Effect of Pavement Type and Condition on the Fuel Consumption of Vehicles

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ABSTRACT

The effect of pavement type and condition (roughness) on the rolling resistance of vehicles is investigated. By means of the relation between the energy requirements and the fuel consumption of vehicles, this effect is used to predict the fuel use on different pavements. It is found that, except for gravel surfaces, pavement type has a minor effect on fuel consumption. Roughness, however, correlates strongly with rolling resistance and therefore with vehicle fuel consumption. This is important for the economic justification of major road maintenance projects.

As a result of two oil crises in the past 10 years, the importance of the fuel consumption of vehicles cannot be overemphasized. Fuel has strategic importance. Moreover, its cost rose to such an extent that it not only caused high inflation rates, but also seriously affected the balance of payments of importing countries. Because fuel is high on the list of expenses of the vehicle owner, savings in fuel consumption play a major role in the economic justification of new road projects. In the past, this was usually the case where geometric improvements were being considered. There is little information available from which the effect of pavement improvements on fuel consumption can be predicted, yet such predictions are imperative for the evaluation of major maintenance operations.

Because of the numerous variables that affect fuel consumption, it is difficult to isolate the specific effect of pavement type and condition (1). This is mainly because the effect is rather small (2). It was therefore decided to determine the relationship between the pavement type and condition and the rolling resistance of vehicles. This relationship can then be used to predict the effect on fuel consumption.

A procedure for determining the rolling resistance of vehicles, which is then related to the type and condition of the pavement, is described. The latter is expressed in terms of road roughness as measured by a Linear Displacement Integrator (LDI). This road roughness value can also be related to the quarter car index (QI) scale developed in Brazil (3).

From the rolling resistance, the fuel consumption of the test vehicles is then predicted by means of the relationship between the energy requirements and fuel use of a vehicle.

FUEL CONSUMPTION AND ENERGY REQUIREMENTS OF VEHICLES

It has been shown that the fuel consumption of a vehicle is directly related to the energy necessary for the movement of the vehicle (4). The different resistances that must be overcome by the energy supplied by the engine are:

- Rolling resistance, R_r;
- Air resistance, R_a; and
- Gradient resistance, R_g.

Energy is also used to overcome transmission losses and the internal friction of the engine.

If

$R_r = (A + BV^2)M$,
$R_a = 0.5\rho C_D A_F V^2$, and
$R_g = MgG$,

then the fuel consumption at constant speed is:

$$F = p_1 + p_2/V + p_3V^2 + p_4G \tag{1}$$

where

R_r = rolling resistance (N),
R_a = air resistance (N),
R_g = gradient resistance (N),
F = fuel consumption (mℓ/km),
V = speed (m/s),
G = gradient (m/m),
p_1 = bAM/η,
p_2/V = idling fuel consumption (mℓ/km),
p_3 = $(bBM + 0.5b\rho C_D A_F)/\eta$,
p_4 = bMg/η,
b = fuel conversion factor (mℓ/kJ),
A,B = rolling resistance coefficients,
M = mass (kg),
η = drive-line efficiency,
ρ = air density (kg/m³),
C_D = aerodynamic drag coefficient,
A_F = frontal projected area (m²), and
g = gravitational acceleration (m/s²).

It is clear that the pavement type and condition can only affect fuel consumption through the rolling resistance and therefore through p_1 and p_3 in Equation 1.

ROLLING RESISTANCE TESTS

Theoretical Background

The combined effect of air and rolling resistance can be determined by using a coasting vehicle (that is, a vehicle running freely, with the engine disengaged) (5). Under these circumstances, there are only three forces acting on the vehicle:

- Rolling resistance,
- Air resistance, and
- Gradient resistance.

From Newton:

$$Ma = R_r + R_a + R_g \tag{2}$$

where a represents deceleration (m/s^2). Therefore

$$Ma = (A + BV^2)M + 0.5\rho C_D A_F V^2 + MgG \quad (3)$$

and

$$a = (A + gG) + (B + 0.5\rho C_D A_F/M)V^2 \quad (4)$$

This is of the form:

$$a = C_1 + C_2V^2 \quad (5)$$

where

$$C_1 = A + gG \quad (6)$$

and

$$C_2 = B + 0.5\rho C_D A_F/M \quad (7)$$

To determine the rolling resistance of a vehicle, the speed is measured at regular intervals (for example, every 10 seconds) during coasting, starting from a maximum speed on a relatively flat section of road with a constant gradient. This is done for both directions. If the decelerations are plotted against the square of the speeds, the values of C_1 and C_2 in Equation 5 can be obtained through a linear regression analysis for both directions. The rolling resistance coefficient A is then equal to the average of the two values of C_1, and the difference between the two values is equal to 2gG.

The rolling and air resistance coefficients contained in C_2 cannot be calculated separately. However, if the value of C_2 differs for different road surfaces, it must be as a result of a change in the value of B, because the air resistance is a constant.

An example of this procedure is shown in Figure 1 for the test car on section 1. The equations for the north- and southbound tests were:

Northbound

$$a = 0.0946 + 4{,}344.10^{-4}\ V^2 \qquad (r = 0.992)$$

Southbound

$$a = 0.2118 + 4{,}147.10^{-4}\ V^2 \qquad (r = 0.997)$$

From the values of C_1, the rolling resistance coefficient

$$A = (0.0946 + 0.2118)/2 = 0.1532\ N/kg$$

and the gradient

$$G = (0.2118 - 0.0946)/(2 \times 9.81) = 0.0060\ m/m.$$

The last value is the same as that given in the construction plans for that specific section of road.

If the value of B from Bester (4) is assumed, the aerodynamic drag coefficient can be calculated from the average of the two values of C_2. In this case:

$B = 6.86 \times 10^{-5}\ m^{-1}$
$M = 1322$ kg
$A_F = 2.3\ m^2$
$\rho = 1.059\ kg/m^3$ (at an altitude of 1500 m above sea level)

Therefore, from Equation 7:

$$C_D = (C_2 - B)M/(0.5\rho A_F) = 0.386.$$

Test Procedures

To determine the effect of road roughness and pavement type on the rolling resistance of vehicles, eight different road sections were chosen for the tests. Each section had to have a sufficient length (±400 m) of uniform gradient and roughness. The pavements on which sections were chosen were as follows: two were of asphaltic concrete, one was a portland cement concrete pavement, four had surface treatments, and one was unpaved. The roughness of each section was determined by using a Linear Displacement Integrator (LDI) developed by the National Institute for Transport and Road Research. These roughness values could be related to the QI scale through the correlation developed by Visser (6). The details of the test sections are given in Table 1.

Two vehicles were used for the tests--a passenger car and a truck with respective masses of 1322 and 7200 kg. The passenger car was fitted with radial tires and the truck was fitted with cross-ply tires. Both vehicles were instrumented to yield accurate speed measurements at fixed time intervals.

For reliable results, the tests had to be conducted in windless conditions, with the correct tire

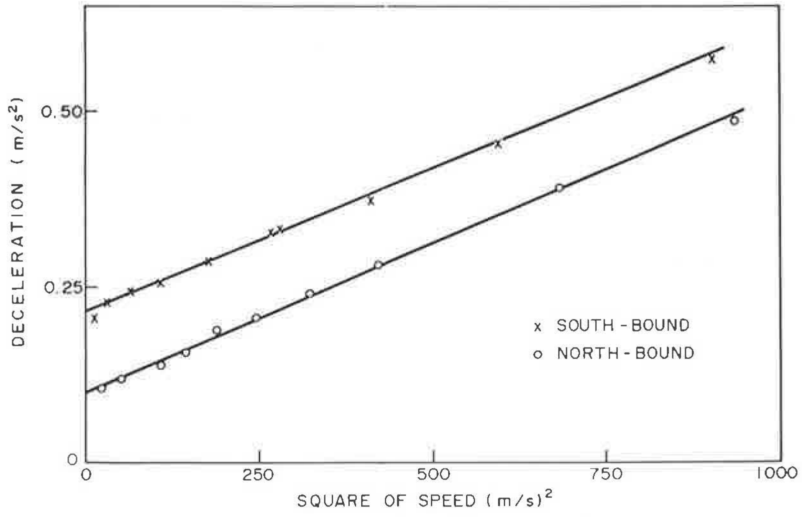

FIGURE 1 Deceleration versus square of speed during coasting.

TABLE 1 Details of Test Sections

Section No.	Pavement Type	Length (m)	Roughness LDI	Roughness QI[a]
1	Asphaltic concrete	1000	0.73	11.8
2	Asphaltic concrete	900	0.69	10.9
3	Concrete	700	0.94	16.5
4	Surface treatment	300	0.73	11.8
5	Surface treatment	600	1.27	23.9
6	Surface treatment	500	1.61	31.6
7	Surface treatment	400	2.34	48.0
8	Unsurfaced	350	3.53	74.7

[a] QI = −4.6 + 22.46 LDI from Visser *(6)*.

pressure and with the tires having been well warmed-up in advance. Because of the limited length of the test sections, all tests had to be repeated with different initial speeds to cover a full range of speeds.

Test Results

The speed of the vehicles during coasting was determined at 10-second intervals. From these speeds, the deceleration over the interval and the average speed during the interval were calculated. Linear regression analyses (see Equation 5) were then performed for both directions of each test section. The average values for both directions are given in Table 2 for the passenger car and in Table 3 for the truck.

TABLE 2 Test Results for Passenger Cars

Section No.	Roughness LDI (m/km)	A (N/kg)	C_2 ($0.10^{-4} m^{-1}$)	r
1	0.73	0.1532	4.246	0.994
2	0.69	0.1532	4.232	0.996
3	0.94	0.1521	4.182	0.995
4	0.73	0.1533	4.268	0.983
5	1.27	0.1583	4.267	0.994
6	1.61	0.1585	4.336	0.996
7	2.34	0.1649	4.410	0.990
8	3.53	0.2418	5.469	0.964

TABLE 3 Test Results for Trucks

Section No.	Roughness LDI (m/km)	A (N/kg)	B ($0.10^{-4} m^{-1}$)	r
2	0.69	0.0877	2.866	0.984
4	0.73	0.0979	3.179	0.931
5	1.27	0.1074	3.189	0.995
7	2.34	0.1213	2.880	0.922
8	3.53	0.1454	3.073	0.769

From these values, the following relationships between road roughness and the various coefficients were established:

Passenger Car

For all surface roads:

$$A = 0.1475 + 0.0073R \text{ (N/kg)} \qquad (r = 0.965) \qquad (8)$$

$$C_2 = (4.149 + 0.108R) \times 10^{-4} \text{ (m}^{-1}\text{)} \qquad (r = 0.884) \qquad (9)$$

Truck

For all roads:

$$A = 0.0808 + 0.0182R \text{ (N/kg)} \qquad (r = 0.984)$$

$$C_2 = 3.04 \times 10^{-4} \text{ (m}^{-1}\text{)} \qquad (10)$$

where R represents road roughness in m/km as measured by the LDI. These relationships are shown in Figures 2, 3, and 4.

Discussion

The roughness of paved roads has an effect, although small, on the rolling resistance coefficients of a passenger car. Unpaved roads have a much greater effect. For a truck, however, only the constant rolling resistance coefficient, A, shows a meaningful relationship with road roughness.

From Figures 2, 3, and 4 it appears that concrete and asphaltic concrete pavements have (for cars and trucks) a lower rolling resistance than roads with a surface treatment. These differences, however, are small and will be disregarded in further calculations. It should be mentioned that concrete and asphaltic concrete pavements with rougher surfaces were not available in the vicinity of Pretoria.

ROLLING RESISTANCE AND FUEL CONSUMPTION

From Equations 1 and 7:

$$p_1 = bAM/\eta$$
$$p_3 = bC_2M/\eta$$

By using the following values of constants for typical South African vehicles, the total fuel consumption at constant speed can be calculated for the two test vehicles (7):

b = 0.085 mℓ/kJ (for cars with petrol engines)
= 0.070 mℓ/kJ (for trucks with diesel engines)
η = 0.90 (for cars)
= 0.86 (for trucks)
p_2 = 450 mℓ/1000s (for cars)
= 600 mℓ/1000s (for trucks).

Passenger Car

On surfaced roads:

$$F = 18.4 + 0.91R + 450/V + (0.0518 + 0.0013R)V^2 + 1224G.$$

On the unpaved road (gravel road) tested (Roughness = 3.53 m/km):

$$F = 30.2 + 450/V + 0.0683V^2 + 1224G.$$

Truck

On all roads:

$$F = 47.4 + 10.67R + 600/V + 0.178V^2 + 5750G$$

where

F = fuel consumption (mℓ/km),
R = road roughness (m/km) as measured by the LDI,
V = speed (m/s), and
G = gradient (m/m).

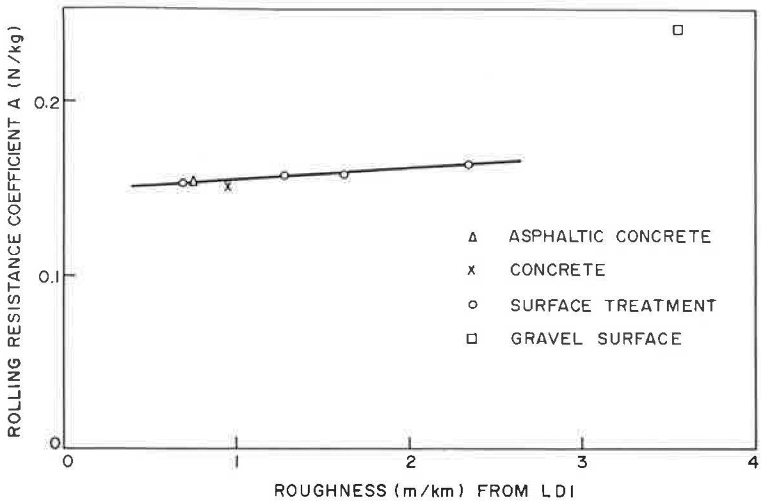

FIGURE 2 Rolling resistance coefficient, A, versus road roughness for test car.

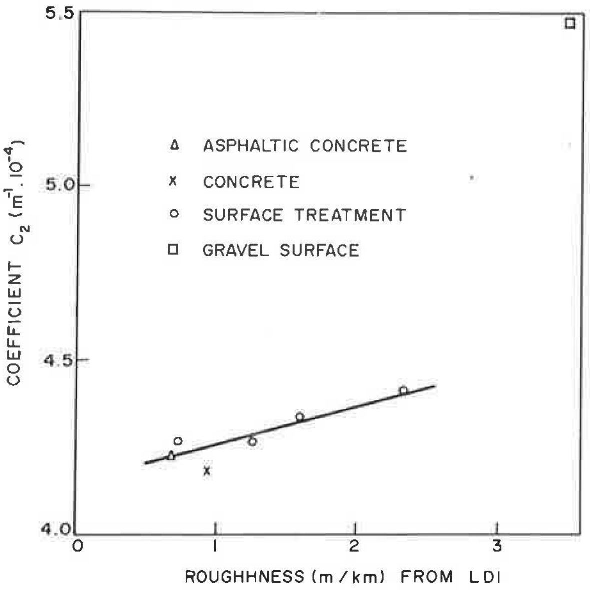

FIGURE 3 Speed-related coefficient, C_2, versus road roughness for test car.

Note that on negative gradients the minimum fuel consumption is p_2/V. When V=0, the distance-based fuel consumption, as in Equation 1, would be infinite and the time-based idling fuel consumption is equal to $p_2/1000$ (mℓ/s).

These formulas can now be used to determine the savings in fuel consumption that will result from improving the condition of pavements, either by new construction or by rehabilitation. So, for instance, if the pavement condition is improved from R = 3.0 to R = 0.6 m/km, the fuel saving will be 3210 liters/year/km for an annual average daily traffic of 1,000 vehicles per day including 20 percent heavy vehicles. Figures 5 and 6 show the fuel consumption of the test vehicles for different road conditions.

CONCLUSIONS

1. The pavement type has a small effect on the rolling resistance and, therefore, on the fuel consumption of vehicles.
2. Both the constant and speed-related rolling resistance coefficients for passenger cars are affected by the condition (roughness) of the pavement.
3. At 80 km/h, a passenger car can use 29 percent more fuel on a gravel road than on a paved road

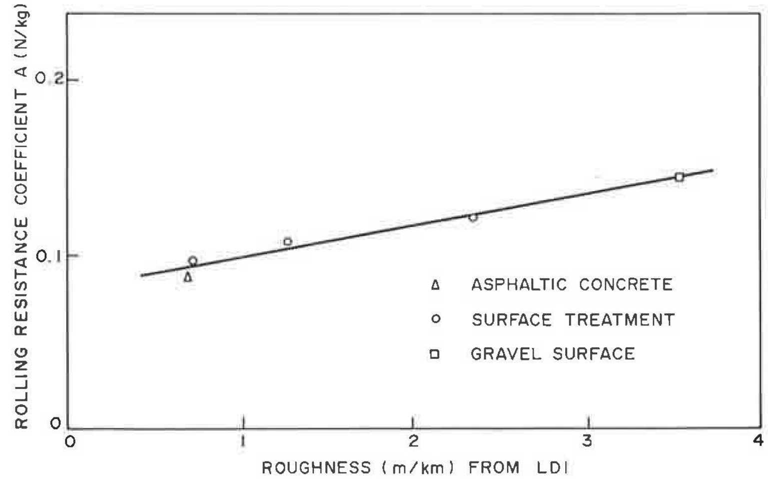

FIGURE 4 Rolling resistance coefficient, A, versus road roughness for test truck.

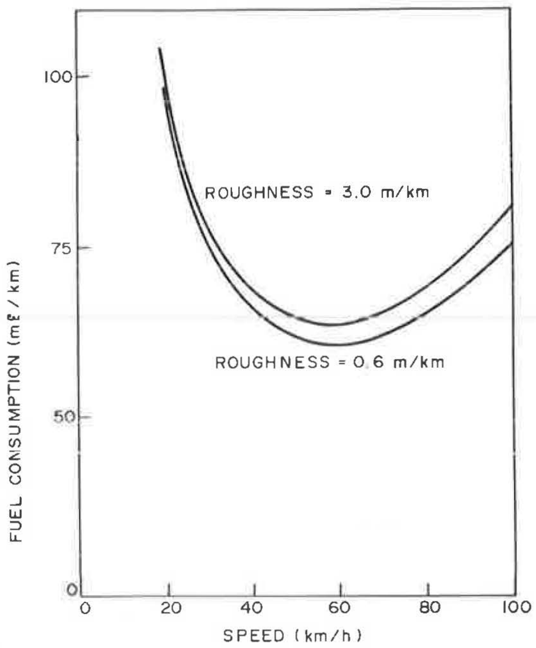

FIGURE 5 Fuel consumption of test car under different road conditions.

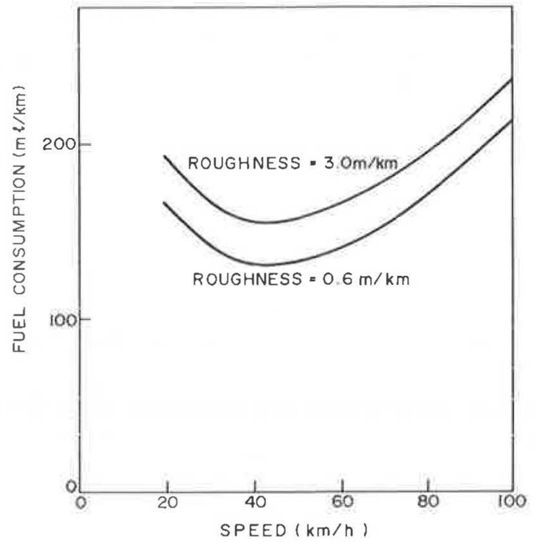

FIGURE 6 Fuel consumption of test truck under different road conditions.

in good condition. It should, however, be remembered that lower speeds are maintained on gravel roads.

4. Only the constant rolling resistance coefficient for trucks is affected by the condition of the pavement.

5. At 80 km/h, a truck can use 18 percent more fuel on a gravel road than on a paved road in good condition.

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The contents of this paper reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official policy of the Pennsylvania Department of Transportation.

Abridgment

Effect of Vehicle and Driver Characteristics on the Psychological Evaluation of Road Roughness

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ABSTRACT

The objective of this paper is to summarize the results of an experiment that evaluated the effects of vehicle size, vehicle speed, residence of rating panel, and training of rating panel on the subjective evaluation of road roughness. The results of the panel ratings indicated that there was no significant effect of the different vehicle sizes or vehicle speeds used on the subjective evaluation of road roughness, and that trained raters (i.e., experts) evaluated roads the same as untrained raters (i.e., laymen). A small but significant effect of panel residence was found.

All panel ratings used the Weaver/AASHO scale employed in previous research (1). Five panels of 21 licensed drivers each--four of Pennsylvania residents and one of Florida residents--were used to obtain the subjective ratings.

Two groups of bituminous test sections--34 in Pennsylvania and 31 in Florida--that span a wide range of roughness were selected for the study. Table 1 summarizes the experimental plan and Table 2 provides an overview of the key variables and the hypotheses that were tested. The test sections spanned a range of roughness from 28 to 639 in. per mile.

EXPERIMENTAL PROTOCOL AND DATA COLLECTION

All test sections were selected, marked, and formed into two routes--one in Pennsylvania and one in Florida. Each section was then measured with a Mays Ride Meter.

Panel members, in groups of three or six, were given detailed instructions on how to rate and then were driven over the route to individually rate each section's ride quality. Mean panel ratings were computed from the individual ratings for each test section for each panel.

TABLE 1 Summary of Experimental Plan

Rating Scale	Weaver/AASHO
Panel	63 Pennsylvania-licensed drivers (3 groups of 21 each) 21 Florida-licensed drivers 21 Florida experts
Sites	34 in Pennsylvania 31 in Florida
Vehicles	2 Pennsylvania K-cars 2 Florida K-cars 1 Pennsylvania subcompact car
Vehicle speeds	One per site equal to the operating speed of the site (except for a subset used in the vehicle speed experiment)
Panel instructions	Given uniformly to all subjects