Fuel Consumption on Congested Freeways

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The effect of interactions between vehicles on freeway fuel consumption is investigated. The relation between energy and fuel consumption during free-flow conditions is established by means of the basic equations of movement. This, together with the acceleration noise due to traffic interaction, is then used to calculate the additional fuel consumption when the smooth flow of vehicles is hampered by the presence of other vehicles. It is found that, for densities less than one-third of the jam density, fuel consumption due to traffic interaction is negligible. For high densities, however, constant-speed fuel consumption can be increased by as much as 50 percent.

As a result of oil shortages, the fuel consumption of vehicles has received increased attention over the past few years. Because of the high traffic volumes on freeways, the effect of traffic interaction on fuel consumption is important for the justification of new facilities or the implementation of different transportation system management strategies. To predict this effect, speed-change cycles have been used (1,2). It is difficult, however, to relate these cycles to traffic volume or density. Capelle (3) hypothesized that "acceleration noise" (the standard deviation of accelerations) on a section of road is equal to the total fuel consumed minus the minimum fuel consumption. In this paper, the effect of acceleration noise on fuel consumption at different speeds will be investigated as a way of predicting additional fuel consumption due to traffic interaction.

This paper first shows how the fuel consumption at constant speed on a constant gradient can be calculated from the basic energy equations. This is then used to predict fuel consumption during acceleration and deceleration. All of these predictions are substantiated by the results of actual field tests with various passenger cars. The fact that accelerations follow a normal distribution is then used to calculate the additional fuel consumption due to acceleration noise.

FUEL CONSUMPTION AT CONSTANT SPEED

To relate fuel consumption to energy, it is first necessary to consider the various forces that act on a vehicle that is being driven at constant speed on a constant gradient. The most important of these are the rolling, air, and gradient resistances. Power is also used to overcome transmission losses and to turn the engine.

Assuming that fuel is directly related to energy, or

$$F = bE \quad (1)$$

the above can be expressed by means of the following formula:

$$F = P_1 + P_2/V + P_3V^2 + P_4G \quad (2)$$

where

F = fuel consumption;
b = a conversion factor;
E = energy;
V = speed;
G = gradient;
P_1, P_3, and P_4 = constants derived from the rolling, air, and gradient resistances; and
P_2 = a constant that is related to idling fuel consumption.

This formula is only valid if the expression $P_1 + P_3V^2 + P_4G$ is positive. If it is negative--e.g., as a result of a negative gradient--then

$$F = P_2/V \quad (3)$$

A fuel flow meter, measuring to the nearest milliliter, was installed in several passenger cars to test the validity of the above equations. A fifth wheel provided accurate measurements of distance and speed. The results for one specific car are given below (each value represents the average of at least four measurements):

Speed (m/s)	Gradient (m/m)	Fuel Consumption (mL/km)
11.11	-0.0065	59.5
11.11	+0.0065	72.5
16.67	-0.0065	55.0
16.67	+0.0065	68.5
22.22	-0.0065	66.5
22.22	+0.0065	79.5
27.78	-0.0065	82.0
27.78	+0.0065	91.5
33.33	-0.0065	108.5
33.33	+0.0065	113.0
36.11	-0.0065	123.0
36.11	+0.0065	130.0
11.11	+0.029	97.5
16.67	+0.029	100.5
22.22	+0.029	109.0
27.78	+0.029	122.5
33.33	+0.029	155.0
16.67	+0.047	115.6
22.22	+0.047	139.6
27.78	+0.047	153.1

By means of a regression analysis on the results, it was found that Equation 2 explains as much as 97.9 percent of the variation ($r^2 = 0.979$) in fuel consumption due to speed and positive and small negative gradients. To test the validity of Equation 3, the fuel consumption for a specific car was predicted for a route of 10 km in rolling terrain (up to 5 percent gradient) for a constant speed of 90 km/h and then actually measured. The predicted amount of 1477 mL, total in both directions, compared well with the measured amount (average of five runs) of 1472 mL. The results for a Continental passenger car with a gross mass of 1400 kg are as follows:

$$F = 14.7 + 440/V + 0.0764V^2 + 1268G \quad (4)$$

where F is in milliliters per kilometer, V is in meters per second, and G is in meters per meter. These values are used in all subsequent calculations.

From Equation 4, the values of the fuel conversion factor b, the air-drag coefficient, the rolling resistance factors, and the idling fuel consumption can be calculated. The frontal projected area of the car is 2.5 m^2, and a 10 percent transmission loss is assumed (1). The coefficient of the V^2 term is made up of the air resistance and the speed-related term of the rolling resistance. I have assumed the latter to be $6.86 \times 10^{-5}\ m^{-1}$, as given by St. John and Kobett (4). The tests were done at an altitude of 1500 m, and therefore the density of the air is 1.059 kg/m^3. This affects the calculation of the air-drag coefficient. The following values are used:

Item	Value
Fuel conversion factor b (L/kW•h)	0.30
Air-drag coefficient	0.552
Rolling resistance (N/kg)	$0.1137 + 6.86 \times 10^{-5}V^2$
Idling fuel consumption (L/h)	1.58

The last three values agree very well with those found in earlier research (2,4). This is proof of the assumption leading to Equation 1. The value b can now be used to predict the additional fuel consumption due to acceleration.

FUEL CONSUMPTION DURING ACCELERATION

Several problems are involved in the measurement of additional fuel consumption due to acceleration:

1. Acceleration is never constant.
2. Acceleration occurs for short periods only.
3. There is a time lag between the moment of measurement in the fuel line and that of actual combustion in the engine. This time lag is also variable and depends on the flow rate of the fuel in the supply line.

For these reasons, it was decided to predict rather than directly measure the additional fuel by means of the theory developed in the previous paragraph. The predictions will then be validated by different means.

From Newton, force = mass x acceleration; thus,

$$E = Mad \tag{5}$$

where

M = mass (kg),
a = acceleration (m/s^2), and
d = distance (m).

However, for an accelerating vehicle, the engine, driveline, and wheel inertias also have an effect. This is compensated for by using the effective mass M_e, which is a function of the inertias and the total gear reduction (5,6). For the 1400-kg test vehicle, the effective mass during acceleration in fourth gear is 1532 kg.

Therefore, the additional fuel consumption due to acceleration in top gear is

$$F_a = bM_e ad/\eta$$
$$= [(0.3 \times 1532 \times 1000)/3600] \cdot (100/90) \cdot a$$
$$= 142\alpha \text{ mL/km} \tag{6}$$

where η is the driveline efficiency. This can also be calculated for the other gears.

An attempt was made to validate Equation 6 by measuring the fuel consumption during acceleration (see Figure 1). For the reasons mentioned earlier, this attempt was not very successful.

By combining Equations 4 and 5, it was possible to predict the total fuel consumption for each 2-s period during a 30-s trip that included two speed-change cycles. In this case, if the expression $14.7 + 0.0764V^2 + 1268G + 142a$ is negative (while deceleration takes place), Equation 3 is applicable. Figure 2 shows the comparison between the calculated and measured fuel consumption. The variability of the time lag, mentioned earlier, is clearly illustrated. During acceleration it is about 1 s, but during deceleration, when the flow rate is low, it is twice as much. Considering the above, the total calculated consumption of 97.3 mL compares well with the measured 101 mL.

It is clear that the combination of Equations 3, 4, and 6 gives a reasonable estimate of the fuel consumption during acceleration and deceleration. It can now be used to calculate additional fuel consumption due to acceleration noise.

ACCELERATION NOISE

Although a motorist may wish to drive at a constant speed, it is impossible to do so. When high traffic volumes are present on the highway, the motorist is often forced to change speed. The geometric characteristics of the highway may also cause accelerations and decelerations. Even on the perfect roadbed, the driver unconsciously varies the speed of the vehicle. These accelerations approximately follow a normal distribution (7). The standard devia-

Figure 1. Additional fuel consumption due to acceleration.

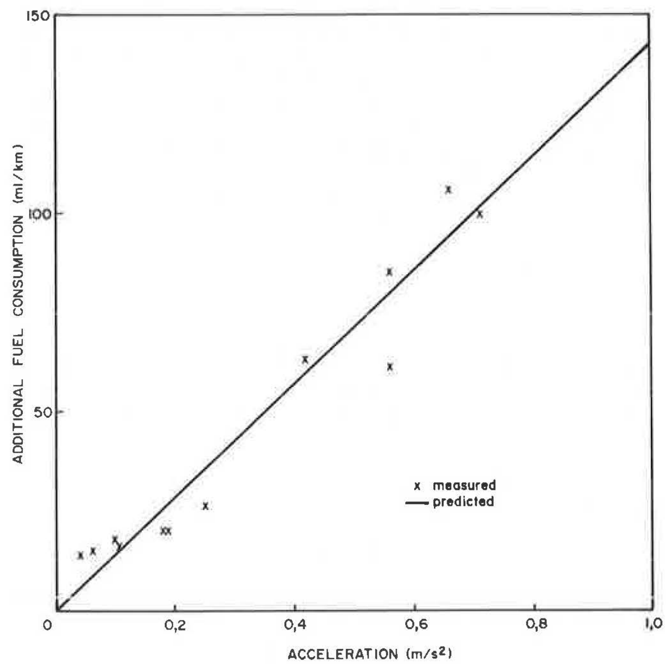
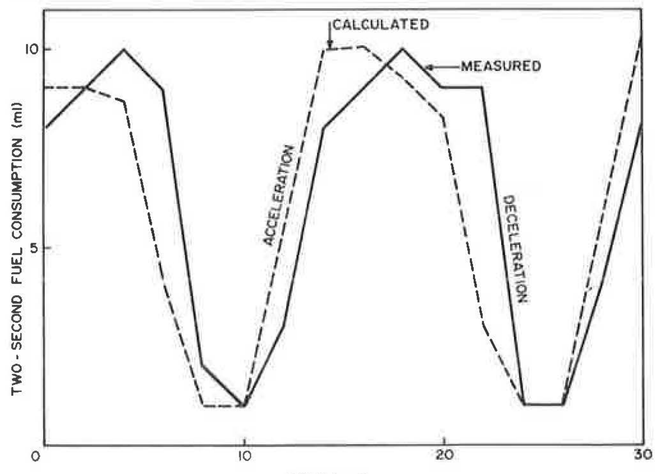


Figure 2. Measured and calculated fuel consumption during acceleration and deceleration.



tion of the accelerations--the acceleration noise--gives an indication of the severity of speed changes.

Acceleration noise has two components: the natural noise (σ_n), which can be ascribed to the driver and the road (8), and the traffic noise (σ), which is generated by traffic interactions. Drew and others (9) showed that

$$\sigma_t = \sigma_{tm} - \alpha k u^2 \quad (7)$$

where

σ_{tm} = maximum noise related to traffic only,
α = $(27\sigma_{tm})/(4u^2{}_f k_j)$,
k = density,
u = speed,
u_f = free-flow speed, and
k_j = jam density.

Assuming a linear relation between speed and density,

$$\sigma_t = \sigma_{tm} - \alpha k[u_f(1 - k/k_j)]^2 \quad (8)$$

This can be written as

$$\sigma_t = \sigma_{tm}[1 - 6.75(k/k_j) + 13.5(k/k_j)^2 - 6.75(k/k_j)^3] \quad (9)$$

The total noise is

$$\sigma = \sigma_t + \sigma_n \quad (10)$$

The relation between acceleration noise and density is shown in Figure 3.

FUEL CONSUMPTION DUE TO ACCELERATION NOISE

The fact that acceleration is a random variable, having the normal distribution $N(o,\sigma^2)$, is now used to calculate the additional fuel consumption due to acceleration noise. The method of calculation is explained with the help of Figure 4, which shows the graph of the normal probability density function f(a). The total area under the curve is equal to one. The shaded area A gives an indication of the proportion of time (or distance, if a spe-

Figure 3. Acceleration noise versus relative density.

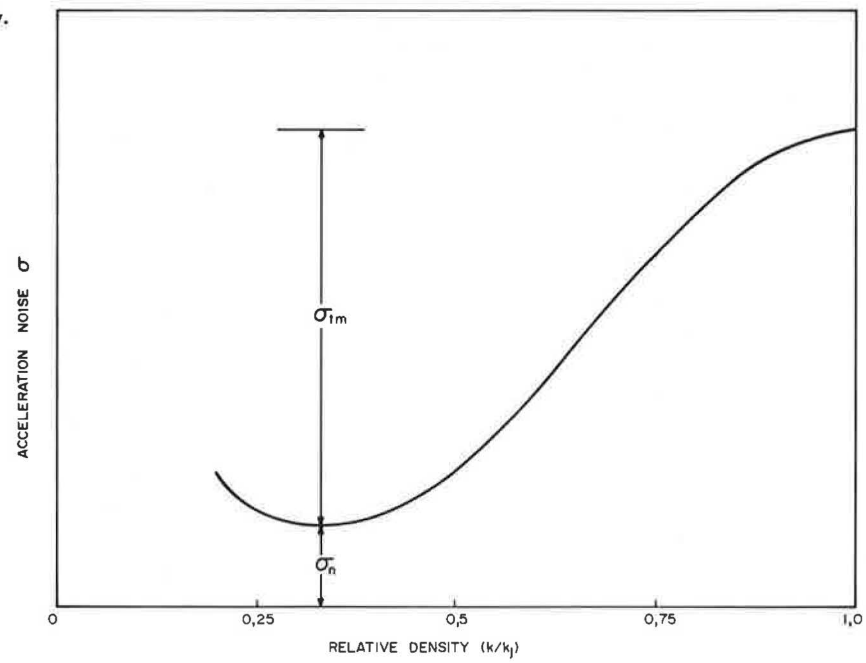


Figure 4. Normal probability density function $f(\alpha)$.

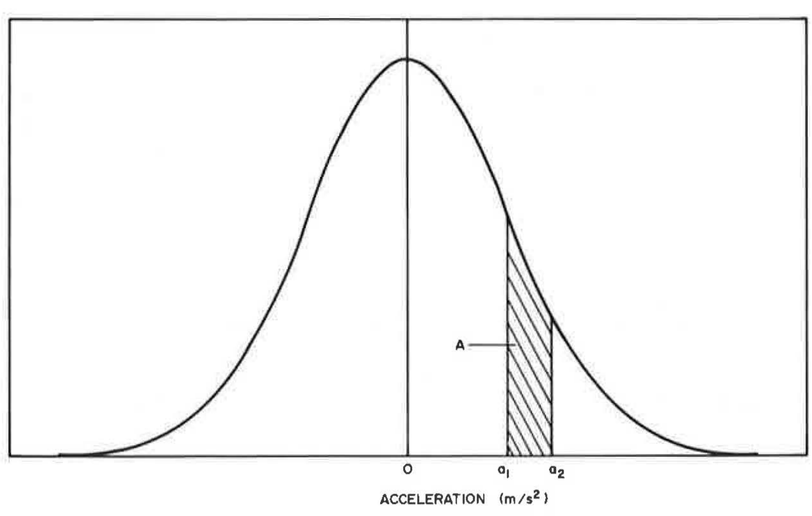
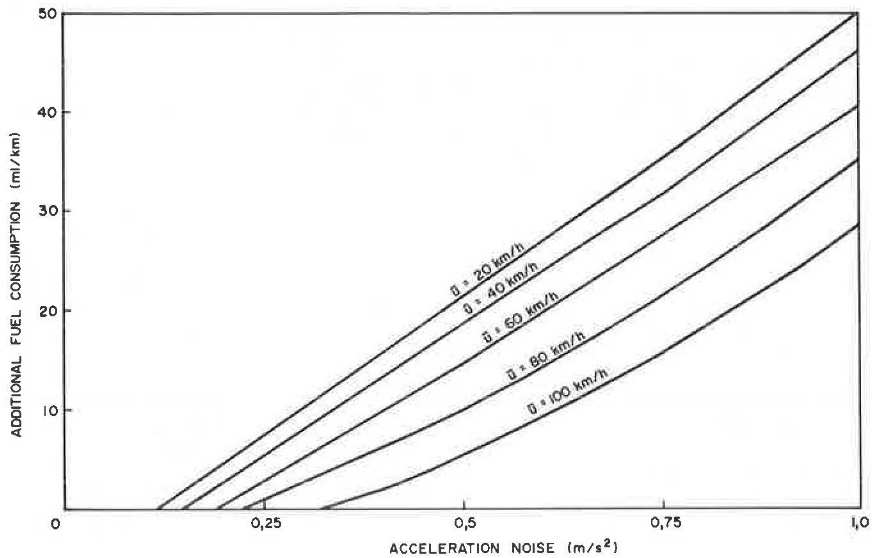


Figure 5. Additional fuel consumption due to acceleration noise.



cific average speed is assumed) during which the acceleration is between a_1 and a_2. With the band sufficiently narrow, it can be said that, for a distance of 1000A meters out of a kilometer, the acceleration is $(a_1 + a_2)/2$. By using Equations 3, 4, and 6 together with numerical integration of f(a), one can calculate the total fuel consumption per kilometer for different average speeds $\bar{u}$. By subtracting constant-speed fuel consumption, the additional fuel consumption due to acceleration noise can be found. The results are shown in Figure 5.

These results can now be used together with Equation 9 to determine the fuel consumption as a result of traffic interaction.

DISCUSSION OF NOISE VALUES

From Figures 3 and 5, the following should be noted:

1. For low values of σ, such as the natural noise for a driver on a high-design type of facility, no additional fuel is consumed.
2. The maximum practical value for σ is about 1.0 m/s² (9). In circumstances in which this does occur, the extra fuel consumption due to traffic interaction can be as much as 50 percent of the free-flow fuel consumption.
3. Figure 20 in the report by Drew and others (9) shows that acceleration noise, measured for speeds higher than 2/3 u_f, is less than 0.12 m/s². This corresponds to densities less than 1/3 k_j. Since a value of $\sigma = 0.12$ m/s² does not contribute to additional fuel consumption, densities lower than 1/3 k_j are disregarded in calculations for additional fuel consumption due to traffic interaction.

CONCLUSIONS

The following conclusions can be drawn:

1. Fuel consumption during free-flow conditions can be calculated from the basic equations of movement.
2. For densities less than one-third of the jam density, fuel consumption due to traffic interaction is negligible.
3. Fuel consumption on freeways can be increased by as much as 50 percent in congested traffic.

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