ROLLING RESISTANCE CHARACTERISTICS OF NEW ZEALAND ROADS

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Transit New Zealand Research Report No. 61

ISBN 0-478-10519-3
ISSN 1170 9405

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Cenek, P.D. 1996. Rolling resistance characteristics of New Zealand roads. *Transit New Zealand Research Report No. 61.* 42 pp.

Keywords: chipseal, coastdown, cost, fuel, fuel consumption, macrotexture, New Zealand, road/tyre interaction, roads, rolling resistance, surface texture, texture, torque, tyres, vehicles, vehicle operation costs, VOC

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EXECUTIVE SUMMARY

1. Background

It is commonly accepted that unpaved roads increase fuel consumption, but until recently little attention was paid to the effect of varying textures of paved surfaces on the level of fuel used. With New Zealand's commitment to achieving the directives issued at the Rio de Janiero Earth Summit conference in 1992 for reducing CO_2 emissions, research which could lead to lower fuel consumption has environmental as well as an economic relevance.

Previously to this conference, economic considerations had chiefly focused on the costs of laying and maintaining the road surface, and on the life span of that surface. Safety considerations have also been a factor, with emphasis placed on ensuring adequate skid resistance. The cost of "surface usage", or the energy consumed by a vehicle in overcoming rolling resistance, is frequently overlooked, possibly because overseas studies often concluded that variations in the rolling resistance characteristics of different pavement types were insignificant.

New Zealand, however, is unusual in global terms in having a road network which utilises pavement types of widely differing properties, ranging from very smooth asphaltic concrete to coarse chipseal surfaces with macrotexture levels not often found in other countries. As macrotexture (road profile wavelengths between 0.5 mm and 50 mm) has been identified as an important surface characteristic affecting rolling resistance, it was conjectured that pavement type could have a significant influence on fuel consumption and so should be incorporated in the New Zealand Vehicle Operating Cost (NZVOC) model by including texture variables in the rolling resistance relationship.

2. Characteristics of Rolling Resistance of New Zealand Roads

A research programme was designed and undertaken between 1988 and 1995 to quantify the influence of pavement texture variables characteristic of New Zealand roads on tyre rolling resistance. Data available in the international literature was reviewed during 1994-95 following analysis of the New Zealand results.

A comparison of the coastdown and steady state torque methods established that the latter method was more suitable for measuring vehicle drag forces on public roads. A Nissan Pulsar car, specially instrumented to measure tyre rolling resistance, was driven over 12 different road surfaces with sand circle-derived texture depths ranging from 0.6 to 2.7 mm, and roughness from 37 to 57 NAASRA counts/km. The difference in rolling resistance between the most extreme surfaces that were tested was 55%.

It is generally accepted that, for a light car, a 20% reduction in tyre rolling resistance will reduce fuel consumption by about 4% for both urban and rural driving. This means that fuel consumption can be expected to vary over a range of 11% for the surfaces investigated.

3. Data Analysis

Subsequent statistical analysis of the acquired rolling resistance data involving stepwise multiple linear and non-linear regressions was performed in 1994. This showed that the combined parameter, roughness x (texture depth)^2, had the highest correlation with the measured coefficients of rolling resistance. The resulting equation is:

$$C_0 = 0.01238 + 0.00043\ IRI_{qc}\ T_{Dsc}^{\ 2} \quad \text{or}$$
$$C_0 = 0.01238 + 1.64 \times 10^{-5}\ R_N\ T_{Dsc}^{\ 2}$$

with a coefficient of determination, $r^2 = 75.3\%$
and standard error of estimation, SE = 0.0009
where C_0 = static coefficient of rolling resistance
IRI_{qc} = International Roughness Index (m/km)
R_N = NAASRA roughness (counts/km)
T_{Dsc} = texture depth (mm) as determined by the sand circle method

This equation suggests that the same decrease in fuel consumption will be achieved by reducing surface texture depth from 2.2 mm (corresponding to a grade 2 chipseal) to 1.4 mm (corresponding to friction course or grade 5 chipseal) as by reducing road roughness from 150 NAASRA counts/km (the upper limit of acceptable roughness) to 70 NAASRA counts/km (the average roughness of the New Zealand state highway network).

Accordingly, pavement macrotexture is as important as pavement roughness in influencing fuel consumption of cars, and both factors must be taken into account in pavement design. However, this result must not be allowed to distract attention from other causes of excessive fuel consumption related to road alignments, traffic control and driving habits, each of which can have greater effects.

4. Conclusions

The programme of on-road rolling resistance measurements and subsequent analysis has led to the following conclusions:

- An on-road test procedure, utilising wheel torque measurement and on-board anemometry, has been developed that can reliably determine the rolling resistance characteristics of road surfaces.

- The static component of rolling resistance is significantly affected by surface texture depth, with an increase of 55% for a 2 mm increase in texture depth. This corresponds to a 11% increase in fuel consumption.
- Road surface quality affects tyre rolling resistance and hence fuel consumption. Fuel consumption could be most reduced through road construction practices that control megatexture (63-500 m wavelengths) and short wave unevenness on roads (0.6-3.2 mm wavelengths). The control of macrotexture is also important, especially where car speeds of 60-70 km/h are common.
- Experimental data from this programme indicate that, over a 20-100 km/h speed range, rolling resistance of passenger car tyres is dependent on vehicle velocity squared.
- Road surface age – traffic loading dependency on rolling resistance has been shown to be directly related to macrotexture and roughness progression characteristics of the road surfacing type.
- International studies indicate that tyre rolling resistance tends to be more sensitive to road surface conditions as the tyre diameter decreases. This is primarily caused by higher tyre inflation pressures and harder rubber tyres used in commercial vehicle tyres, which result in smaller hysteresis loss.
- Rolling resistance is increased by as much as 45% on gravel roads, relative to sealed roads, for commercial vehicles. This has been attributed to the effect of pavement deflection bowl which forms under a heavy wheel, and may be substantial on flexible sealed pavements common in New Zealand.

5. Recommendations

- Given that an overall improvement of 1% in fuel economy applied to New Zealand's overall road transport fuel use would save the consumer around $30 million annually, and that fuel consumption is related to road roughness and surface characteristics, further studies to identify cost-effective road design and construction practices which could lead to reduced fuel use by New Zealand's vehicle fleet, should be encouraged.
- Given the flexible nature of New Zealand sealed pavements, which deflect to varying degrees under heavy wheel loads, the relationship between the size and shape of the pavement deflection bowl and rolling resistance characteristics of commercial vehicle tyres should be investigated.

ABSTRACT

New Zealand's road network utilises pavement types of widely differing properties, ranging from very smooth asphaltic concrete to coarse chipseal surfaces having macrotexture levels not often found elsewhere in the world. A research programme was undertaken between 1988 and 1995 to investigate the effect of surface texture of a road on the rolling resistance of a typical tyre/car combination. Data available in the international literature was reviewed during 1994-95 following analysis of the New Zealand results.

A comparison of the coastdown and steady state torque methods established that the latter was more suitable for measuring vehicle drag forces on public roads. Accordingly, it was used to obtain static and dynamic rolling resistance coefficients for 12 different road surfaces having approximately the same roughness, but with macrotexture depths which ranged from 0.6 mm to 2.7 mm.

The coarsest textured surface investigated had a static component of rolling resistance that was 55% greater than that of the smoothest. Regression analyses established that the static component of rolling resistance is strongly correlated to surface profile wavelengths between 0.5 mm and 50 mm. In addition, a limited investigation of rolling resistance changes related to road surface age–traffic loading effects was conducted for a porous friction course surface. The traffic loading dependency of rolling resistance was shown to be interdependent with the macrotexture and roughness progression characteristics of the road surfacing type.

1. INTRODUCTION

It is commonly accepted that unpaved roads increase fuel consumption, but until recently little attention was paid to the effect of varying textures of paved surfaces on the level of fuel used. With New Zealand's commitment to achieving the directives issued at the Rio de Janiero Earth Summit conference in 1992 for reducing CO_2 emissions, research which could lead to lower fuel consumption has environmental as well as an economic relevance.

The choice of road surface to be used in any given situation involves the consideration of several factors: maintenance, environmental, economic, and road safety. Economic considerations have chiefly focused on costs of laying and maintaining a surface, and on the life span of the surface. The cost of surface usage, i.e. the energy consumed by a vehicle in overcoming the resistance of the road (the rolling resistance) is a further consideration that is frequently overlooked.

Often, previous studies have concluded that the difference in fuel consumption over the range of surfaces available is insignificant compared with overall fuel consumption (Bester 1984, du Plessis and York-Hart 1987).

New Zealand's road network utilises pavement types of widely differing properties, ranging from very smooth asphaltic concrete to coarse chipseal surfaces with macrotexture levels not often found elsewhere in the world. Macrotexture has been identified as the most important surface characteristic affecting rolling resistance (Lees 1983). It might, therefore, be expected that pavement type may have a greater influence on fuel consumption in New Zealand than it does in other countries.

A research programme was designed and undertaken between 1988 and 1995 to address the relationship of road surface on fuel consumption for the surfaces used for New Zealand roads. As the energy used in overcoming rolling resistance comprises only a fraction of total energy usage, the percentage change in fuel consumption will be smaller for a given percentage change in rolling resistance. The ratio between the change in rolling resistance and the resulting change in fuel consumption is typically taken to be about 5:1 (Lees 1983, Descornet 1990). Consequently, rolling resistance is a far more sensitive function of road surface type than is fuel consumption. Therefore, the research programme was concerned with the measurement of the former rather than the latter.

This report describes the development of a test method for the on-road determination of both static and dynamic components of rolling resistance and its application to a variety of New Zealand road surfaces to establish the effects of road surfacing type and condition on the rolling resistance of a representative tyre–car combination. In addition, the significant findings of the New Zealand research, recorded in this report, are assessed in the context of international on-road rolling resistance studies involving both cars and heavy commercial vehicles available to 1995. The review was undertaken to:

- Allow the New Zealand results to be compared with similar investigations in other countries;
- Establish whether road surface parameters have the same effect on the rolling resistance of commercial vehicle tyres as for passenger car tyres.

2. DETERMINATION OF ROLLING RESISTANCE FORCES

2.1 Theoretical Background

The following derivation of a mathematical model for describing the total drag force which acts on a vehicle has been taken from Passmore and Jenkins (1988). It has been modified in the context of instrumenting a vehicle for use on public roads to gather rolling resistance data.

Tractive effort (F_T) is taken to be the total forces resisting the straight line motion. Mathematically, it can be expressed* as:

$$F_T = F_D(V) + M_e \frac{dV}{dt} + Mg \sin \alpha \quad (1)$$

where F_T = tractive effort
$F_D(V)$ = drag force
$M_e \frac{dV}{dt}$ = inertial force
$Mg \sin \alpha$ = gravitational force

The main difficulty is associated with establishing the characteristics of the *drag force function* (F_D (V)). It consists of mechanical and aerodynamic terms, and it is assumed that it is possible to consider their contributions independently as below:

$$F_D(V) = F_M + F_A \quad (2)$$

Mechanical drag force (F_M) includes the tyre rolling resistance, driveline losses, undriven wheel losses, and suspension losses. Generally these effects are combined for ease of modelling.

Rolling resistance (F_R) is a function of many operational variables, among them are tyre type, tyre inflation pressure, tyre cord temperature, applied torque, ambient air temperature, road surface, and velocity (Lees 1983). Only the last four of these are of interest as the other functions can be held constant.

A common representation of rolling resistance for tractive effort modelling is:

$$F_R = Mg\,(C_0 + C_n V^n) \quad (3)$$

The speed-dependent contribution is generally assumed to be linear, n = 1 (Passmore and Jenkins 1988) or quadratic, n = 2 (Bester 1984, Ljubic 1982).

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* See Nomenclature (p.42) for explanation of symbols and units.

Ambient air temperature is an external effect imposed on the tyres which causes a direct change to the tyre characteristic. Rolling resistance reduces as the ambient temperature increases. A simple correction is therefore applied to give:

$$F_R = Mg\ \{[C_0 + C_n V^n]\ [1 + K_T\ (T_s - T_o)]\} \qquad (4)$$

The temperature correction factor, K_T, takes a value of 0.013 per °C (Passmore and Jenkins 1988).

Tyre drag is a function of the normal load (Mg) which is reduced by the presence of aerodynamic lift of the vehicle. Including this effect into the model, the normal load (Mg) in equation (4) is modified as:

$$\text{normal load} = Mg - \tfrac{1}{2}\ \rho\ A\ C_L(\psi)\ V_r^2 \qquad (5)$$

where ρ = air density (kg/m^3)
V = vehicle speed (m/s)

The *lift coefficient characteristic* $C_L(\psi)$ is determined from either model or full scale wind tunnel tests.

Driveline resistance (F_{dr}) is incurred in transmitting power from the engine to the axle shafts. The losses from this resistance are a function of vehicle speed and driveline oil temperature. They are modelled as either a linear (equation (6)) or a quadratic (equation (7)) function of vehicle speed, although the quadratic form is preferred (Passmore and Jenkins 1988):

$$F_{Dr}(V) = A_t + B_t\ V \qquad (6)$$
$$F_{Dr}(V) = A_t + B_t\ V + C_t\ V^2 \qquad (7)$$

Undriven wheel resistance (F_u) depends on bearing friction and brake drag. A linear variation with speed is adequate, resulting in:

$$F_U(V) = A_u + B_u\ V \qquad (8)$$

Suspension damping losses are related to the absorption of the relative movements of the wheels and body by the shock absorbers. This movement is primarily caused by defects in the longitudinal evenness of the road surface. To include suspension losses is difficult and leads to increased complexity of the model (Korst and Funfsinn 1977). Accordingly, a low roughness level (IRI_{qc} < 2.5 m/km) was a requirement of the test sections so that the contribution from suspension losses would be minimised, roughness in this case being defined as surface profile wavelengths greater than 0.5 m.

Aerodynamic drag force (F_A) for a road vehicle is dominated by the wake that develops behind the vehicle (Passmore and Jenkins 1988), and is therefore primarily normal pressure drag. In practice, the magnitude of the aerodynamic drag force is a function of the relative attitude of the vehicle to the airstream, in particular yaw angle (ψ). The aerodynamic drag force is commonly written as:

$$F_A = \tfrac{1}{2}\ \rho\ A\ C_d(\psi)\ V_r^2 \qquad (9)$$

The *drag coefficient characteristic*, $C_d(\psi)$, is a minimum at zero degrees yaw, increasing to a maximum somewhere between 25° and 40° yaw. Like $C_L(\psi)$, it can be determined from either model or full scale wind tunnel tests.

Summing the mechanical and aerodynamic forces gives the mathematical model of the *total drag force* (F_D) on a vehicle as:

$$\begin{aligned} F_D(V) = {} & (Mg - \tfrac{1}{2}\,\rho\, A\, C_L(\psi)\, V_r^2)\,([C_o + C_n\, V^n]\,[1+ K_T\,(T_o - T_s)]) \\ & + [A_t + B_t\, V + C_t\, V^2] \\ & + [A_u + B_u\, V] \\ & + \tfrac{1}{2}\,\rho\, A\, C_d(\psi)\, V_r^2 \end{aligned} \tag{10}$$

The unknowns in equation (10) are the coefficients C_0, C_n and $C_d(\psi)$. The third term is modelled as $[C_{do} + \Delta C_d\,(\psi)]$ to indicate the variation of aerodynamic drag with yaw angle. If driveline and undriven losses are not removed from the data, they will be incorporated in the derived values of C_0, C_n and C_{do}. However, provided the same warm-up procedure is adopted, these losses will be constant from test to test, and so are unimportant in road surface comparisons. A minimum warm-up period of 20 minutes is suggested for tyres and the vehicle to reach normal operating conditions (Passmore and Jenkins 1988).

From above, pre-requisites for accurate tractive effort measurement include:

- on-vehicle anemometry to measure aerodynamic yaw angle and total relative air speed;
- accurate aerodynamic drag and lift characteristics of the test vehicle;
- detailed road grade information for the test sites;
- a warm-up (conditioning) period of at least 20 minutes to allow the tyres, bearings, etc. to reach equilibrium conditions;
- accurate vehicle speed and wheel torque measurement.

2.2 Test Methods

Two test methods are widely used for determining the tractive effort coefficients C_0, C_n and C_{do}: the velocity–time coastdown method and the steady state torque method.

The *coastdown method* is to allow the vehicle to coast down to a slower speed by disengaging the motor from the wheels and to measure the subsequent position–time trajectory from which deceleration and thus resistance is computed. The resistive force causing the deceleration includes driveline losses.

The *steady state torque method* involves the vehicle being driven at steady speeds between 20 km/h and 100 km/h. At each steady speed, wheel torque along with total relative air speed and aerodynamic yaw angle are continuously measured. The wheel torque is divided by the dynamic tyre radius to obtain the force which is corrected for the ambient wind. During the steady state test, the wheel torque meter records the total resistance excluding the driveline losses.

Before investigating the effect of New Zealand pavement types on tyre rolling resistance, both test methods were used on two different test sections: a smooth textured asphaltic concrete surface (site A), and a coarse textured grade 4 chipseal (site B). The results were compared in an attempt to establish the relative accuracies of the two methods.

2.3 Experimental Methodology

The instrumentation, test procedures, and data analysis are described in detail in Cenek and Shaw (1990), and so only the principal features are presented here.

2.3.1 Instrumentation

The test vehicle was a 1985 Nissan Pulsar fitted with 175/70, SR13 steel belted radial tyres. It was equipped with a data acquisition system which simultaneously measured torque at the left hand driven wheel, body and wheel strut accelerations, vehicle velocity, and relative wind speed and direction.

2.3.2 Data Acquisition

All measured variables, with the exception of wheel strut accelerations, were low-pass filtered at 1 Hz to suppress high frequency noise, and sampled at a frequency of at least 4 Hz via an AXVIIC 12 bit analogue/digital converter attached to a PDP 11/23+ micro-computer. The wheel strut accelerations were sampled at 200 Hz and bandpass filtered between 0.2 and 100 Hz, enabling power spectra of the wheel response to be generated.

2.3.3 General Test Practices

The general test practices required for tractive effort measurement applied to both steady state and coastdown methods, and involved:

- measuring ambient air temperature and barometric pressure at the site;

- weighing the vehicle before and after every test session, and taking the mass during testing as a linear function of distance travelled;

- closely monitoring tyre pressures, which were set before testing when the tyres were cold, and maintaining them at constant pressure during testing;

- warming up the test vehicle for a minimum period of 20 minutes before testing;

- acquiring a calibration file at intervals during testing to check the zeros of the transducers.

2.4 Data Analysis

2.4.1 Coastdown Method

As outlined earlier, the equation of motion for a vehicle during coastdown may be written:

$$M_e \frac{dV}{dt} = - Mg\,(C_0 + C_n V^n) - \tfrac{1}{2}\,\rho\, A\,(C_{do} + \Delta C_d(\psi))\, V_r^2 - Mg \sin\alpha \qquad (11)$$

A non-linear least squares technique was used to fit velocity data to equation (11). The algorithm, which is presented in detail in Swift (1991), minimises the sum of squares of the residual function F(C):

$$F(C) = \sum_{i=1}^{m} [r_i(C)]^2 = \sum_{i=1}^{m} [V_i - V(t_i, C)]^2 \qquad (12)$$

where C is the vector of parameters, i.e. $C = (C_0, C_n, C_{do}, V_o)$.

Here V_i is the measured velocity at time t_i, and $V(t_i, C)$ is the model velocity at t_i obtained from integration of equation (11).

Before commencing the experimental work, preliminary studies using rounded data from the analytic solution of equation (11), with $n = 1$, were carried out. These indicated that, with a maximum velocity error of 0.1 ms^{-1}, errors in C_0 and C_{do} would not exceed 5%. The corresponding error in C_1 was as large as 20%, indicating that C_1 would be less well determined than the other two parameters.

2.4.2 Steady State Torque Method

Separating the tractive effort (F_T) equation into known and unknown terms results in:

$$F_T - Mg \sin\alpha - M_e \frac{dV}{dt} - \tfrac{1}{2}\,\rho\, A\, \Delta C_d(\psi)\, V_r^{\,2} \qquad (14)$$
$$= F_R + \tfrac{1}{2}\,\rho\, A\, C_{do}\, V_r^{\,2}$$

The rolling resistance term, F_R, takes the general form of equation (3). To obtain average values, equation (14) is integrated with respect to distance using the transformation $dx = V\,dt$ and divided by the total distance travelled, D. The distance averaged form of equation (14) therefore becomes:

$$Y = Mg\, C_0 + C_{do}\, X + Mg\, C_n\, VN \qquad (15)$$

where:

$$Y = 1/D \int_0^D [F_T - Mg \sin\alpha - M_e \frac{dV}{dt} - \tfrac{1}{2}\,\rho\, A\, \Delta C_d(\psi)\, V_r^{\,2}]\, V\, dt \qquad (16)$$

$$X = \tfrac{1}{2}\,\rho\, A\; 1/D \int_0^D V_r^{\,2}\, V\, dt \qquad (17)$$

$$VN = 1/D \int_0^D V^{n+1}\, dt \qquad (18)$$

All quantities in Y can be readily determined, as can X and VN. Therefore regressing Y against X and VN yields the required drag coefficients C_0, C_n and C_{do}.

3. EVALUATION OF ON-ROAD METHODS FOR DETERMINING ROLLING RESISTANCE

3.1 Coastdown Method

A total of 12 coastdowns were performed, six at site A and six at site B. The experimental data were analysed by allowing:

1. all three coefficients (C_0, C_n, C_{do}) to vary (three parameter model); and
2. C_0 and C_{do} only to vary, keeping C_n constant (the two parameter model).

Case 1 lead to unrealistic values of the parameters. Computed values of the variance of error for each of the two cases were similar, but the confidence limits on the parameters C_0 and C_{do} in the three parameter model were 10 times larger than those in the two parameter model. All datasets were therefore analysed with the dynamic rolling resistance coefficient arbitrarily set to $C_1 = 0.0002$ s/m for the linear case and $C_2 = 0.000018$ s^2/m^2 (quadratic case). For the vehicle used in the tests, a +50% variation in C_1 lead to a consistent variation in each of C_0 and C_{do} of -4.5%. A corresponding variation in C_2 lead to a variation in C_{do} of -9% with C_0 unaffected. It is expected that an estimate of C_1 or C_2 with an uncertainty of less than 50% can be obtained from a laboratory test on a single tyre/drum machine combination.

In Table 3.1, which summarises the results of the analysis, both linear and quadratic rolling resistance models show a significant difference in the rolling resistance between the two surfaces, the smooth textured site A having a static rolling resistance coefficient that was about 24% less than the coarse textured site B.

Table 3.1 Mean parameter values with 95% confidence, for two parameter coastdown model.

Site	**Linear** **n = 1, C_1 = 0.0002 s/m**	**Quadratic** **n = 2, C_2 = 0.000018 s^2/m^2**
A (smooth)	C_0 = 0.0136 ±0.0009 C_{do} = 0.485 ±0.019	C_0 = 0.0158 ±0.0007 C_{do} = 0.424 ±0.020
B (rough)	C_0 = 0.0184 ±0.0008 C_{do} = 0.522 ±0.010	C_0 = 0.0204 ±0.0008 C_{do} = 0.437 ±0.018

3.2 Steady State Torque Method

The instrumented vehicle was driven at near constant speed along the test road sections. Measurements were made at five speeds equally spaced between 20 km/h and 100 km/h, and were made in two directions. The outward and the return runs were made in the same lane for site A. Runs were repeated for at least five sets of speeds in either direction, so at least 10 measurements at each speed were made at each site. In practice, rather than determining the gradient term $Mg \sin\alpha$ in Y, a dummy variable taking the value +1 for outward runs and -1 for return runs was added to the regression model. This simply and adequately compensated for gradient effects.

The results presented in Table 3.2 show that the coefficient of the static component of rolling resistance is well determined with standard deviations at least half those obtained with the coastdown method. The driving torque data also provided evidence for a quadratic rolling resistance model. The consequence of taking n equal to 2 is that the two independent variables in equation (15) are highly correlated. If the actual wind speed relative to the ground is zero, then X and V2 are identical and the regression of equation (15) will be unable to distinguish between the coefficients C_{do} and C_2. Therefore to ensure that the regression was yielding consistent results, unaffected by collinearity of the independent variables, final coefficient values were calculated from regressions on the variables, "X - V2" and "X + V2". Identical results were obtained to those derived from regressions directly on X and V2.

Table 3.2 Mean parameter values derived from steady state wheel torque data.

Site	C_0	C_2 (s^2/m^2)	C_{do}	K_V (Ns^2/m^2)	r^2
A	0.0124 ±0.0003	0.000014 ±0.000004	0.59 ±0.04	0.83 ±0.09	0.993
B	0.0151 ±0.0005	0.000019 ±0.000004	0.51 ±0.04	0.76 ±0.08	0.995

From Table 3.2, it is clear that a successful distinction can be drawn between C_2 and C_{do}. Nevertheless, their standard deviations are relatively large when compared with C_0 and hence the significance of the values obtained is reduced. Furthermore, the lesser the ambient wind speed, the greater is the resulting collinearity between X and V2, and so the larger are the standard deviations of the regression derived coefficients C_2 and C_{do}.

A more useful measure for the purpose of comparison between road surfaces might be the combined parameter K_V defined by equation (19). This represents the variation with speed of the driving force required to maintain the vehicle at a constant speed:

$$K_V = \tfrac{1}{2}\rho A C_{do} + M g C_2 \qquad (19)$$

Because C_{do} is invariant, K_V should be a function of road surface only. The use of K_V to compare surfaces was found to be especially valuable when the steady state torque measurements were made in near to calm conditions, so that the collinearity of V2 and X made independent evaluation of C_{do} and C_2 difficult.

3.3 Comparison of Results

The steady state torque method resulted in lower coefficients of the static component of rolling resistance than the coastdown method. This difference is attributed primarily to the characteristics of the test methods. During a coastdown, the drag forces acting on the test vehicle, and implicitly contributing to C_0, include brake drag, wheel bearing drag, and driveline drag. Of these, only the first two contribute to the rolling resistance term calculated by the driving torque method, which should therefore be lower. Passmore and Jenkins (1988) show that comparable coefficients can be obtained if driveline losses are eliminated from the coastdown force/velocity data. This is achieved by acquiring wheel torque data during the coastdown. It is, however, reassuring that the observed trends between road surface types, the main object of this investigation, are consistent irrespective of method. Furthermore, the derived C_{do} values also show good agreement.

4. ROLLING RESISTANCE CHARACTERISTICS OF NEW ZEALAND ROADS

The steady state torque method was used to determine the static and dynamic rolling resistance coefficients for 12 test sites, covering the range of New Zealand sealed road surfaces. The steady state torque method was selected in preference to the coastdown method because:

1. the statistical accuracy of the static coefficient of rolling resistance was higher for a similar number of test runs;
2. it provided reliable information on the speed variance of rolling resistance; and
3. the required test speed range of 20 to 100 km/h fell within legal speed limits for public roads.

A survey of available literature (Shaw and Cenek 1986) indicated that macrotexture and roughness of the road surface exert a considerable effect on the rolling resistance of vehicles. Measurements were therefore carried out in the wheelpaths to quantify the test sites in terms of these two parameters.

Macrotexture (T_{Ma}) of the road describes the individual pieces of aggregate in the surface. For this exercise, macrotexture measurements were made using the sand circle method (to obtain T_{Dsc}), and two laser-based devices: the TRRL Mini Texture Meter (to obtain T_{DMTM}), and the stationary laser profilometer developed by the Swedish Road and Traffic Institute (VTI) (to obtain T_{Dsc}). The relationships between these measures are as follows:

$$T_{Dsc} = 0.34 + 2.16\, T_{Ma} \qquad (20)$$

$$T_{Dsc} = -0.20 + 2.27\, T_{DMTM} \qquad (21)$$

Because it is an internationally recognised measure, all macrotexture measurements were converted to sand circle texture depth using equations (20) and (21).

Road roughness of the test surfaces were measured using the NAASRA roughness meter, which is a response type mechanical device fitted to a passenger vehicle to register cumulative relative vertical displacement of the vehicle body in one direction (Prem 1989). NAASRA roughness measures can be converted to the quarter car International Roughness Index (IRI_{qc}) using:

$$\text{NAASRA (counts/km)} = 26.2\, IRI_{qc}\ \text{(m/km)} \qquad (22)$$

The characteristics of the test sites, environmental conditions during the measurements, and the associated steady state torque results are summarised in Tables 4.1 and 4.2 respectively. Note in Table 4.1a that, for site 4, two different surfaces were measured because the surface was relaid between 1986 and 1988. The opportunity was also taken to remeasure the rolling resistance characteristics of the newly laid surface after it had been exposed for 30 months to an average daily traffic count of approximately 12,600 vehicles.

The steady state torque measurements were made over two separate periods: during February and March 1988 (reported in Cenek and Shaw 1990), and during May 1991 (reported in Cenek 1991). The latter measurements concentrated on smooth textured roads.

Table 4.1a. Details of test sites and site descriptions.

Site no.	**State Highway no.**	**Section**	**Surface**	**Characteristic chip size (mm)**	**Seal date**	**Average daily traffic count**	**Driving torque test date**
1	2	856/16.20-16.83	Grade 2, chipseal	13-16	Jan 87	2,000	Feb 88
2	2	873/5.03-5.48	Grade 2, chipseal	13-16	Jan 79	1,770	Feb 88
3	2	946/6.8-7.4	Grade 3, chipseal	10-13	Nov 86	7,000	Feb 88
4a	2	946/9.9-10.5	Grade 4, chipseal	7-10	Nov 86	12,600	Feb 88
4b	2	946/9.9-10.5	Friction course	-	Feb 88	12,600	Feb 88
4c	2	946/9.9-10.5	Friction course	-	Feb 88	12,600	May 91
5	1N	833/0-1.70	Grade 4, chipseal	7-10	Feb 84	3,940	May 91
6	2	905/6-10	Grade 5, chipseal	5-7	Jan 89	3,500	May 91
7	56	0/9-10	Grade 6, chipseal	3-5	Nov 89	5,246	May 91
8	2	946/5.1-6.1	Friction course	-	Nov 89	11,000	May 91
9	2	946/6.4-7.4	Friction course	-	Mar 89	8,900	May 91
10	2	946/14.45-15.88	Asphaltic concrete	-	Feb 74	10,000	May 91
11	2	962/2.8-3.3	Asphaltic concrete	-	1969	9,700	Mar 88

Table 4.1b. Environmental conditions recorded while measurements were being made.

Site no.	**Air temperature (°C)**	**Barometric pressure (kPa)**
1	18	100.6
2	19	100.6
3	24	101.0
4a	21	101.8
4b	23	101.1
4c	10.7	101.1
5	8	100.3
6	14.3	99.1
7	9.2	101.6
8	13	99.3
9	11.2	100.7
10	14.7	101.0
11	6	102.4

Table 4.1c. Details of test sites and associated surface profile characteristics.

Site No.	Longitudinal roughness		Macrotexture (mm)					VTI profilometer megatexture (mm) (T_{Me})
	NAASRA (counts/km)	IRI_{qc} (m/km)	Sand circle (T_{Dsc})	VTI profilometer			TRL MTM (T_{DMTM})	
				T_{Ma}	T_F	T_R		
1	48	1.83	2.7	1.93	0.72	1.93	-	1.19
2	57	2.18	2.3	-	-	-	-	-
3	42	1.60	1.7	-	-	-	-	-
4a	50	1.91	2.0	-	-	-	-	-
4b	50	1.91	2.37*	0.94	0.50	0.79	-	0.43
4c	44	1.68	1.85*	-	-	-	0.70	-
5	45	1.72	1.89*	-	-	-	0.92	-
6	37	1.41	2.16*	-	-	-	1.04	-
7	44	1.68	1.75*	-	-	-	0.86	-
8	45	1.72	1.36*	-	-	-	0.69	-
9	42	1.60	1.42*	-	-	-	0.71	-
10	52	1.98	1.38*	-	-	-	0.69	-
11	39	1.50	0.64*	0.14	0.08	0.12	-	0.11

Notes:

T_{Ma} = macrotexture: includes wavelengths 2-50 mm (third octave bands)
T_F = fine texture: includes wavelengths 2-6 mm
T_R = rough texture: includes wavelengths 10-50 mm
T_{Me} = megatexture: includes wavelengths 63-500 mm (third octave bands)
* = converted sand circle depth

Table 4.2 Driving torque results.

Site	Surface	$C_0 \times 10^{-2}$	$C_2 \times 10^{-5}$ (s^2/m^2)	C_{do}	K_V (Ns^2/m^2)	r^2
1	Grade 2, chipseal	1.92 ±0.03	2.5 ±0.2	0.47 ±0.03	0.78 ±0.06	0.995
2	Grade 2, chipseal	1.78 ±0.03	2.0 ±0.3	0.49 ±0.03	0.75 ±0.06	0.995
3	Grade 3, chipseal	1.55 ±0.05	1.7 ±0.4	0.50 ±0.04	0.73 ±0.08	0.994
4a	Grade 4, chipseal	1.51 ±0.05	1.9 ±0.4	0.51 ±0.04	0.76 ±0.08	0.995
4b	Friction course	1.52 ±0.04	1.8 ±0.3	0.53 ±0.03	0.75 ±0.07	0.996
4c	Friction course	1.41 ±0.04	0.9 ±0.9	0.60 ±0.10	0.80 ±0.20	0.994
5	Grade 4, chipseal	1.64 ±0.04	3.7 ±0.4	0.45 ±0.04	0.90 ±0.09	0.995
6	Grade 5, chipseal	1.46 ±0.04	2.8 ±0.4	0.50 ±0.04	0.85 ±0.09	0.996
7	Grade 6, chipseal	1.41 ±0.03	2.3 ±0.4	0.57 ±0.04	0.91 ±0.09	0.996
8	Friction course	1.44 ±0.05	2.2 ±0.7	0.53 ±0.04	0.80 ±0.20	0.992
9	Friction course	1.36 ±0.03	2.4 ±0.3	0.54 ±0.03	0.87 ±0.07	0.997
10	Asphaltic concrete	1.39 ±0.04	1.4 ±0.9	0.60 ±0.10	0.80 ±0.20	0.994
11	Asphaltic concrete	1.24 ±0.03	1.4 ±0.4	0.59 ±0.04	0.83 ±0.09	0.993

5. DISCUSSION OF RESULTS

5.1 Static Coefficient of Rolling Resistance, C_0

The derived values of C_0 and their associated errors summarised in Table 4.2 have been plotted against sand circle texture depth and road roughness of the test surfaces in Figures 5.1 and 5.2 respectively. These plots show a strong, convex curvature in the macrotexture relation, whereas the curvature of the roughness relation is very flat and almost linear.

A multiple linear regression fit of C_0 against a number of possible predictor variables was carried out using both forward and backward stepwise solution procedures to choose those variables contributing significantly to the fit. The predictor variables were IRI_{qc}, T_{Dsc}, T^2_{Dsc}, $IRI_{qc} \times T_{Dsc}$, $IRI_{qc} \times T^2_{Dsc}$, and T_0. Both procedures indicated that of all variables tested, the combination parameter $IRI_{qc} \times T^2_{Dsc}$ gave the greatest contribution to the fit, and no other parameter trialled gave a significant improvement. The resulting fit is shown in Figure 5.3, with the regression equation being:

$$C_0 = 0.0124 + 0.00043\ IRI_{qc} \times T_{Dsc}^{\ 2} \qquad (23)$$

The statistics of the model given by equation (23) indicate a standard error of only 0.0009 and a coefficient of determination, r^2, of 75.3%.

A non-linear least squares regression was also performed on the model form given by equation (24) below:

$$C_0 = a + b\ IRI_{qc}^{\ m} \times T_{Dsc}^{\ n} \qquad (24)$$

The resulting estimates of the unconstrained parameters and their associated standard errors are given in Table 5.1, along with the statistics of the associated fit. The m-power and n-power values of 1.2 and 2.5 respectively are consistent with the relations shown in Figures 5.1 and 5.2. However, the most important features of the non-linear least squares regression analysis to note are the large uncertainties associated with the power estimates brought about by the small number of observations (13 in total) and the negligible improvement in fit over the model described by equation (23). Therefore equation (23) is the preferred model for predicting C_0 from simultaneous roughness and texture measurement in terms of simplicity (whole number powers) and satisfactory standard error of estimation. This model suggests that macrotexture and roughness effects combine to influence tyre rolling resistance, and hence fuel consumption of passenger cars.

Another important feature of the regression analyses performed is that no significant effect of temperature on C_0 has been identified. This result confirms that temperature effects were properly accounted for in the experimental design.

Figure 5.1 Static coefficient of rolling resistance versus sand circle texture depth.

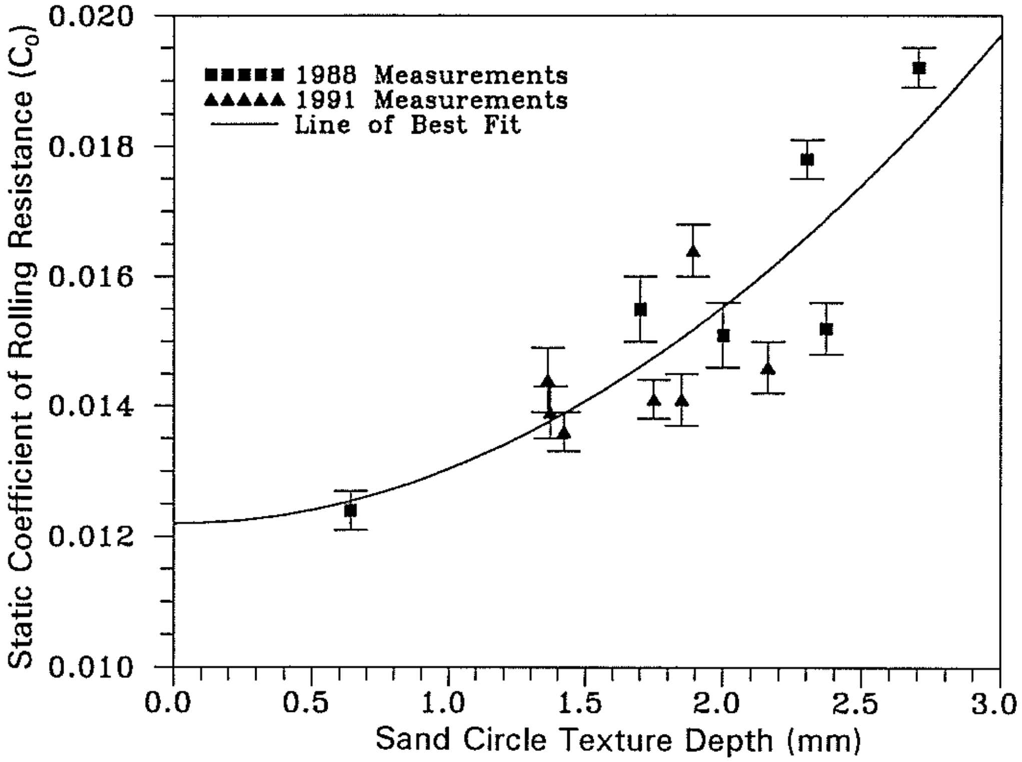


Figure 5.2 Static coefficient of rolling resistance versus road roughness.

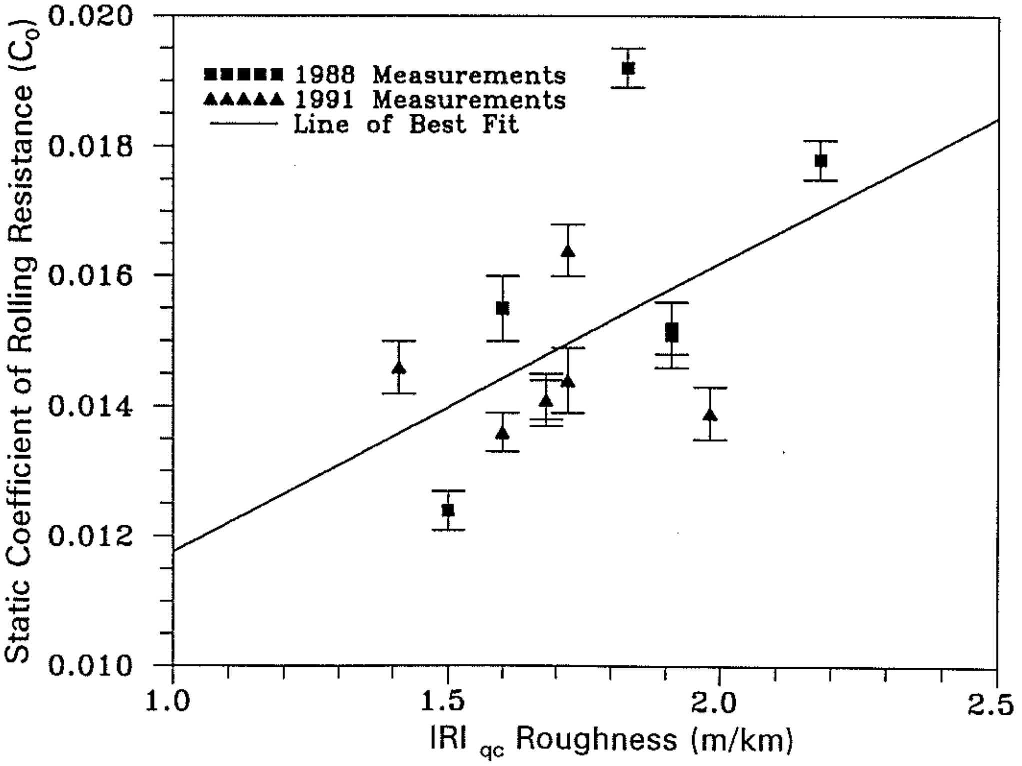


Figure 5.3 Static coefficient of rolling resistance versus combined roughness/texture parameter, $IRI_{qc} \times T_{Dsc}^2$.

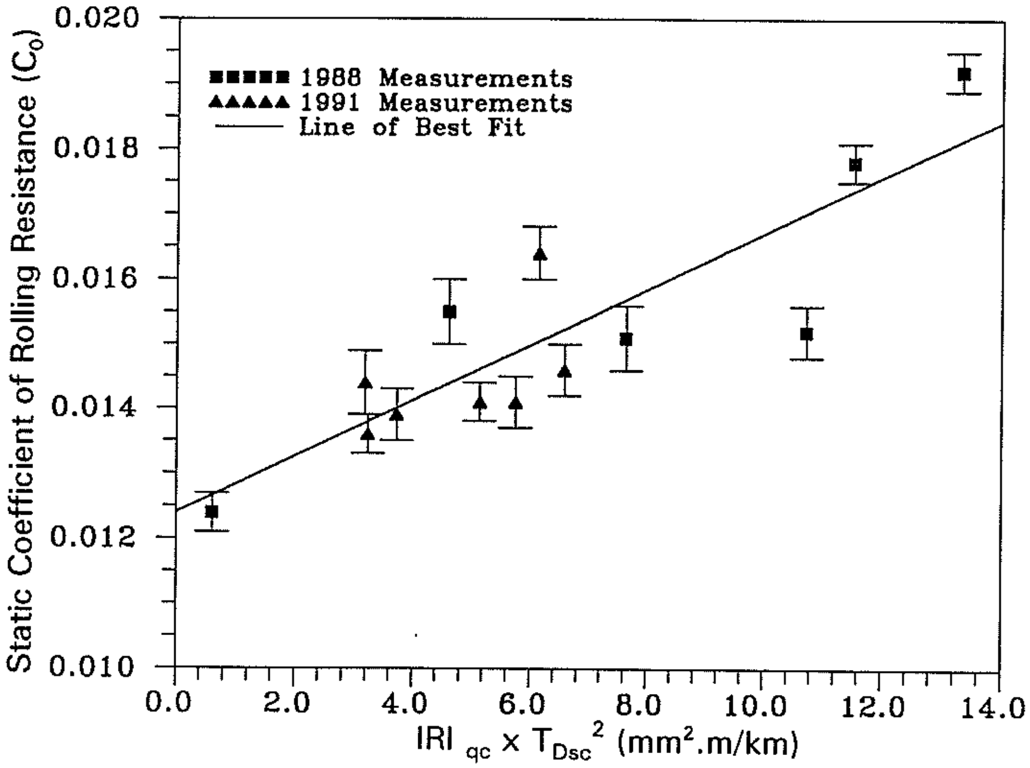


Table 5.1 Non-linear least squares regression model for static coefficient of rolling resistance $C_0 = a + b\,IRI_{qc}^m \times T_{Dsc}^n$.

Parameter	Estimate	Standard error
a	0.0130	0.0010
b	0.0002	0.0004
m	1.22	1.13
n	2.50	1.32

Standard error of estimation (C_0):	0.0009
Coeffient of determination, r^2:	75.6%
No. of observations:	13

It is generally accepted that, for a passenger car, a 20% reduction in tyre rolling resistance will reduce fuel consumption by about 4% for both urban and rural driving (Descornet 1990). The difference in rolling resistance between the tested surfaces given in Table 4.2 is 55%. Accordingly, fuel consumption can be expected to vary over a range of 11% for the surfaces investigated.

Equation (23) suggests that the same decrease in fuel consumption will be achieved by reducing surface texture depth from 2.2 mm (corresponding to a grade 2 chipseal) to 1.4 mm (corresponding to porous friction course or grade 5 chipseal) as by reducing road roughness from 5.7 m/km IRI_{qc} (150 NAASRA counts/km), the upper limit of acceptable roughness, to 2.7 m/km IRI_{qc} (70 NAASRA counts/km), the average roughness of the New Zealand state highway network.

The decrease in fuel consumption predicted by equation (23) for the above reductions in texture depth and roughness is 3% if roughness is taken to be 2.7 m/km IRI_{qc} while texture is varied, and if macrotexture is 1.4 mm while roughness is varied.

5.2 Dynamic Coefficient of Rolling Resistance, C_2

The dependency of C_2 and the related combined parameter K_V on macrotexture and roughness is graphically shown in Figures 5.4 to 5.7, and the results of a regression analysis performed on the plotted data are summarised in Table 5.2. The low values of the correlation coefficients squared suggest that both macrotexture and roughness have no significant effects on these two velocity dependent parameters. However, the standard errors associated with the derived C_2 and K_V values are such that more definitive measurements are required to prove their independency of road surface characteristics. A reduction in the standard errors of C_2 and K_V can be effected either by making a greater number of measurements at each test site or conducting the tests in windier conditions.

Table 5.2 Relationships between parameters of dynamic coefficient of rolling resistance (C_2 and K_V) and pavement texture (T_{Dsc}) and roughness (IRI_{qc}).

Regression model	**Standard Error**	**r^2 %**	**No. of observations**
$C_2 = 0.000013 + 0.000004\ T_{Dsc}$	0.000007	9.7	13
$C_2 = 0.000030 + 0.000005\ IRI_{qc}$	0.000007	2.5	13
$K_V = 0.870 - 0.0329\ T_{Dsc}$	0.06	9.1	13
$K_V = 1.05 - 0.137\ IRI_{qc}$	0.05	24.1	13

Figure 5.4 Dynamic coefficient of rolling resistance, C_2, versus sand circle texture depth.

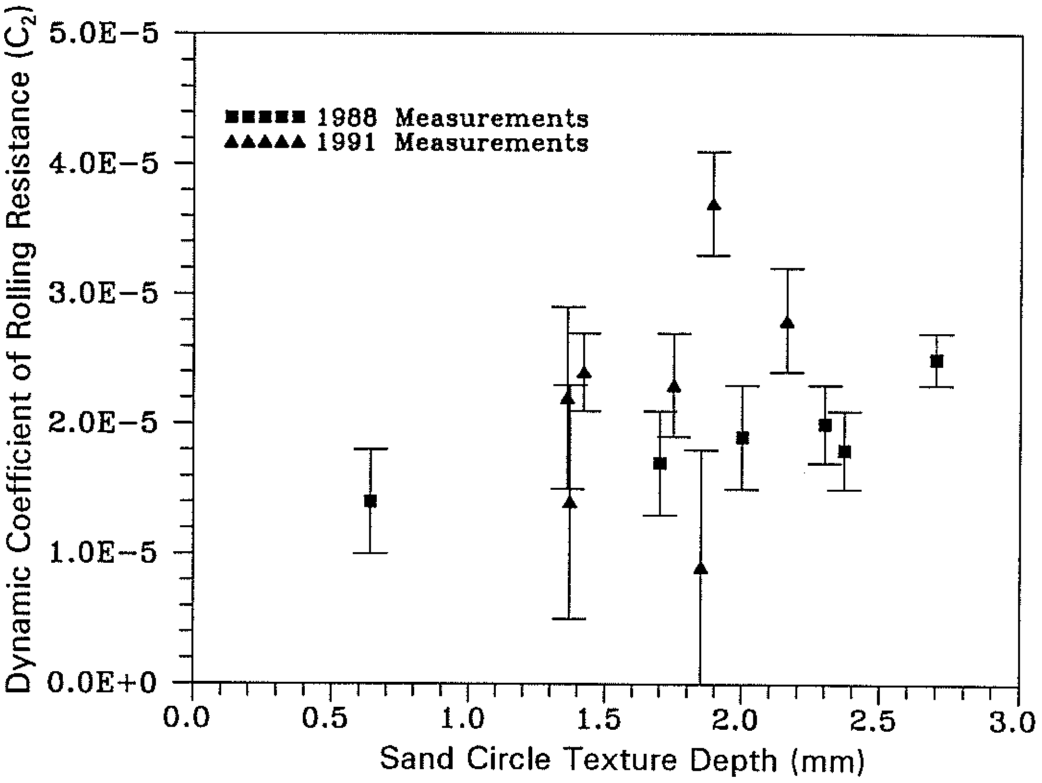


Figure 5.5 Dynamic coefficient of rolling resistance, C_2, versus road roughness.

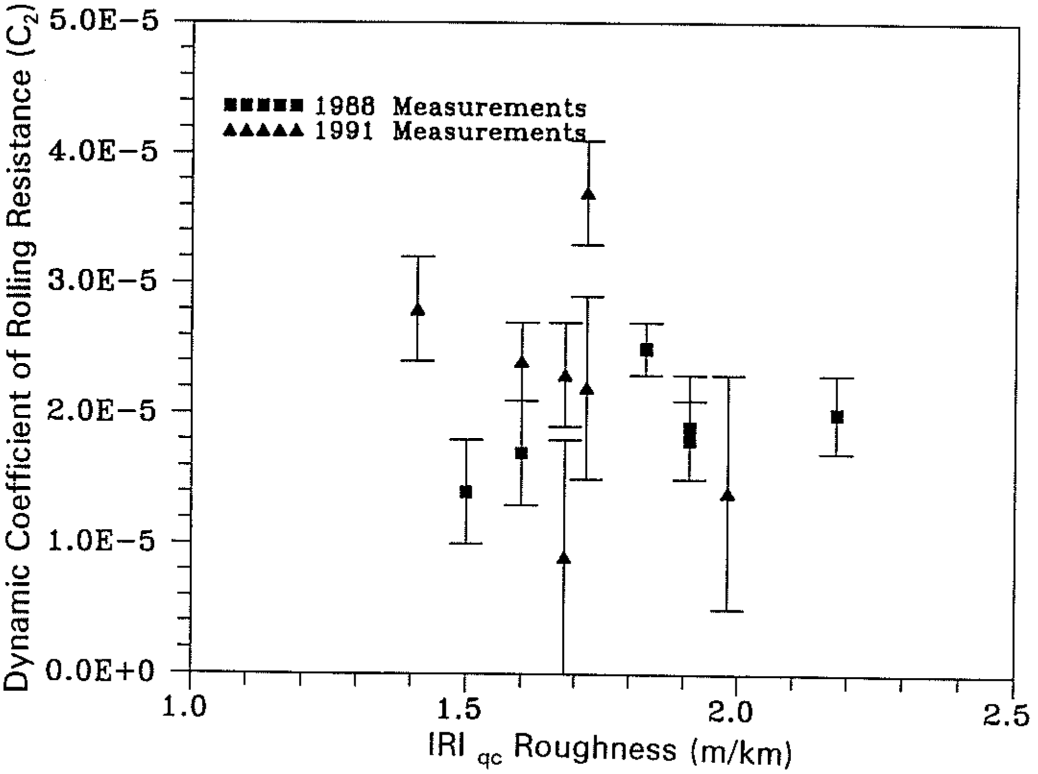


Figure 5.6 Coefficient of V^2 in tractive effort, K_V, versus sand circle texture depth.

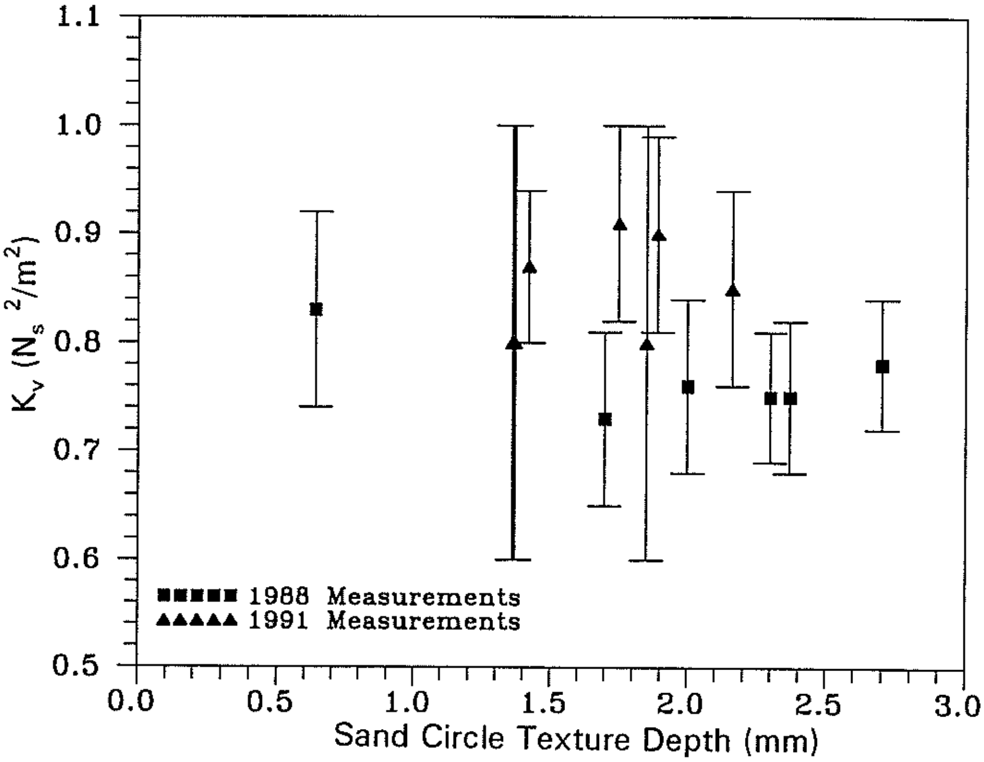
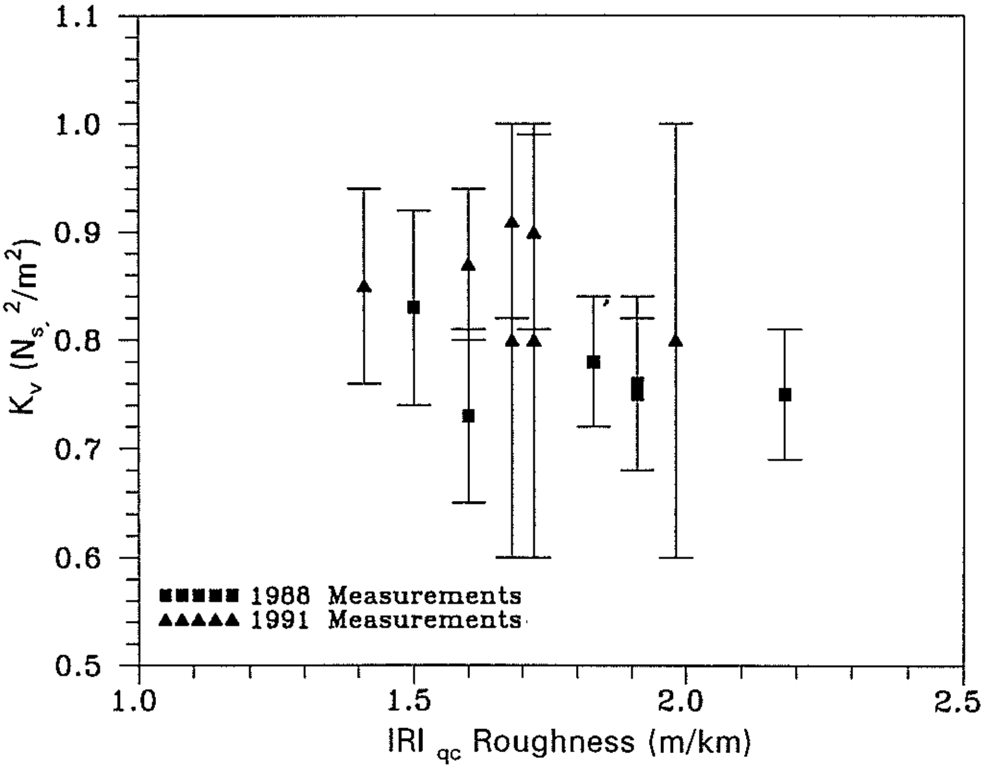


Figure 5.7 Coefficient of V^2 in tractive effort, K_V, versus road roughness.



5.3 Road Surface Age–Traffic Dependency of Rolling Resistance

A difference of 7% was found for the friction course surface of site 4 between the measurements performed in 1988 ($C_0 = 0.0152$) and in 1991 ($C_0 = 0.0141$). The standard error in determination of both C_0 values was about 3%, and so the difference is significant, suggesting a traffic loading dependency on rolling resistance.

In Table 4.1c, note that over the three year period 1988 - 1991, both the macrotexture and roughness of site 4 have been reduced by about 22% and 12% respectively. Substitution of these pavement values in equation (23) results in a predicted change in C_0 of 0.002 compared with 0.001 measured, which can be regarded as adequate agreement. Accordingly, the road surface age – traffic dependency of rolling resistance is very much tied to the progressive change in macrotexture (T_{Dsc}) and roughness (IRI_{qc}) characteristics) of a pavement surface.

Models for macrotexture and roughness progression of common New Zealand bituminous and chipseal surfaces are presented in Houghton et al. (1990), and Cenek and Patrick (1991) respectively.

6. OVERVIEW OF OTHER ROLLING RESISTANCE STUDIES

Under the auspices of the TC1 Committee of PIARC (Surface Characteristics), B07 Committee of TRB (Surface Properties - Vehicle Interaction), and E17 Committee of ASTM (Pavement Management Technologies), a number of international symposia on road surface characteristics have been held since the late 1980s*. Sessions on fuel efficiency and rolling resistance have featured in two:

1. First International Symposium on Surface Characteristics, State College (Pennsylvania), 8/9 June 1988; and

2. Vehicle-Road Interaction II, Santa Barbara, California, 17-22 May 1992.

The principal findings associated with the papers presented are summarised below. Also, the level of agreement with the New Zealand results contained in this report is investigated where possible.

6.1 Passenger Car-related Studies

6.1.1 Descornet (1990)

Descornet (1990) used a unique "quarter car" trailer designed and built by the Belgian Road Research Centre to investigate the influence of road surface characteristics on the rolling drag experienced by a car tyre. Rolling resistance measurements were made on 50 road sections, each 500 m long, at different speeds ranging from 10 to 80 km/h. The pavement types included bituminous mixes, chipseals, concrete and cobblestones. The static coefficient of rolling resistance was found to range between 0.013 and 0.021 corresponding to an estimated variation in fuel consumption of 9%. The main surface-related influencing factor was identified as surface profile irregularities in a wavelength range lying between macrotexture and roughness, i.e. 50 mm and 500 mm.

6.1.2 Laganier and Lucas (1990)

To estimate the influence of macrotexture and roughness of sealed roads on fuel consumption of medium sized cars (weighing about 800 kg, and with typical petrol consumption of 7 ℓ/100 km), Laganier and Lucas (1990) utilised three tests:

1. Laboratory simulation of roughness on a vibration bench;

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*

PIARC	Permanent International Association of Road Congresses, Paris
TRB	Transportation Research Board, Washington DC, USA
ASTM	American Society for Testing and Materials, Philadelphia, USA

2. Test track comparisons of surfacings having extreme values of macrotexture (mini texture meter-derived texture depths from 0.1 to 3 mm) but the same degree of roughness; and

3. Analysis of direct fuel consumption measurements on a sampling of actual roads having a range of macrotexture and roughness.

Rolling resistance was directly measured by a dynamometer hub installed on a non-driving front wheel. This hub had four three-direction quartz transducers allowing simultaneous measurement of the forces and couples about all three axes.

For the range of pavements investigated (they were sealed roads of the French highway system), the variation in fuel consumption ranged from:

- 0 to 0.4 ℓ/100 km (about 0-5%) for roughness ratings from excellent to poor; and
- 0 to 0.4 ℓ/100 km (about 0-5%) for macrotextures ranging from fine to exceptionally coarse.

This research showed that pavement macrotexture is as important as pavement roughness in influencing fuel consumption of cars, and so both factors must be taken into account in pavement design.

6.1.3 Sandberg (1990)

Sandberg (1990) conducted an experiment in which a Volvo 242 car, instrumented to accurately measure fuel consumption, was run at 50, 60 and 70 km/h over 20 road surfaces with various textures. The road profiles of these surfaces were measured with a mobile laser profilometer so that texture profile spectra over a 2-mm to 3500-mm texture wavelength range could be generated for each surface. The fuel consumption data at each speed and averaged over the three speeds were regressed against the texture profile spectrum data. The following results were obtained:

1. Fuel consumption varied by approximately 11% from the smoothest to the roughest road tested if texture wavelengths in the range 0.6-3.2 m (shortwave roughness) are considered, to approximately 7% if texture wavelengths in the range 2-50 mm (macrotexture) are considered.

2. The correlation between fuel consumption and texture was as high as 0.90 (correlation coefficient, r) in the roughness range 0.6-3.2 m and reduces at shorter wavelengths, down to about 0.60 at wavelengths corresponding to common maximum aggregate sizes used in roads. Therefore fuel consumption appears to be influenced by shortwave roughness (0.6-3.2 m wavelengths) and megatexture (50-500 mm wavelengths) but somewhat less by macrotexture (2-50 mm wavelengths).

3. Megatexture seems to have a considerable influence on fuel consumption when its excitation comes close to the wheel hop frequency at medium speeds, but its relative influence reduces at higher speeds. By comparison, macrotexture promotes tyre impact hysteresis losses which become pronounced at between 60-70 km/h.

Sandberg's results demonstrate that road surface profiles have considerable impact on fuel consumption, and that the largest potential for improved pavement design and construction is to minimise profile amplitudes over wavelengths in the range 0.6-3.2 m. Also, special attention to macrotexture requirements is necessary wherever car speeds of 60-70 km/h are common. Roughness at longer wavelengths (up to 50-100 m) were not covered in this experiment.

6.1.4 Delanne (1994)

Delanne (1994) summarised research performed by the Laboratoire Central des Ponts et Chaussées (LCPC) aimed at finding relationships between road irregularities and road user qualities for light vehicles. Table 6.1, which considers riding comfort, safety, noise and fuel consumption, shows that the main problem in developing low-fuel-consumption road surfaces concerns macrotexture. Texture between 0.5 to 50 mm wavelengths is required for high speed adherence on compact wearing courses but is responsible for extra fuel consumption, interior and exterior low frequency vehicle noise, and vehicle vibrations. Only open graded 10 mm asphaltic concrete and drainage asphalt friction courses were found to meet minimum texture levels for safety, as specified in France (i.e. 0.8 mm sand patch texture depth), while providing good rolling resistance and tyre–road noise characteristics.

Table 6.1 Effects of road irregularities (Delanne 1994).

Road irregularities	**Riding comfort**	**Safety**	**Noise/vibration**	**Fuel consumption**
Long wavelength, octave 16-32 m	Bad	Bad	Not directly related	Bad
Medium wavelength, octave 4-8 m	Bad	Bad	Not directly related	Bad
Short wavelength, octave 1-2 m	Very bad	Very bad	Bad	Very bad
Megatexture, octave 0.625-0.5 m	Very bad	Very bad	Very bad	Bad
Macrotexture, octave 0.0625 m	Not related	Good for high speed	Very bad	Bad
Microtexture	Not related	Good for all speeds	Not directly related	Not directly related

6.2 Commercial Vehicle-related Studies

6.2.1 Du Plessis et al. (1990)

Du Plessis et al. (1990) conducted a comprehensive experiment to investigate the effects of road surface characteristics on fuel consumption, as a first step toward establishing reliable vehicle operating cost (VOC) relations for South African conditions. Two medium sized trucks and two buses were chosen for coastdown tests to determine rolling resistance over a series of road sections covering the ranges of surface conditions encountered locally (i.e. from good paved to poor unpaved). For the paved surfaces, the roughness levels ranged from about 1 to 6.5 IRI_{qc} and sand patch-derived texture depths (T_{Dsp}) from 0.5 to 4 mm. All the test vehicles ran on 1100 x 20 cross ply tyres.

A regression analysis performed on 475 observations showed that tyre rolling resistance of commercial vehicles was sensitive to tyre pressure and roughness, but not to texture depth, vehicle mass, depth of loose material and surface aggregate size (in terms of sieve size). In contrast to passenger car tyres, the insensitivity to texture depth was attributed to the higher tyre pressures and harder rubber tyres associated with commercial vehicle tyres.

The model form is:

$$C_0 = 0.0208 + 0.0003\ IRI_{qc} - 0.000018\ T_p \qquad (r^2 = 0.56,\ SE = 0.0016) \qquad (25)$$

Equation (25) can be explained as:

1. an increase in roughness, IRI_{qc}, results in increased rolling resistance;
2. an increase in tyre pressure, T_p, decreases rolling resistance.

6.2.2 Gyenes and Mitchell (1994)

Both effects are consistent with laboratory and on-road based rolling resistance studies of commercial vehicle types conducted by the Transport Research Laboratory (TRL) and reviewed in Gyenes and Mitchell (1994).

Over the tested range of paved road surfaces the static coefficient of tyre rolling resistance ranged from 0.009 to 0.011 for a tyre inflation pressure of 640 kPa, representing a 20% difference.

6.2.3 Ramshaw and Williams (1981)

Ramshaw and Williams (1981) considered the effect of surface texture on the rolling resistance of a 7.00 by 20 radial ply commercial vehicle tyre. The relationship between surface texture depth and rolling resistance as measured with the Motor Industry Research Association (MIRA) single wheel rolling resistance trailer (Carr and Rose 1966) at a slow speed of 2 km/h was found to be:

$$C_0 = 0.0081 + 0.0003 \times T_{Dsp} \qquad (r^2 = 0.76) \qquad (26)$$

Their measurements showed a difference of about 6% in the rolling resistance of a goods vehicle tyre over lightly brushed concrete and BS594 motorway-type asphalt. For the same texture range, equation (23) indicates a difference of about 44% in the rolling resistance of a passenger car tyre for a nominal IRI_{qc} roughness of 2.7 m/km, which is close to the average roughness level of the state highway network.

This result points to passenger car tyres being far more sensitive to texture depth than commercial vehicle tyres. Findings by Du Plessis et al. (1988) are therefore not necessarily at variance as the coastdown test procedures utilised could not resolve rolling resistance forces to the same sensitivity and accuracy as could the MIRA single wheel rolling resistance trailer.

6.2.4 Davis Engineering (1984)

In Canada, a specially designed test rig for measuring on-road rolling resistance and bearing friction loss for free rolling tyres of large trucks has been used to investigate differences between sealed and gravel and wet and dry roads (Davis Engineering 1984).

The rig demonstrated that on a gravel road at 40 km/h, the rolling resistance coefficient was approximately 60% higher (0.010 compared to 0.016) than for a sealed pavement at the same conditions (10:20 bias ply tyre inflated to 560 kPa).

Rolling resistance on a very wet pavement was found to be 21% higher than on a dry pavement (0.009 compared to 0.011 for an 11R22.5 radial ply tyre inflated to 540 kPa). The observed higher rolling resistance on the wet surface can be explained at least partially by the cooler operating temperature of the tyre, which reduces its flexibility.

6.2.5 Fancher and Winkler (1984)

At the University of Michigan Transportation Research Institute, equations for estimating rolling resistance (F_R) of heavy truck tyres of both the radial and bias ply types were developed (Fancher and Winkler 1984). These are:

$$F_R = (0.0041 + 0.000025\ V)\ C_h\ Mg \text{ for radial tyres} \tag{27}$$

$$F_R = (0.0066 + 0.000029\ V)\ C_h\ Mg \text{ for bias ply tyres} \tag{28}$$

where V = speed in km/h
C_h = road surface coefficient = 1.0 for smooth concrete
= 1.2 for worn concrete, cold asphalt
= 1.5 for hot asphalt

The variation in road surface coefficient, C_h, suggests that the effect of the pavement deflection bowl which forms under a heavy wheel may be substantial on gravel roads and thin pavements. Rolling resistance of commercial vehicle tyres is clearly a minimum on hard, smooth, dry surfaces. Increases in speed results in an increase in tension in the belted tread of the tyre caused by centrifugal force, which tends to increase the vertical stiffness. This effect produces the straight line relationship of increase in rolling resistance coefficient with increase in tyre speed given by equations (27) and (28).

Comparing passenger car and commercial vehicle tyres, relationships between texture depth and roughness, and rolling resistance appear to be similar. However, commercial vehicle tyres have lower rolling resistance coefficients because of their larger dimensions and higher inflation pressures.

6.3 Comparison of Studies of Rolling Resistance

6.3.1 Road Surface Texture Effects

The rolling resistance data derived from the driving torque method presented in this report were compared with on-road fuel consumption measurements conducted by the Swedish Road Traffic Research Institute, VTI (Sandberg 1990) (Figure 6.1). The following procedure was used to convert the static rolling resistance coefficient values to equivalent fuel consumption values at 70 km/h:

1. The asphaltic concrete surface of site 11 was selected as the reference surface, and the excess rolling resistance produced by the other test surfaces were calculated on a percentage basis.
2. The excess rolling resistance was divided by 5 to obtain fuel consumption (from Lees 1983, Descornet 1990).
3. Quite arbitrarily, a value of 7.35 ℓ/100 km fuel consumption was assigned to site 11. Fuel consumption of the other sites was calculated by applying the excess values derived in (2) above.

The macrotexture values for the New Zealand test sites were converted to logarithmic values by using the relation below to be consistent with VTI's measures of macrotexture:

$$T_{Ma}\,(\mathrm{dB}) = 20 \log_{10} \{0.001\,[(T_{Dsc} - 0.34)/2.16]\} \tag{29}$$

Previous work, with the exception of Sandberg (1990) and Laganier and Lucas (1990), has tended to favour a linear dependency of passenger car tyre rolling resistance with surface texture. Figure 6.2 shows the New Zealand results superimposed over those of Laganier and Lucas. In deriving the percentage increase in fuel consumption, an influence factor of rolling resistance on fuel consumption of 0.2, as recommended by Descornet (1990), has been adopted. As for the VTI comparison, the New Zealand data has been normalised against the asphaltic concrete surface of site 11, this having the lowest texture depth.

Both sets of data plotted in Figure 6.2 highlight a strong texture dependence of fuel consumption which increases in a non-linear fashion. However, the effect of texture is more pronounced in the New Zealand data. This effect may be caused by greater tyre and suspension excitation related to New Zealand chipseal construction design which uses comparatively large sizes of sealing chips and spacings. Future New Zealand studies therefore should seek to quantify levels of macrotexture (0.5-50 mm wavelengths), megatexture (63-500 mm wavelengths), and shortwave unevenness (0.63-3.15 m wavelengths) as these road profile wavelengths have been shown to be all significantly correlated to fuel consumption.

6.3.2 Road Roughness Effects

Two widely reported studies investigated the relation between rolling resistance of passenger car tyres and road roughness. The first, performed in South Africa, used the coastdown technique, and runs were made over eight test sections ranging in roughness between 0.9 and 5.8 m/km IRI_{qc} (Bester 1984). The test sections were all chipseals with texture depths of about 2 mm.

The relationship derived from the study may be written as follows:

$$C_0 = 0.0152 + 0.00043 \, IRI_{qc} \qquad (30)$$

Equation (30) has been incorporated in the South African National Institute for Transport and Road Research (NITRR) fuel model and subsequently selected for the New Zealand Vehicle Operating Cost (NZVOC) model (Bennett 1989).

The second study formed part of the Brazil – United Nations Development Programme (UNDP) – World Bank highway research project (Watanatada et al. 1987) and involved four road test sections ranging in roughness between 2 and 14 m/km IRI_{qc}. Again, the coastdown technique was applied to derive coefficients of rolling resistance. This study yielded the following relationship:

$$C_0 = 0.0218 + 0.00061 \, IRI_{qc} \qquad (31)$$

Substitution of texture depths of 1 mm and 1.2 mm into equation (23) generates roughness coefficients identical to those in equations (30) and (31) respectively. Therefore, the relationships between rolling resistance and roughness are numerically very similar despite the relatively small range of roughness (1.41 to 2.18 m/km IRI_{qc}) used in the New Zealand study reported herein. The differences in the constant term appear to be a function of vehicle and tyre types and tyre operating conditions such as inflation pressure and tyre temperature.

Both overseas studies and the reported New Zealand study show that roughness has a marked effect on the rolling resistance of passenger car tyres and that over a roughness range of 1 to 14 m/km IRI_{qc} the relationship appears to be linear.

Figure 6.1 Linear regression of fuel consumption on road surface macrotexture. Comparison of Swedish and New Zealand data.

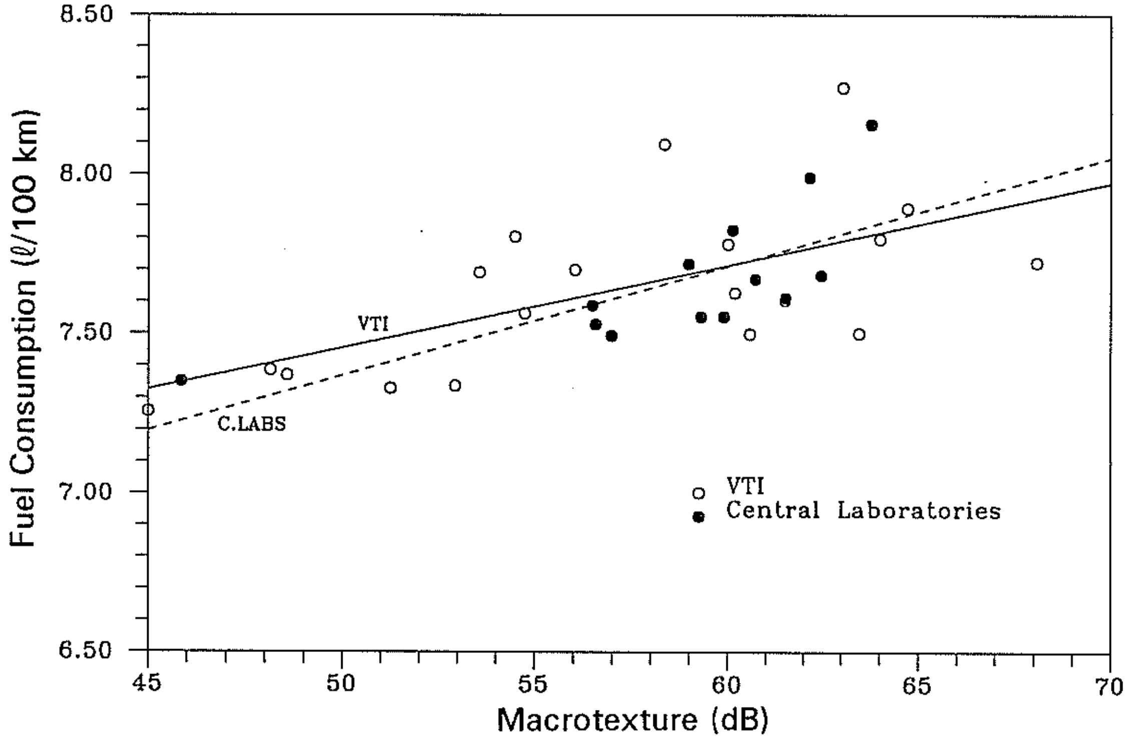
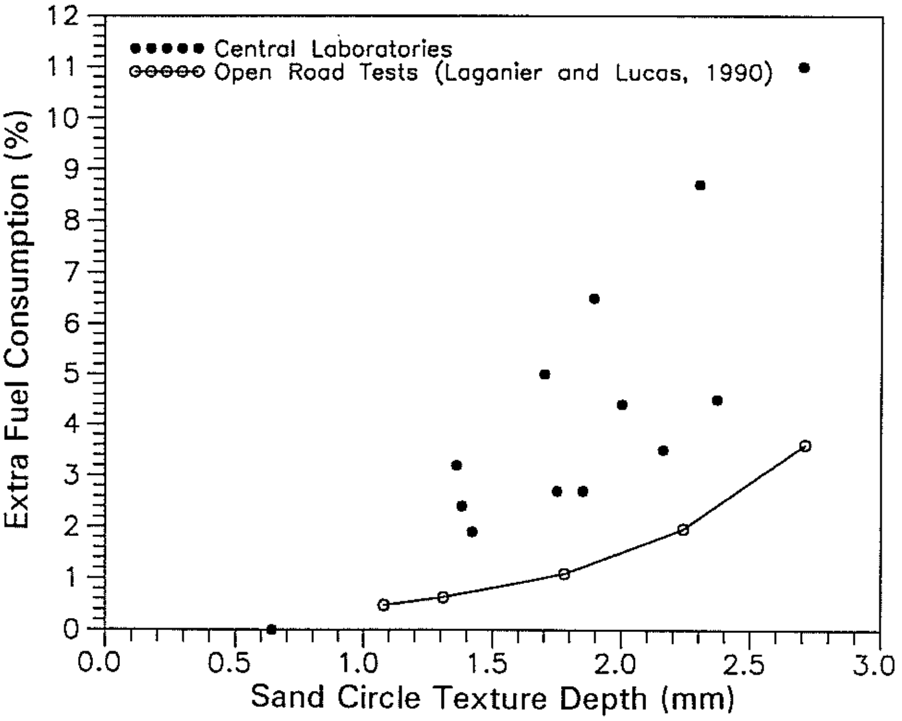


Figure 6.2 Texture and extra fuel consumption.
Comparison of French and New Zealand data.



6.3.3 Dynamic Component of Rolling Resistance

The C_2 values presented in Table 4.2 include the contributions of both the dynamic driveline resistance and quadratic rolling resistance from the road surface. Chassis dynamometer tests yielded the following relationship for no load:

$$\frac{F_{dr}}{Mg} = 1.6 \times 10^{-5} V^2 \tag{32}$$

This relationship was not affected by gear selection.

If the driveline contribution is subtracted, the C_2 value of the majority of surfaces is reduced to about 8.0×10^{-6} (s^2/m^2). Bester's South African study showed C_2 for passenger cars to be dependent on roughness as follows:

$$C_2 = (6.99 + 0.64\ IRI_{qc}) \times 10^{-6} \tag{33}$$

Equation (33) predicts C_2 values of between 7.89×10^{-6} and 8.40×10^{-6} (s^2/m^2) for the New Zealand test road sections.

Despite the good agreement between predicted and measured values of C_2, further research is recommended to investigate relationships between C_2 and macrotexture and roughness because the contribution of the speed-dependent part to the total coefficient of rolling resistance can be significant at open road speeds (e.g. C_2 equals about 0.006 at 100 km/h).

7. CONCLUSIONS

This programme of on-road rolling resistance measurements has led to the following conclusions:

- An on-road test procedure, utilising wheel torque measurement and on-board anemometry, has been developed that can reliably determine the rolling resistance characteristics of road surfaces.

- The static component of rolling resistance is significantly affected by surface texture depth, as determined from the sand circle method, with a measured increase of 55% resulting from a 2 mm increase in texture depth. This corresponds to a 11% increase in fuel consumption if a ratio of 5:1 between rolling resistance and fuel consumption changes is used.

- Both the New Zealand results and reviewed overseas studies demonstrate that road surface quality has a considerable impact on tyre rolling resistance and hence fuel consumption. The largest potential for reducing fuel consumption through road construction practices appears to lie in controlling megatexture (63 to 500 mm wavelengths) and, most of all, in controlling short wave unevenness on roads (0.6 to 3.2 mm wavelengths). The control of macrotexture is also important, especially wherever car speeds of 60-70 km/h are common.

- Experimental data from this programme indicate that, over a 20-100 km/h speed range, rolling resistance of passenger car tyres is dependent on vehicle velocity squared. However, more definitive measurements are required to establish whether this dynamic component of rolling resistance is independent of both surface texture and roughness.

- Road surface age – traffic loading dependency on rolling resistance appears to be directly related to macrotexture and roughness progression characteristics of the road surfacing type.

- International studies indicate that tyre rolling resistance tends to be more sensitive to road surface conditions as the tyre diameter decreases. This is primarily caused by higher tyre inflation pressures and harder rubber tyres used for commercial vehicle tyres, which results in smaller hysteresis loss.

- Relative to sealed roads, rolling resistance measurements obtained in overseas studies increase by as much as 45% on gravel roads for commercial vehicles. This increase has been attributed to the effect of the pavement deflection bowl that forms under a heavy wheel, and may be substantial on the flexible sealed pavements common in New Zealand.

8. RECOMMENDATIONS

The recommendations are:

- Given that an overall improvement of 1% in fuel economy applied to New Zealand's overall road transport fuel use would save the consumer around $30 million annually, and that this report shows that fuel consumption is related to road roughness and surface characteristics, further studies to identify cost effective road design and construction practices which could lead to reduced fuel use by New Zealand's vehicle fleet should be encouraged.

- Given the flexible nature of New Zealand sealed pavements which deflect to varying degrees under heavy wheel loads, the relationship between the size and shape of the pavement deflection bowl and rolling resistance characteristics of commercial vehicle tyres should be investigated.

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APPENDIX: NOMENCLATURE

A	Vehicle frontal area (m^2)
A_t	Transmission loss constant (N)
A_u	Undriven wheel loss constant (N)
B_t	Transmission loss linear coefficient (Ns/m)
B_u	Undriven wheel loss linear coefficient (Ns/m)
C_0	Static coefficient of rolling resistance
C_n	Speed dependent coefficient of rolling resistance where $n=1$ is the linear coefficient (s/m) and $n=2$ is the quadratic coefficient (s^2/m^2)
C_{do}	Aerodynamic drag coefficient at zero yaw
ΔC_d	Yaw angle aerodynamic drag variation coefficient
C_t	Transmission loss squared term (Ns^2/m^2)
$C_d(\psi)$	Coefficient of drag against yaw angle characteristic
$C_L(\psi)$	Coefficient of lift against yaw angle characteristic
D	Distance (m)
F_A	Aerodynamic drag force (N)
$F_D(V)$	Total drag force function (N)
F_{dr}	Dynamic component of driveline resistance (N)
F_M	Mechanical drag force (N)
F_R	Rolling resistance force (N)
F_T	Tractive effort (N)
F_U	Undriven wheel resistance (N)
g	Gravitational acceleration (m/s^2)
IRI_{qc}	International Roughness Index, quarter car simulation (m/km)
K_T	Temperature correction coefficient (K^{-1})
K_V	Coefficient of V^2 in tractive effort (Ns^2/m^2)
M	Vehicle mass (kg)
M_e	Vehicle effective mass (kg)
R_N	NAASRA roughness (counts/km)
r_i	Residual error at point i (m/s)
T_{Dsc}	Sand circle texture depth (mm)
T_{Dsp}	Sand patch texture depth (mm)
T_{DMTM}	TRRL mini texture meter texture depth (mm)
T_{Ma}	Macrotexture (mm)
T_o	Observed temperature (K)
T_p	Tyre pressure (kPa)
T_s	Standard ambient temperature (K)
t	Time (s)
V	Vehicle speed (m/s)
V_r	Total relative air speed (m/s)
α	Road gradient (deg)
ρ	Air density (kg/m^3)
ψ	Yaw angle (deg)