolutions	Fuel Consumed (cc)	Fuel Temperature (°C)	Fuel Consumption Corrected for Fuel Temperature and Distance (cc/mile)
5	2325	266.7	40.0	274.8
1	2348	251.0	40.0	256.1
2	2220	252.4	41.0	272.5
5	2291	271.2	41.0	283.7
3	2356	272.6	41.0	277.3
4	2239	265.3	41.0	284.0
1	2348	260.3	41.0	265.7
4	2319	280.7	41.0	290.1
5	2302	278.9	42.0	291.0
4	2322	284.5	41.0	293.6
3	2334	268.3	41.0	275.8
1	2360	256.7	41.0	260.7
3	2341	265.3	41.0	271.6
2	2216	250.8	41.0	271.3
3	2349	265.8	42.0	271.8
2	2238	252.6	41.0	270.5
4	2333	270.0	42.0	278.0
2	2239	251.5	41.0	269.2
1	2373	252.1	42.0	255.2
5	2350	274.1	42.0	280.2

Table 1-A

Fuel Consumption (cc/mile)

Trial	1.0 mph/sec	2.0 mph/sec	3.0 mph/sec	4.0 mph/sec	5.0 mph/sec
1	256.1	272.5	277.3	284.0	274.8
2	265.7	271.3	275.8	290.1	283.7
3	260.7	270.5	271.6	293.6	291.0
4	255.2	268.2	271.8	278.0	280.2
$\overline{x}$	259.4	270.9	274.1	286.4	282.4
s	4.83	1.39	2.87	6.88	6.79
% $s/\overline{x}$	1.86%	.50%	1.05%	2.4%	2.4%

Attachment I

Calculation of Vehicle Energy Demand

The total energy demanded from the vehicle over any cycle is the time integral of the instantaneous power requirement:

$$E = \int_{T_i}^{T_f} P dt \tag{1}$$

Where:

E = the total energy demand,

P = the instantaneous power requirement,

T_i = the initial time of the beginning of the cycle,

T_f = the final time at the end of the cycle.

The power required can, of course, be expressed as the product of the instantaneous force times the velocity of the vehicle. For the simple cycles of this project; that is, ramp accelerations followed by a steady speed cruise, the forces acting on the vehicle may be expressed as:

$$F = m \frac{dv}{dt} + f_0 + f_2 V^2 \tag{2}$$

Physically the first term represents the inertial effect, the second term primarily represents tire losses, while the third term represents the aerodynamic drag or dynamometer power absorption. It should be noted that equation (2) does not contain any term representing energy dissipated in the vehicle brakes; therefore, this equation is only applicable to cycles in which the vehicle brakes are not used.

Combining equations (1) and (2) and integrating:

$$E = \int_{T_i}^{T_f} F v dt$$

$$= \int_{T_i}^{T_f} (m \frac{dv}{dt} + f_0 + f_2 v^2) v dt$$

$$= \int_{T_i}^{T_f} (m \frac{dv}{dt} vdt) + \int_{T_i}^{T_f} f_0 vdt + \int_{T_i}^{T_f} f_2 v^3 dt$$

$$= m \int_{V(T_i)}^{V(T_f)} vdv + f_0 \int_{T_i}^{T_f} vdt + f_2 \int_{T_i}^{T_f} v^3 dt$$

$$= 1/2\ mv^2 \Big|_{V(T_i)}^{V(T_f)} + f_0 \int_{T_i}^{T_f} vdt + f_2 \int_{T_i}^{T_f} v^3 dt \qquad (3)$$

The simple cycles of this report start with the vehicle at rest; that is:

$$V(T_i) = 0 \qquad (4)$$

Using,

$$V(T_f) = V_f \qquad (5)$$

The first term of (3) becomes:

$$1/2\ mv^2 \Big|_{V(T_i)}^{V(T_f)} = 1/2\ mV_f^2 \qquad (6)$$

This term is, as expected the kinetic energy of the vehicle at the final steady speed cruise.

The second term, the time integral of the velocity is, by definition the distance traveled:

$$\int_{T_i}^{T_f} vdt = D \qquad (7)$$

Therefore, using equations (6) and (7) in equation (3):

$$E = 1/2\ mV_f^2 + f_0 D + f_2 \int_{T_i}^{T_f} v^3 dt \tag{8}$$

For these cycles, or in fact for any cycles in which the vehicle brakes are not used, only the aerodynamic drag term dependent on the detailed velocity versus time characteristics of the cycle.

Because of the simple characteristics of the cycles used in this program, even the aerodynamic term of equation (8) can be integrated in closed form. First, the integral can be separated into two components, the acceleration segment and the cruise segment.

$$\int_{T_i}^{T_f} v^3 dt = \int_{T_i}^{T_c} v^3 dt + \int_{T_c}^{T_f} v^3 dt \tag{9}$$

Where:

T_c = the time at which the cruise segment is initiated.

Since the acceleration is constant:

$$V_c = aT_c$$

or, (10)

$$T_c = V_c/a$$

Where:

V_c = the constant cruise velocity

In terms of a and V_c equation (9) becomes:

$$\int_{T_i}^{T_f} v^3 dt = \int_{T_i}^{T_c} (at)^3 dt + \int_{T_c}^{T_f} V_c^3 dt$$

$$= a^3 \frac{t^4}{4}\Bigg|_{T_i}^{T_c} + V_c^3\ t\Bigg|_{T_c}^{T_f}$$

Choosing to call the initial time T_i to be zero:

$$\int_{T_i}^{T_f} v^3 dt = 1/4 a^3 T_c^4 + V_c^3 (T_f - T_c) \tag{12}$$

For the particular cycles under investigation the final velocity is the cruise velocity.

$$V_f = V_c \tag{13}$$

Therefore:

$$E = 1/2\, mV_c^2 + f_o D + f_2\, [1/4 a^3 T_c^4 + V_c^3(T_f - T_c)] \tag{14}$$

$$= 1/2\, mV_c^2 + f_o D + f_2[1/4\, V_c^3 T_c + V_c^3 T_f - V_c^3 T_c]$$

$$= 1/2\, mV_c^2 + f_o D + f_2 V_c^3 (1/4\, T_c + T_f - T_c]$$

$$= 1/2\, mV_c^2 + f_o D + f_2 V_c^3 (T_f - 3/4\, T_c]$$

The time at which cruise condition is reached T_c is given by equation (10). The condition for T_f is that the total distance traveled remain constant for the different accelerations. That is:

$$D = \int_{T_i}^{T_c} at\,dt + \int_{T_i}^{T_f} V_c\,dt \tag{15}$$

$$= 1/2\, at_2 \Big|_{T_i}^{T_c} + V_c t \Big|_{T_c}^{T_f}$$

Calling the initial time $T_i = 0$,

$$D = 1/2\, aT_c^2 + V_c(T_f - T_c) \tag{16}$$

Using equation (10) and solving for T_f,

$$D = 1/2a \frac{V_c^2}{a^2} + V_c T_f - V_c V_c/a$$

$$= 1/2 \frac{V_c^2}{a} + V_c T_f - \frac{V_c^2}{a}$$

$$= V_cT_f - 1/2 \frac{V_c^2}{a}$$

$$V_cT_f = D + 1/2 \frac{V_c^2}{a} \qquad (17)$$

$$= \frac{2aD}{2a} + V_c^2$$

$$Tf = \frac{2aD + V_c^2}{2aV_c}$$

Equations (14, (17), and (10) provide the complete algrebraic expression for the energy demand for the vehicle over the simple cycles used in this study.

Dynamometer Representation

In the case of dynamometer tests it is reasonable to assume that the power absorbed by the PAU is proportional to the velocity cubed, and that the remainder of the power absorbed by the vehicle-dynamometer system occurs in the tires and dynamometer bearings and is linear in velocity.

The indicated dynamometer power absorption at 50 mph may, therefore, be equated to:

$$IHP(V) = f_2V^3$$

$$f_2 = \frac{IHP(50)}{(50\ mi/hr)^3} \qquad (18)$$

The vehicle-dynamometer coastdown is a measure of the total dissipation forces acting on the system and may be used to determine f_0:

$$f_0 + f_2V^2 \simeq M \frac{\Delta V}{\Delta t}$$

$$f_0 = M \frac{\Delta V}{\Delta t} - f_2V^2 \qquad (19)$$

Example Calculation

In this program, the following parameters were used for all dynamometer tests:

$IHP = 10.4$

$I = 3750$ lbs. $= 1705$ kg

$\Delta t = 12.42$ (vehicle-dynamometer coastdown time)

$V_c = 55$ mi/hr $= 24.59$ m/sec

Consequently from equation (18):

$$f_2 = \frac{10.4 \text{ hp}}{(50 \text{ mi/hr})^3} \quad (20)$$

$$= \frac{10.4 \text{ hp hr}^3}{125 \times 103 \text{ mi}^3} \left(\frac{\text{mi}}{1.609 \times 10^3 \text{m}}\right)^3 \left(\frac{3600 \text{ sec}}{\text{hr}}\right)^3$$

$$= 0.695 \frac{\text{nt sec2}}{\text{m}^2}$$

Computing f_o from equation (19),

$$f_o + f_2 V^2 = \frac{(1705 \text{ kg})(4.47 \frac{\text{m}}{\text{sec}})}{12.42 \text{ sec}} = 613 \text{ nt} \quad (21)$$

Therefore:

$$f_o = 613 \text{ nt} - f_2 V^2$$

$$= 613 \text{ nt} - 0.695 \text{ nt} \frac{\text{sec}^2}{\text{m}^2} \left(22.35 \frac{\text{m}}{\text{sec}}\right)^2$$

$$= 613\text{nt} - 347$$

$$= 266 \text{ nt} \quad (22)$$

Considering the specific case of an acceleration of 1 mi/hr-sec the time to reach the 55 mi/hr cruise speed is given by equation (10).

V_c = 55 mi/hr = 24.59 m/sec

a = 1 mi/hr-sec = 0.447 mi/sec^2

$$T_c = V_c/a$$

$$= \frac{24.59 \text{ m/sec}}{0.447 \text{ m/sec}^2} \qquad (23)$$

$$= 55 \text{ sec}$$

The final time at the completion of the cruise is, from equation (17):

$$T_f = \frac{2(0.447 \text{ m/sec}^2)(1{,}609 \text{ m}) + (24.59 \text{ m/sec})^2}{2(0.447 \text{ m/sec}^2)(24.59 \text{ m/sec})}$$

$$T_f = \frac{1438 \text{ m}^2/\text{sec}^2 + 604 \text{ m}^2/\text{sec}^2}{22 \text{ m/sec}^3}$$

$$= 93 \text{ sec}$$

The total energy may now be calculated using equation (14) and the values for f_o, f_2, T_c, and T_f from the previous equations:

$$E = 1/2 \, mV_c{}^2 + f_oD + f_2V_c{}^3 \, (T_f - 3/4 \, T_c)$$

$$= 1/2(1705 \text{ kg})\left(\frac{24.6 \text{ m}}{\text{sec}}\right)^2 + (266\text{nt})(1{,}609\text{m})$$

$$+ 0.695 \text{ nt } \frac{\text{sec}^2}{\text{m}^2} \left(\frac{24.6 \text{ m}}{\text{sec}}\right)^3 (93 - 3/4 \; 55)\text{sec}$$

$$= 0.516 \times 10^6 \text{ nt m} + 0.428 \times 10^6 \text{ nt m}$$

$$+ 0.695 \text{ nt } \frac{\text{sec}^2}{\text{m}^2} \left(\frac{24.6 \text{ m}}{\text{sec}}\right)^3 (51.75)\text{sec}$$

$$= (0.516 + 0.428 + 0.535) \times 10^6 \text{ J}$$

$$= 1.479 \times 10^6 \text{ J}$$

The total energy for the remaining four acceleration rates are shown below:

2 mph/sec $E = (0.516 + 0.428 + 0.606) \times 10^6$ J

$E = 1.55 \times 10^6$ J

3 mph/sec $E = (0.516 + 0.428 + 0.629) \times 10^6$ J

$E = 1.573 \times 10^6$ J

4 mph/sec $E = (0.516 + 0.428 + 0.638) \times 10^6$ J

$E = 1.582 \times 10^6$ J

5 mph/sec $E = (0.516 + 0.428 + 0.649) \times 10^6$ J

$E = 1.593 \times 10^6$ J

Comparison to Test Results

The actual fuel energy expended in this experiment is compared to the theoretical energy demand in Table I and Figure I. A fuel-energy efficiency value is also shown in Table I. The calculations assume a value of 32023 J/cc of fuel.1/

A linear regression line fit to the data yielded a 0.926 correlation coefficient indicating a linear relation between theoretical energy demand and fuel energy consumed. The efficiency ratio of theoretical energy demand to fuel energy expended remains nearly constant, around 17.7 percent. This also indicates a good correlation between the two parameters. However, the efficiency value for the highest acceleration rate, 5.0 mph/sec, is misleadingly high. Since the higher acceleration rates exceeded the vehicle acceleration capability, the actual vehicle work was significantly less than the theoretical energy demand. The energy efficiency for the 5.0 mph/sec acceleration mode was omitted since the actual work, as discussed earlier, was nearly the same as the 4.0 mph/sec acceleration trials.

It is interesting to note from the theoretical energy model that the increased energy demand at the higher acceleration rates are not a result of the increased acceleration rates themselves. Mathematically the increase in energy with an increase in acceleration rate results solely from a change in the f_2v^2, or aerodynamic drag term, while the inertial and rolling resistance terms remain constant. The increased energy demand is a result of the vehicle reaching a cruising speed sooner and maintaining the speed for a longer period of time. Thus, the maximum aerodynamic drag force simulated by the dynamometer power absorber, which increases with the square of vehicle speed, acts on the vehicle for a longer period of time when the vehicle is accelerated to a cruise speed quickly.

The model is a physical approximation of the energy required to operate this vehicle over the given cycles. The actual fuel consumption correlates very well to the theoretical energy demand. However, the model does not treat all vehicle factors which may influence fuel consumption and which might change with changing acceleration rates. Examples include automatic transmission shift speed and peak combustion temperature.

1/ D.E. Foringer, "Gasoline Factors Affecting Fuel Economy," SAE Paper No. 650427.

Figure A-I

Theoretical Energy Consumed Vs
Actual Fuel Energy Consumed

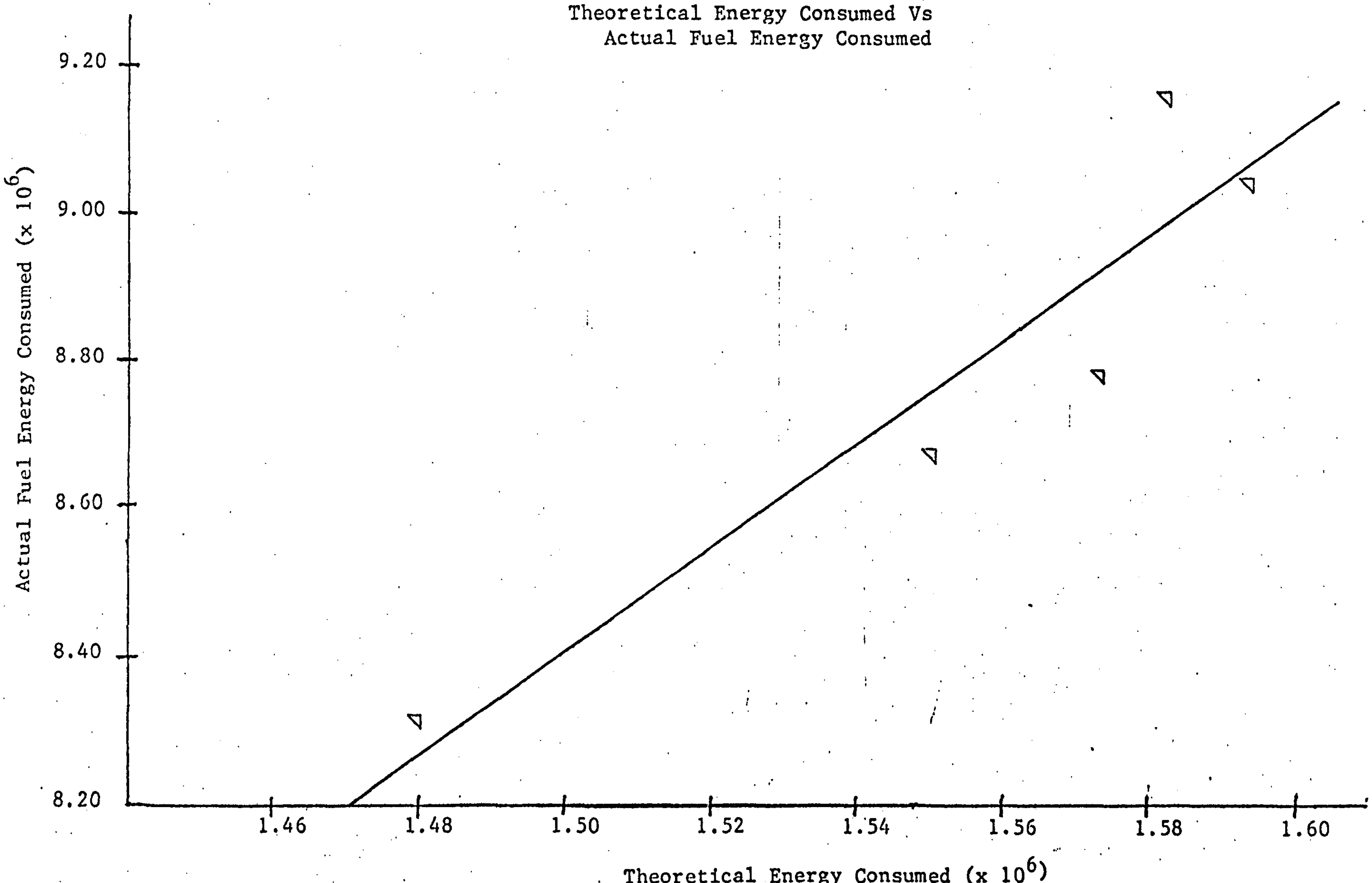


Table I

Trial Acceleration Rate	Theoretical Energy Demand for a 1.0 Mile Trial	Average Fuel Energy Expended for a 1.0 Mile Trial	Percent Efficiency
1 mph/sec	1.479×10^6 J	8.307×10^6 J	17.8
2 mph/sec	1.550×10^6 J	8.675×10^6 J	17.9
3 mph/sec	1.573×10^6 J	8.778×10^6 J	17.9
4 mph/sec	1.582×10^6 J	9.171×10^6 J	17.3