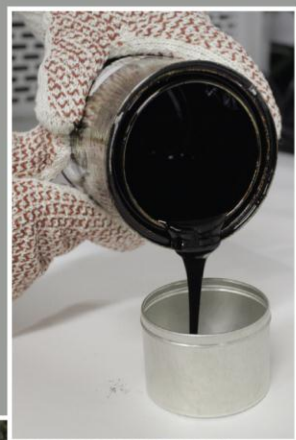
NCAT Report 11-05



SYNTHESIS OF THE EFFECTS OF PAVEMENT PROPERTIES ON TIRE ROLLING RESISTANCE

By
Robert L. Jackson
J. Richard Willis
Michael Arnold
Clay Palmer

National Center for Asphalt Technology
NCAT
at AUBURN UNIVERSITY

277 Technology Parkway ■ Auburn, AL 36830

SYNTHESIS OF THE EFFECTS OF PAVEMENT PROPERTIES ON TIRE ROLLING RESISTANCE

By

Robert L. Jackson
J. Richard Willis
Michael Arnold
Clay Palmer

National Center for Asphalt Technology
Auburn University, Auburn, Alabama

August 2011

DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the sponsor(s) or the National Center for Asphalt Technology, or Auburn University. This report does not constitute a standard, specification, or regulation. Comments contained in this paper related to specific testing equipment and materials should not be considered an endorsement of any commercial product or service; no such endorsement is intended or implied.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

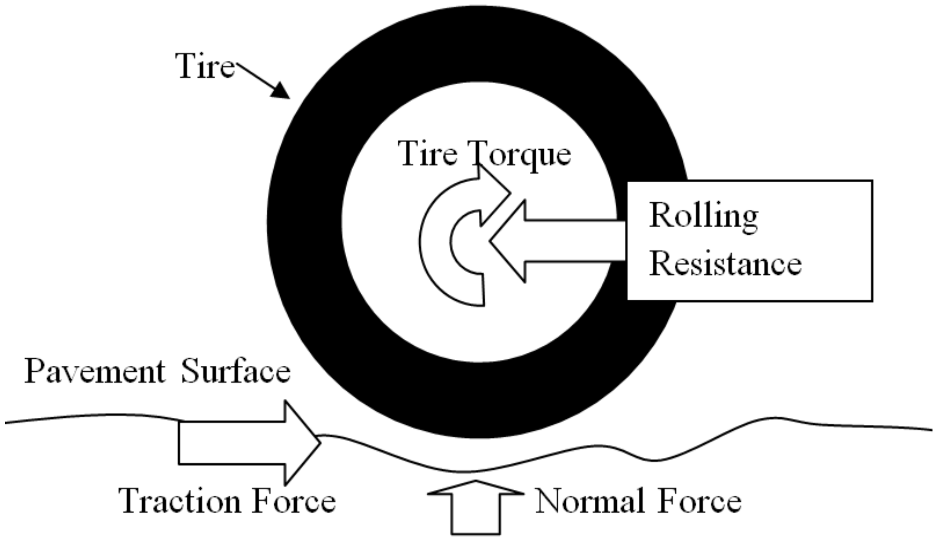
1. INTRODUCTION

In 2009, approximately 72% of the oil produced and 29% of the total energy consumed in US was accounted for by the transportation sector *(1)*. While the average fuel economy of vehicles has increased from 11.9 miles/gallon to 17.4 miles/gallon between 1973 and 2000, the fuel economy of heavy trucks has only increased from 5.5 to 6.2 in the same time period. In addition, the average annual mileage of heavy trucks has increased from about 15,370 to 25,254 miles during this time. Therefore, as the costs of energy resources continue to rise due to these increases in demand, and the public is becoming more environmentally conscientious, and the interest in improving vehicle fuel economy has escalated. While numerous factors such as vehicle aerodynamics and engine efficiency influence overall energy efficiency, one mechanism that dissipates energy inefficiently is in the contact between the tire and the pavement. This loss is often quantified by the rolling resistance, and it is also affected by the properties of the road pavement.

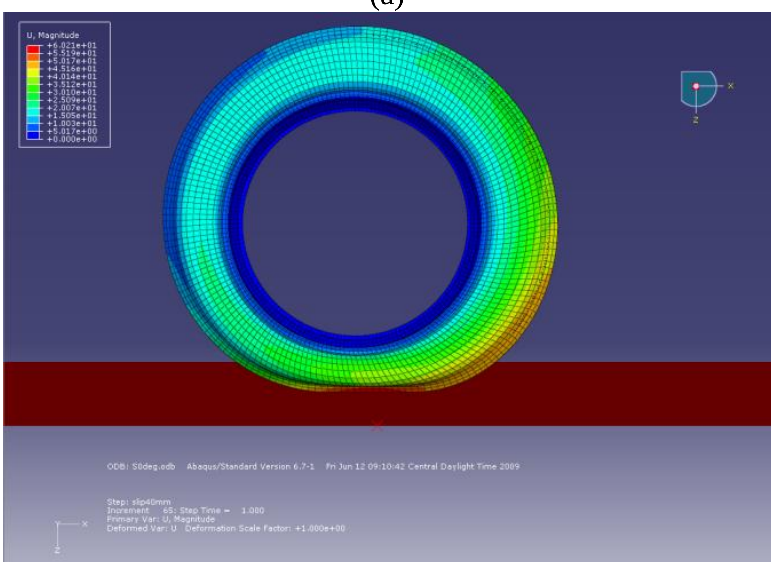
The main objective of this work was to objectively investigate the influence of pavement type (i.e., asphalt and concrete) on the rolling resistance of vehicle tires by reviewing existing literature. Therefore, it was important to research the influence of specific pavement properties such as stiffness and surface geometry on rolling resistance. This work also summarizes and evaluates the existing methods used to measure the rolling resistance, and quantifies the influence of the properties. A recommendation is made based on the existing literature and its limitations.

1.1 Definition of Rolling Resistance

Rolling resistance is the force required to keep an object such as a wheel or tire moving *(2)*. At a constant speed, the rolling resistance force is equal to the traction force between the road and tire (Figure 1.1(a)). The torque turning the tire then balances with the moment or torque created by the traction force. Forces contributing to the rolling resistance include friction losses at the rolling interface due to slip, friction in the bearings (internal), aerodynamic drag (there is not universal consensus that this should be considered part of rolling resistance), and hysteretic losses due to deformation of the rubber. An ideal rigid cylinder or wheel rolling with no slip against a perfectly smooth, level and rigid surface would have no rolling resistance. Rolling resistance is neither equivalent nor proportional to the friction between the tire and the road. Rather, rolling resistance is due primarily to hysteretic losses from deformations induced on the wheel or tire by the pavement. The hysteretic losses are due to the fluctuating stresses and strains induced in the tire during rolling as the tread comes in and out of contact, as shown in Figure 1.1(b). Some losses can occur due to deformation of pavement surface but are generally negligible except for unbound roadway surfaces. Rolling resistance is sometimes referred to as rolling friction, but this is not the same physical mechanism as sliding or solid against solid friction. The rolling resistance coefficient is determined by dividing rolling resistance by normal load.



(a)



(b)

Figure 1.1 Schematic of the (a) Forces Affecting a Tire Interacting with a Road and (b) Example Stress and Displacements Inside a Loaded and Torqued Tire via Finite Element Analysis *(3)*

2. FACTORS THAT AFFECT ROLLING RESISTANCE

Factors that affect the rolling resistance include air drag, properties and material composition of the wheel or tire, the tire's geometry, the road composition, and the roughness of both the tire and the road. Most research on rolling resistance tends to explore these factors independently, which diminishes the understanding of the relative magnitudes of the effects associated with each factor. Rolling resistance studies are affected by other experimental variables such as air temperature, vehicle speed, and tire-inflation pressure. Beuving *(4)* provides an illustration of the effects of vehicle speed on fuel consumption due to these factors. At 30 mph, rolling resistance consumes approximately 50% of the total energy used by the vehicle while internal friction uses 25% and air drag consumes the other 25% *(4)*. At 60 mph, however, rolling resistance consumes only 30% of the total vehicle energy while internal friction uses 20% and air drag consumes 50%. Increasing the vehicle velocity to 70 mph reduces the impact of rolling resistance to 20% of vehicle energy consumption *(4)*.

3. THE EFFECT OF PAVEMENT PROPERTIES ON ROLLING RESISTANCE

A literature review identified approximately 20 publications that investigated the effect of pavements on rolling resistance. A summary of the findings of each is given in Table 3.1, and the findings are also discussed in detail in the following sections. These studies evaluated the effects of such properties as pavement stiffness, smoothness, and pavement texture.

Surface texture and unevenness create vibrations in the tires and suspension. Energy is lost in these vibrations because the shock absorbers and the tires to absorb this energy, thus improving passenger comfort and reducing vehicle vibrations. Therefore, surface texture influences fuel consumption by inducing these vibrations. Micro texture affects the energy lost due to wear and small scale contact on the tires. Evenness affects the wear and energy loss mostly in the shock absorbers*(5)*. The conventions for defining the different scales of pavement roughness are discussed in section 3.2.

Table 3.1 Summary of Papers Addressing the Effect of Pavement on Rolling Resistance

Ref. #	Experimental or Theoretical Methodology	Most Influential Texture Scale	Change in Resistance (RR) or Fuel Consumption (FC) from Roughness	Rolling Resistance (RR) and Fuel Consumption (FC) Relation	Other Losses	Other Important Factors
(4)	Analysis of previous experimental work	--	Roughness influences FC by up to 10%; no difference between asphalt and concrete	10% change in RR accounts for a 3-4% change in FC	Drag and driveline	--
(6)	Experimental coast down method	--	Both constant and speed-related RR coefficients affected by roughness for cars; only the constant RR coefficient affected by roughness for trucks	Lower RR results in lower FC	Drag and gradient	--
(7)	Used both coast-down and steady state torque tests	--	24% difference between smooth and rough surfaces	--	Drag and gradient	--
(8)	Theoretical	--	--	Can effect FC by up to 30%	--	Contact pressure between road and tire
(9)	Hydraulic bench test, hub sensor on track, fuel consumption on road	Short wavelength roughness (1-2 m)	Up to 50% increase in RR from 1.5 mm increase in roughness	Lower RR results in better FC improvements up to 6%	Shocks	Road alignment
(10)	Experimental dynamometer and track	--	5.3% increase in the laboratory test and 8% difference in the road test	--	--	Road noise increases with roughness
(11)	Towed trailer method	Mega-texture	Surface condition can affect RR by 47%	Max. fuel savings of 9%	--	Temperature and velocity
(12)	Theoretical	Roughness, macro and mega-texture.	Equations provided. For trucks the RR could increase by as much as 50% due to roughness	FC effected by RR up to 7%	Road gradient	Tire load and temperature
(13)	Experimental coast-down method and fuel consumption	--	Increasing IRI from 60 to 120 resulted in 1.8% increase in RR at 30 mph and 6% at 55 mph	Factor 0f 0.18 (i.e., 22% RR increase = 4% FC increase)	Stiffness	Lack of data for load, tire type, vehicle type, etc.
(14)	An experiment determined the rolling resistance of four different surfaces	Macro-texture and evenness	Smoother road results in lower RR	RR must be reduced by 6-7% to reduce FC by 1%	--	Surface texture, softness or loose material

Ref. #	Experimental or Theoretical Methodology	Most Influential Texture Scale	Change in Resistance (RR) or Fuel Consumption (FC) from Roughness	Rolling Resistance (RR) and Fuel Consumption (FC) Relation	Other Losses	Other Important Factors
(15)	Road Tests on the NCAT test track	--	Increased roughness has resulted in higher fuel consumption of test trucks		--	Vehicle wear
(16)	Reviewed previous experimental results	Mega-texture	--	--	--	Tire noise
(17)	Experimented with a hydraulic bench and on a track	--	Lower roughness results in better FC	--	Shocks	Road alignment
(18)	Theoretical	--	10% from poor to good pavement finish	Both improve w/ less roughness	Tire, shocks	Velocity
(19)	Experimental using fuel consumption	Mega and macro-texture	10x increase in IRI increases FC by 2 to 16%. 10x increase in megatexture increases FC by 8 to 14%; increase in macrotexture (MPD) from 0.3-3 increases FC by 2 to 21%.	%FC/%RR ratio is 0.25	--	--
(20)	Experimental fuel consumption on a track	--	Increasing road roughness increased FC by 4.5%; rehabilitation used to reduce roughness	--	Fatigue failures of vehicles	--
(21)	Theoretical	--	Increasing roughness by 26.7% increases RR by 38.7%	--	Tire, shocks	Velocity
(22)	Falling weight deflectometer and towed trailer	--	A 0.5 mm increase in mean profile depth results in a 10% increase in RR	--	Road stiffness	--
(23)	Experimental, focusing mostly on the tire.	--	Suggests that RR of very soft surfaces (dirt, sand) could be twice that of hard pavements surfaces (concrete, asphalt)	--	--	Tire composition
(24)	Tested the responses wrt rolling resistance by changes in velocity, tire type, and size	--	--	--	Drag and shocks	Velocity, tire type, tire pressure, and tire size

3.1 Pavement Surface Geometrical Profile

Several key pavement characteristics that affect vehicle performance are related to surface geometries, more commonly referred to as texture and roughness.

In pavement engineering, surface geometries are classified by wavelength scales (Table 3.2). Some researchers have used different terms for describing pavement profiles. The smallest scale is termed "microtexture," which applies to wavelengths less than 0.5 mm. Microtexture deals with the texture of aggregate particles on the pavement surface and is a primary characteristic that affects skid resistance *(5)*. Wavelengths in the range of 0.5 to 50 mm in the surface geometry are considered "macrotexture" *(19, 25)*. This is the general surface relief of the pavement that is visible to the naked eye. Macrotexture is primarily controlled by the aggregate gradation of the surface layer for asphalt pavements (Figures 3.1) and by texturing methods for concrete pavement, such as tining or brooming. Additionally, research at the NCAT Pavement Test Track has shown that increasing the percent passing the #8 sieve will decrease the overall macrotexture of a pavement at the time of construction (Figure 3.1). Macrotexture affects tire-pavement noise and skid resistance, particularly in wet weather.

Table 3.2 Conventional Definitions of the Different Scales of Pavement Surface Geometries *(25)*

Texture Classification	Relative Wavelengths
Microtexture	$\lambda < 0.5$ mm
Macrotexture	0.5 mm $< \lambda <$ 50 mm
Megatexture	50 mm $< \lambda <$ 500 mm
Roughness/Smoothness	0.5 m $< \lambda <$ 50 m

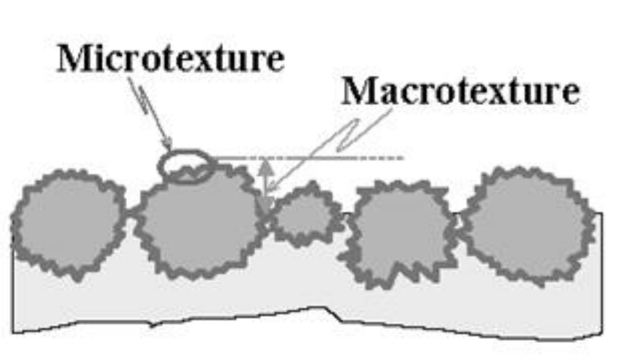


Figure 3.1 Schematic of the Effect of Aggregate on Different Scales of Texture *(25)*

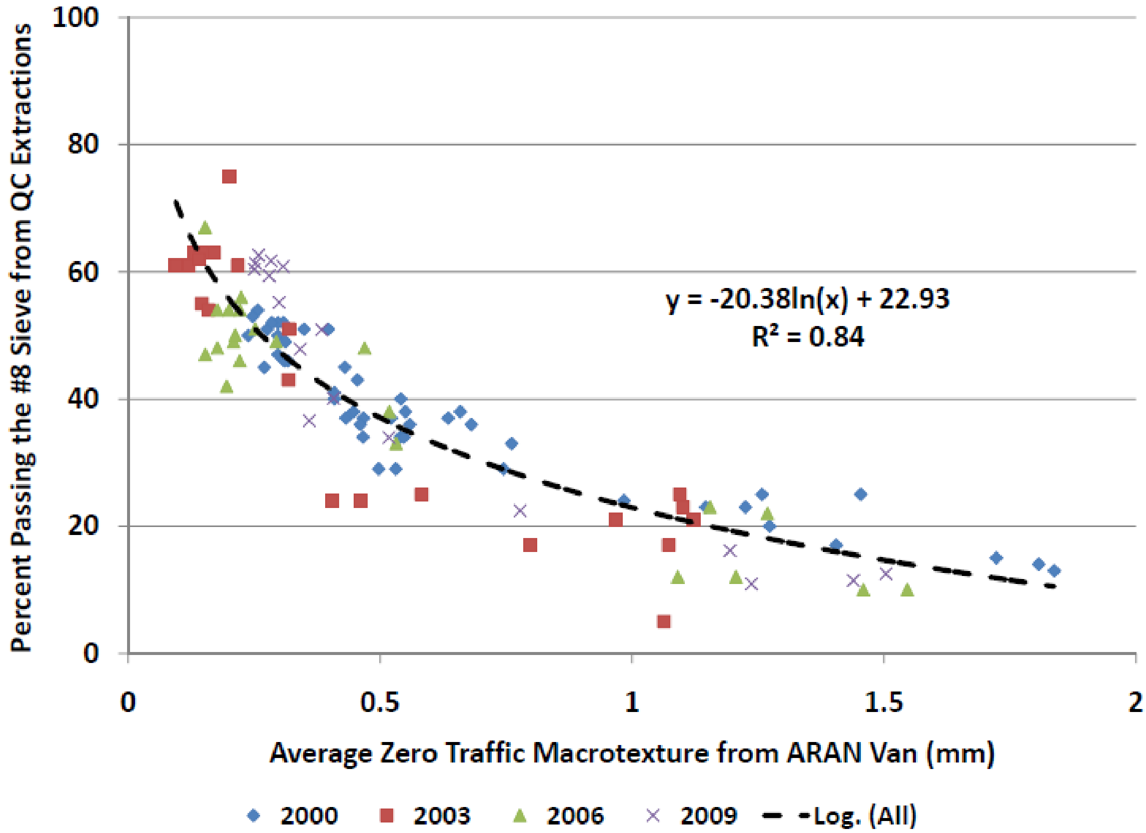


Figure 3.2 Effects of Aggregate Gradation on Macrotexture

A common method to quantify the surface roughness in the study of machine friction and wear for manufactured machine parts is the standard deviation of the profile heights, also known as the root mean square (RMS) roughness *(26)*. However, the RMS roughness can vary significantly based on the sample length or size of the area being considered. Therefore, researchers have more recently used Fourier Transform and Fractal techniques to characterize the structure of roughness over many different scales *(27, 28)*. A surface can be characterized over multiple scales by transferring it into the frequency domain and using a spectrum.

Fractal analysis of surfaces is now being applied in the area of autonomous vehicle control *(29)*, which suggests that it may also be applicable to pavements *(30-37)*. Sayles and Thomas *(36)* suggest the existence of a common fractal structure over many different types and scales of surfaces, including paved roads and tracks.

Surface geometries with wavelengths above 50 mm, often referred to as large-scale roughness, have a greater influence on rolling resistance. Profile wavelengths between 50 and 500 mm are considered megatexture. Megatexture affects rolling resistance by creating vibration inputs in the tire and suspension system. Descornet *(11)* concluded that megatexture was the main factor in rolling resistance and could affect fuel usage by up to 9%. Macrotexture and megatexture can be quantified using the Mean Profile Depth, which is defined as the average profile depth of two halves of a surface within a given baseline (Figure 3.3).

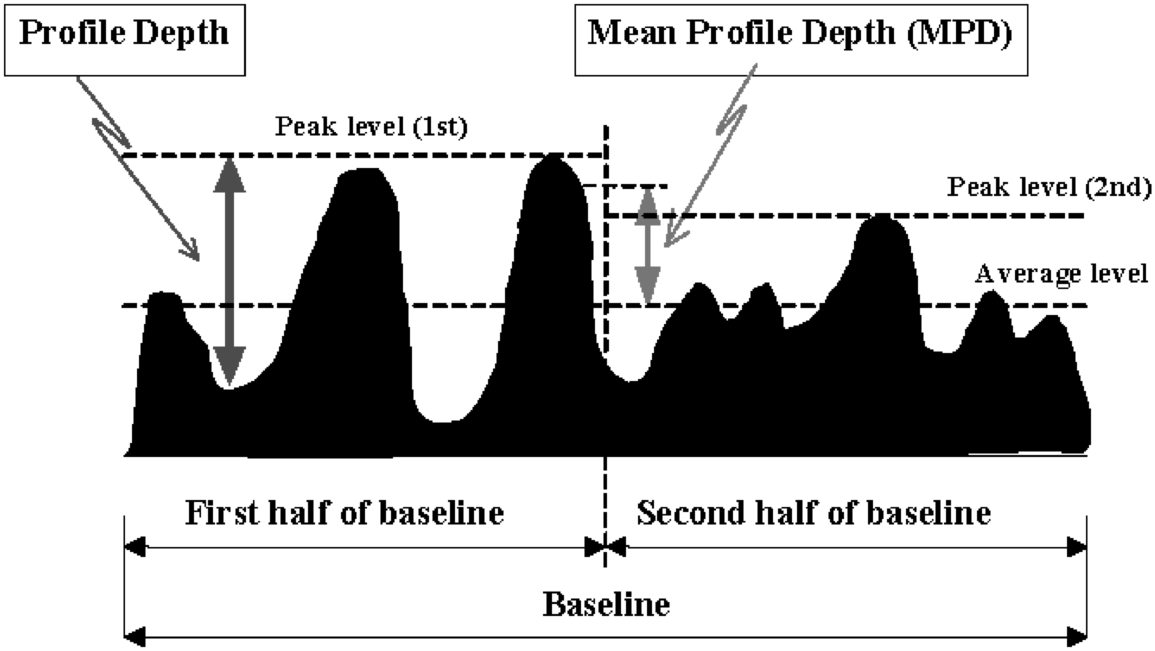


Figure 3.3 Schematic of How the Mean Profile Depth is Calculated *(25)*

Pavement roughness, typically with wavelengths greater than 0.5 m, is generally cited as the profile characteristic having the greatest influence on rolling resistance because this range causes impacts or gross deformation of the tire and shocks that induce vibrations and hysteresis losses (Figure 3.4). Hysteresis is the energy lost between the loading and unloading of the tires and shock absorbers. A synonym to roughness is unevenness, and an antonym is smoothness. A sub-category of this range between .5 and 5 m is sometimes referred to as shortwave unevenness.

The most common measurement of pavement roughness is the International Roughness Index (IRI), which is based on how a driver perceives the roughness of a road. Technically, IRI is the reference average rectified slope (RARS80) of a quarter-car simulation traveling at 80 km/h over a measured surface profile, taken in the wheel tracks. The average rectified slope is the displacement of a vehicle suspension over a given distance and is reported in units of m/km or in/mile.

Applied Research Associates, Inc. conducted a study for the Ontario Ministry of Transportation in 2007 that assessed the initial smoothness of both asphalt and Portland cement concrete (PCC) pavements *(38)*. The average initial IRI of the asphalt pavements assessed in the research was 0.83 m/km while the average IRI of the PCC pavements was 1.34 m/km. This showed that asphalt pavements were initially smoother than PCC pavement structures.

Mahoney et al.*(39)* recently conducted a study that assessed pavement smoothness over time across Oregon and Washington State. The average HMA IRI for Oregon and Washington were 1.0 m/km and less than 1.0 m/km, respectively. For PCC, the average IRI for Oregon was 1.5 m/km while Washington had an average PCC IRI of 2.0. Additionally, the HMA pavements in Oregon were older than the PCC pavements while still maintaining superior smoothness.

Hammarstrøm et al.*(13)* suggested that at 50 mph, increasing the IRI of a road from 60 in/mile to 120 in/mile would increase the rolling resistance by 6%. Schmidt and Ullidtz *(40)* also quantified how changing the IRI influences fuel economy. They suggested that reducing the IRI of a roadway by only 6% can reduce fuel consumption by between 1.8 to 2.7%. Du Plessis et al. *(12)*showed that fuel economy could be increased by 20% for 1 ton trucks and buses under ideal conditions by improving the roughness of a roadway from 20 to 200 Quarter-car Index. While these conditions are extreme, the research suggests that road-surface properties on average can increase fuel consumption by around 7%.

Other studies have suggested that driving on smoother pavements can increase fuel economy by as much as 4–4.5% *(20, 22, 40-42)*. However, since IRI is based on the response of a passenger car suspension traveling on the profile and not the actual profile itself, researchers have noted that it is challenging to directly relate IRI to rolling resistance, particularly for heavy commercial vehicles.

Sandberg *(19)* investigated the effect of different scales of the surface roughness on the vehicle energy consumption. The experiment was conducted using twenty different road surfaces, three different speeds, and one type of car. The test speeds were 50, 60, and 70 km/h. The test vehicle was a manual, four-speed Volvo 242. The project road surface wavelength ranged from 2 to 3500 mm. The experiment showed shortwave unevenness was the most important factor in determining fuel consumption. It can cause up to 10% changes in the fuel consumption. Macrotexture can affect fuel consumption by up to approximately 5%. At low speeds, evenness and megatexture are the most influential profile scales on fuel consumption. At high speeds, the evenness, megatexture, and macrotexture were all influential on fuel consumption. Sandberg also notes that while road surface texture contributes to energy losses in tires and the suspension, good macrotexture is needed to prevent hydroplaning.

Hammarstrøm et al.*(13)* also determined that increased the MPD of a pavement by 1 mm can increase the rolling resistance by up to 17% at 30 mph. At 60 mph, the same increase in MPD increases the rolling resistance by 30%. This would result in 5.1% and 9% decreases, respectively, in fuel economy based solely on texture.

Since rolling resistance appears to be dominated by fairly large-scale parts of a pavement profile, and friction is affected more by small-scale features *(37)*, it may be possible to optimize a surface spectrum that minimizes rolling resistance and maximizes friction. Not only does maximizing the friction improve driver control of a vehicle, more friction will also keep the tire surface from slipping against the road. Slippage against the road could actually decrease rolling resistance because it would dissipate more energy. Hence, in some cases, friction and rolling resistance could be inversely related.

Therefore, a smoother road can decrease fuel consumption by decreasing the vibrations of the tire and suspension. However, due to the dynamic effects of such resonance, the deflections and energy losses will vary based on the scale of roughness, vehicle speed, and vehicle type.

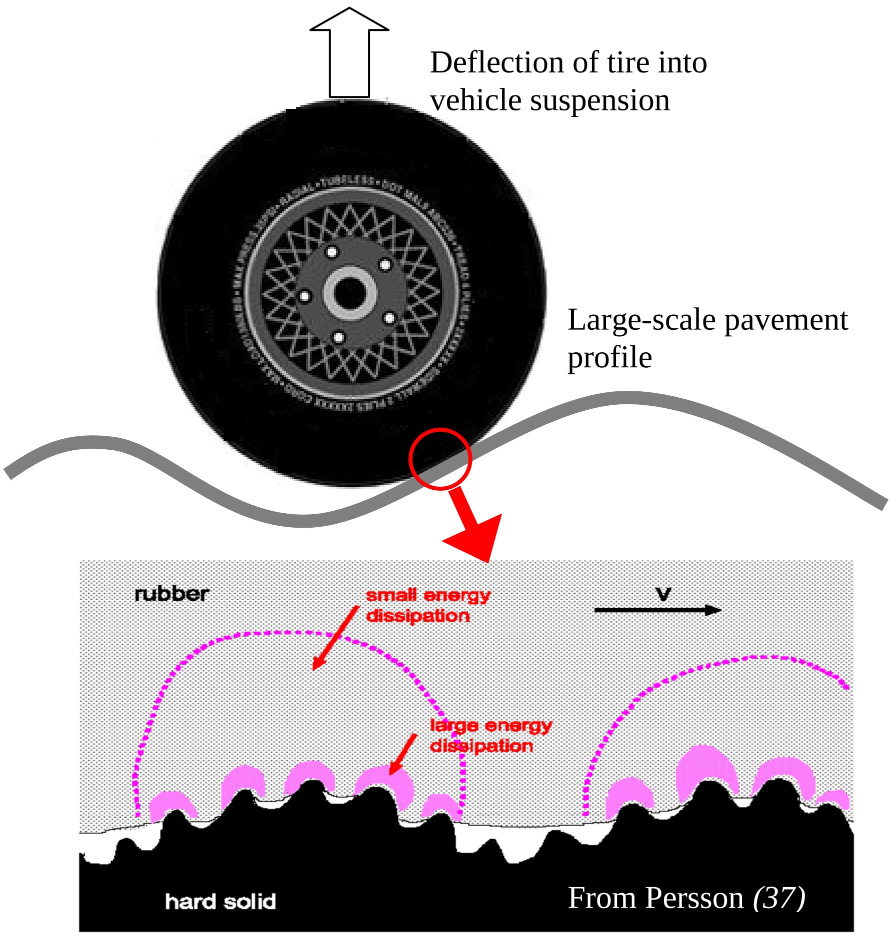


Figure 3.4 Illustration of How Roughness on Different Scales Deforms the Tire *(37)*

3.1 Pavement Deformation

The pavement in contact with the tire will also deform and, therefore, dissipate some energy during the interaction. Schmidt *(43)* concluded since energy is lost due to pavement deflection, it is best to have stiffer pavement. He suggested that rolling resistance due to pavement deflection accounts for only about 4% of total rolling resistance. However, other references also concluded that the effect of pavement deflection on rolling resistance was even smaller *(22, 41, 42)*. Pavements are much stiffer than tires (by about 2–3 orders of magnitude*[44])* and vehicle suspension components. Therefore, most deformation and energy loss is associated with the tire.

For instance, modeling the tire-road interface as two springs in series (Figure 3.5), the effective stiffness of the interface is dominated by the tire.

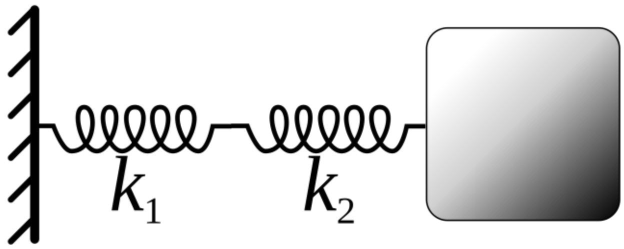


Figure 3.5 Two Springs in Series to Consider Tire and Pavement Contact

This is confirmed by an approximate calculation using typical bulk material properties and information for a typical tire and asphalt pavement . Since the contact force on the tire and pavement must be the same, the energy-loss ratio between the tire and the pavement is proportional to deflection of each. Assuming that both the tire and pavement behave as linear elastic elements (i.e., springs) results in the following relationship:

$$\frac{E_{tire}}{E_{pavement}} \approx \frac{\delta_{tire}}{\delta_{pavement}} = \frac{F/k_1}{F/k_2} = \frac{k_2}{k_1} \tag{1}$$

where E is the energy loss, δ is the deflection, F is the contact force, k_1 is the stiffness of the tire, and k_2 is the stiffness of the pavement.

The stiffness of a standard reference tire (k_1) is about 240 N/mm *(3, 45)*. To approximate the stiffness of the asphalt pavement (k_2) it is assumed that it behaves as a compressed column of material. The thickness of the column is taken as the thickness of a typical asphalt pavement for heavy trafficking, or approximately 0.36 m. Then cross-sectional area of the column is approximated as the contact area of a typical tire contact patch at 0.01 m^2. Finally, a conservatively small elastic modulus of asphalt at 1,000 N/mm^2 is assumed, corresponding to fairly high-temperature cases. Then the stiffness of the asphalt (k_2) is predicted to be approximately 28,100 N/mm. Using Eq. (1), the energy loss of the tire is approximately 117 times larger than the energy lost in the pavement. For commercial truck tires, stiffness values range from approximately 750 to 1,050 N/mm *(46)*. For this class of vehicles, the energy loss in the tire is still 30 times more than that lost in the pavement.

This results in the pavement accounting for 0.85% of the rolling resistance energy loss, which matches well with other works *(22, 41, 42)* that suggest this value may be around 1% *(22, 41)*. Since rolling resistance does not have a 1:1 relationship with fuel economy, the impact of pavement deflection and stiffness on fuel economy appears to be minimal.

Perriot also examined the influence of pavement fuel consumption *(42)* using a viscoelastic model for asphalt pavements and concluded that pavement deflections would only account for 0.005 to 0.5% of fuel consumption depending on the type of vehicle. As almost all research findings show, the rolling resistance is effectively independent of the pavement stiffness *(4, 9-11, 14, 19, 20, 40).*

4. EXPERIMENTAL METHODS FOR MEASURING ROLLING RESISTANCE

Researchers have used many different methods to measure the rolling resistance of tires and pavement combinations. They can be generally characterized into three basic methods: 1) bench tests (laboratory), 2) vehicle-based methods, and 3) towed trailer methods.

Many studies that are primarily interested in tire and vehicle suspension effects on rolling resistance prefer to use laboratory-controlled conditions. These studies are referred to as bench tests and include equipment such as a falling weight deflectometer, vibration rigs, or conventional tire test stands in which the tire is driven against a drum, or conveyor belt. A common method for assessing operating parameters of tires and their influence on rolling resistance is using a drum tire dynamometer (Figure 4.1). During free rolling (no torque) the forces are measured at the tire hub. Since the test surface is curved, it is difficult to test actual pavement profiles directly. DeRaad did attempt to measure the effect of the road profile on rolling resistance by using a drum with different surface textures *(10).*

Figure 4.1 Drum Type Tire Test (http://jiurongwheel.com)

Since the road profiles cause a rolling tire to translate in the vertical direction, vertical displacements can also be applied directly to a vehicle wheel to replicate this motion. This is known as a hydraulic dynamic test *(9)* in which a wheel is vibrated to match a measured road profile. The temperature change of the shock absorber was measured to determine the energy lost in the suspension. This method is effective at measuring the portion of rolling resistance that is due to deflection of the suspension rather than the actual tire carcass.

Vehicle-based methods for rolling resistance use techniques such as fuel consumption calculations, the coast-down method, and placing force transducers in the actual vehicle. Some studies have used the measured fuel consumption of vehicles *(9, 12, 14)* to indirectly quantify rolling resistance on pavements via calculations. A similar technique is the coast-down method *(9, 14, 47)* in which either the vehicle speed is measured at regular intervals during coasting, the total time or distance for the vehicle to stop is measured, or the change in velocity is measured over a predetermined distance. Since rolling resistance is defined as the force required to keep a tire rolling at a constant velocity, this force can also be measured directly. In some studies, a dynamometer was attached to the hub of a non-driving front wheel of a car *(9)*. Forces measured in the x-, y-, and z-directions are then used to calculate rolling resistance. If the dynamometer is placed on a driven tire, the force accelerating the car and opposing air drag and internal friction must be removed from the calculation. Wheel torque, total relative air speed, and aerodynamic yaw are then continuously measured. Wheel torque is divided by the drive wheel diameter to determine the output force. The output force is then correlated with the relative air speed to determine the rolling resistance. However, since other sources of energy loss such as air drag and internal friction exist in a moving vehicle, it is difficult to isolate the portion that is due to rolling resistance in all these vehicle-based tests.

Therefore, trailers have been devised to isolate the forces measured for rolling resistance from the powertrain and to minimize air drag. Descornet *(11)* used this approach to quantify tire rolling resistance using a trailer device that measured the deflection of a beam suspending the tire (Figure 4.2). The coefficient of rolling resistance was determined from the deflection angle, θ. For the comparison of the rolling resistance between different pavement types, it appears the trailer method is the most feasible.

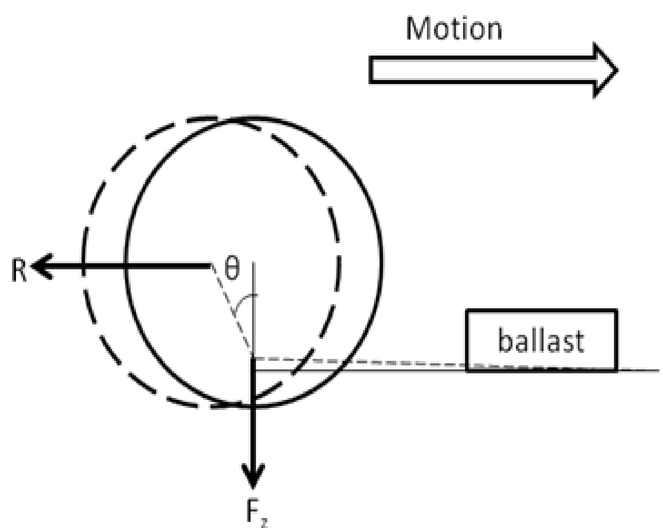


Figure 4.2 Force Balance Schematic of a Trailer Device Used to Measure Rolling Resistance *(11)*

5. MAINTAINING SMOOTH PAVEMENTS

Most state highway agencies have smoothness requirements for asphalt and concrete pavements during the construction process, requiring contractors to build pavements to some standard of smoothness. Implementation of smoothness specifications was primarily motivated by the basic perception that the driving public equates smoothness with pavement quality. Additional roadway design and construction criteria could be developed to improve smoothness. Thus, incentives for smooth construction could be repaid in fuel savings.

Since states require new pavements to have a certain smoothness, the real challenge to developing a fuel-efficient pavement network would be maintaining the fuel efficiency of pavement structures. Over time, both asphalt and concrete pavements develop distresses throughout the entire pavement structure that affect both the roughness and textural components of the surface layer. However, fully developing the concepts related to perpetual pavement design would aid state agencies in maintaining smooth pavements.

Perpetual pavements have four primary design criteria *(48, 49)*;

1. Perpetual pavements should have a wearing course life of 20 years.
2. Perpetual pavements should have a structural design life of 40 to 50 years.
3. Perpetual pavements use a mill and fill as their primary surface rehabilitation.
4. Perpetual pavements contain their distresses to the top few centimeters of the pavement surface.

Since perpetual pavements are designed to resist bottom-up fatigue cracking, over time the stress accumulation at the pavement surface leads to surface cracking. This would increase both the textural and roughness measurements of the roadway; however, after a designated period of time, this distressed pavement layer would be removed and replaced with a new smooth surface. This surface would be placed on top of a distress-free, strong asphalt structure. In a sense, the roughness and textural numbers would return to near that of the original pavement. If this design philosophy were adopted, it would aid in the design, construction, and maintenance of pavements, which could reduce vehicle rolling resistance.

6. COST BENEFITS

While it will cost money to implement and maintain fuel-efficient pavements, there are noted cost benefits in fuel and vehicle wear. A socio-economic study was conducted in Denmark *(50)* to determine the true cost-benefit of reducing the rolling resistance of its pavement structures. The study recommended Denmark require road IRI values to be below 0.9 m/km and have a maximum profile depth of 0.6 mm. If these standards were implemented, approximately 99.8% of the roads in the country would have to be rehabilitated. The cost of repaving 3,717 km of roadways was estimated to be 3,474 million DKK ($637,463,862 US). However, it was estimated the average fuel savings for pavements with controlled smoothness and texture would save the country 3.3% on fuel costs. Over 15 years, the country would save almost $3.78 billion dollars, including the rehabilitation costs.

A comprehensive cost-benefit analysis is needed to fully understand the impact smoother pavements with better texture would have on the United States economy. While statistics show the US consumed approximately 143 billion gallons of gasoline and 32 billion gallons of diesel fuel in 2009 *(51)*, researchers and economists cannot quantify how much fuel efficiency can be improved based on pavement properties until the current condition of US roadways is assessed.

7. CONCLUSIONS

This work summarizes more than two dozen references on tire rolling resistance and the effect of pavement. The key parameters of the pavement that affect rolling resistance have been identified. Pavement roughness and texture are very influential characteristics, with large-scale roughness being the most important. Further research is needed to optimize pavement texture for rolling resistance without sacrificing friction/safety. Stiffness of the road does not appear to have a significant effect on the rolling resistance or fuel economy of vehicles. Rolling resistance of a tire on concrete or asphalt pavements with the same profile or texture should be practically identical. The literature suggests that improvements in pavement roughness could directly improve fuel efficiency by approximately 2-6%. Of course, tire rolling resistance is also dependent on factors such as tire type, inflation pressure, temperature, weather conditions, speed, and more. Fuel efficiency will, therefore, be influenced by all these factors in addition to other losses not related to tire rolling resistance, such as aerodynamic drag, engine friction, etc...

8. RECOMMENDATIONS

Based on the results in this report, there is only superficial qualitative understanding of the relationship between pavement properties and rolling resistance. Therefore, additional studies on rolling resistance under controlled conditions while monitoring all the influential parameters is suggested. Several plausible methods for measuring rolling resistance were identified. For further research of the effects of pavement characteristics on rolling resistance, an isolated trailer containing a rolling tire appears to be the best option. This trailer would consist of a force transducer connecting a weighted rolling tire and a covered trailer that aerodynamically isolates the tire. Data would be recorded in real time either to a computer in the towing vehicle or via a wireless connection to a nearby stationary computer. This trailer could then be pulled over various asphalt and pavement types at different speeds and loads (previous works do not appear to thoroughly investigate the effect of tire load). The surface profiles of the pavements would be characterized using several different methods, including the traditional IRI method and spectral methods. Different types of tires and inflation pressures could also be investigated on different pavements, as it is believed that stiffer tires will be influenced less by the pavement roughness. Pavement texture, roughness, and stiffness would be measured using the inertial profilers and falling weight deflectometers to fully capture the pavement properties that may affect rolling resistance and fuel economy. Since these pavement measurements are routinely measured on the wide variety of asphalt test pavements on the NCAT Pavement Test Track, it is well suited for rolling resistance experiments. Additional pavements should be included in the experimental plan so that the research includes a complete range of pavement types and surface conditions. These pavements should come from the four different climatic regions of the country. Additionally, the rolling resistance of each pavement should be quantified seasonally to determine how pavement temperature, ambient air temperature, and humidity also impact vehicle fuel economy.

It is also recommended that a full socioeconomic analysis be conducted for the United States to determine the costs and benefits of using pavements with less rolling resistance. This research will need to assess the current state of the US roadways in terms of smoothness and texture. What are appropriate smoothness and textural thresholds for maintaining appropriate rolling resistance? How much will it cost to rehabilitate and maintain these conditions? How much fuel will be saved based on these changes to the highway infrastructure? This study can also be used to assess how the carbon footprint of the transportation sector could change given the reduction in fuel usage and increase in construction maintenance.

9. REFERENCES

1. Review, D.A.E., *Annual Energy Review*. 2009, U.S. Department of Energy. p. DOE/EIA-0384.
2. Browne, A., K.C. Ludema, and S.K. Clark, *Mechanics of Pneumatic Tires*. Vol. Monograph 122. 1971: National Bureau of Standards.
3. Krithivasan, V., R.L. Jackson, R.W. Green, and S.-Y. Choe. *Characterization of Tire Behavior by a Finite Element Method*. in *Proceedings of the 28th Annual Meeting and Conference on Tire Science and Technology*. 2009. Akron, OH.
4. Beuving, E., T. De Jonghe, D. Goos, T. Lindahl, and A. Stawiarski. *Fuel Efficiency of Road Pavements*. in *3rd Eurasphalt @ Eurobitume Congress*. 2004. Vienna, Austria.
5. Oecd, *Road Surface Characteristics: Their Interaction and Their Optimization*, in *Road Transport Research*. 1984, Organisation for Economic Co-operation and Development.
6. Bester, C.J., *Effect of Pavement Type and Condition on the Fuel Consumption of Vehicles.* Transportation Research Record 1000, 1984: p. 28-32.
7. Cenek, P.D., *Rolling Resistance Characteristics of New Zealand Road Surfaces.* American Society for Testing and Materials, 1994. **ASTM STP 1225**: p. 248-262.
8. Clapp, T.G. and A.C. Eberhardt, *Computation and Analysis of Texture-Induced Contact Information in Tire-Pavement Interaction.* Transportation Research Record 1084, 1986: p. 23-29.
9. Delanne, Y., *The Influence of Pavement Unevenness and Macrotexture on Fuel Consumption.* American Society for Testing and Materials, 1994. **ASTM STP 1225**: p. 240-247.
10. Deraad, L.W., *The Influence of Road Surface Texture on Tire Rolling Resistance.* Society of Automotive Engineers Technical Paper Series, 1978: p. 780257.
11. Descornet, G., *Road-Surface Influence on Tire Rolling Resistance*, in *Surface Characteristics of Roadways: International Research and Technologies*, W.E. Meyer and J. Reichert, Editors. 1990, American Society for Testing and Materials: Philadelphia. p. 401-415.
12. Du Plessis, H.W., A.T. Visser, and P.C. Curtayne, *Fuel Consumption of Vehicles as Affected by Road-Surface Charactoristics*, in *Surface Charactoristics of Roadways: International Research and Technologies*, W.E. Meyer and J. Reichert, Editors. 1990, American Society for Testing and Materials. p. 480-496.

13. Hammarström, U., R. Karlsson, and H. Sörensen, *Ecrpd, Energy Conservation in Road Pavement Design, Maintenance and Utilisation, Road Surface Effects on Rolling Resistance - Coast Down Measurements with Uncertainty Analysis in Focus*. 2008, Swedish National Road and Transport Research Institute.
14. Gyenes, L. and C.G.B. Mitchell, *The Effect of Vehicle-Road Interaction on Fuel Consumption*, in *Vehicle-Road Interaction*, B.T. Kulakowski, Editor. 1994, American Society for Testing and Materials: Philadelphia. p. 225-239.
15. Heffernan, M.E., *Simulation, Estimation, and Experimentation of Vehicle Longitudinal Dynamics That Effect Fuel Economy*, in *Mechanical Engineering*. 2006, Auburn University: Auburn, AL. p. 144.
16. Hegmon, R.R., *Some Results from Ongoing Research on Road Roughness*, in *Vehicle, Tire, Pavement Interface*, J.J.H.a.J.C. Wambold, Editor, ASTM: Philadelphia. p. 14-31.
17. Laganier, R. and J. Lucas, *The Influence of Pavement Evenness and Macrotexture on Fuel Consumption*, in *Surface Characteristics of Roadways: International Research and Technologies, Astm Stp 1031*, W.E. Meyer and J. Reichert, Editors. 1990, ASTM: Philadelphis. p. 454-459.
18. Lu, X.P., *Effect of Road Roughness on Vehicular Rolling Resistance*, in *Astm Stp 884*, T.D. Gillespie and M. Sayers, Editors. 1985, ASTM: Philadelphia. p. 143-161.
19. Sandberg, U.S.I., *Road Macro and Mega Texture Influence on Fuel Consumption*, in *Surface Characteristics of Roadways: International Research and Technologies (Astm Stp 1031)*, W.E. Meyer and J. Reichert, Editors. 1990, American Society for Testing and Materials: Philadelphia. p. 460-479.
20. Sime, M., *Techbrief: Westrack Track Roughness, Fuel Consumption and Maintenance Cost*. 2000, Federal Highway Administration. p. FHWA-RD-00-052.
21. Soliman, A.M.A., *Effect of Road Roughness on the Vehicle Ride Comfort and Rolling Resistance.* SAE TECHNICAL PAPER SERIES, 2006: p. 2006-01-1297.
22. Ullidtz, P., B. Schmidt, B. Jensen, and O. Nielsen. *Energy Reduction through Improved Road Pavement Characteristics*. in *16th World Meeting International Road Federation*. 2010. Lisbon, Portugal.
23. Walter, J.D. and F.S. Conant, *Energy Losses in Tires.* Tire Sci. and Technol., 1974. **2**(4): p. 235-281.
24. Velinsky, S.A. and R.A. White, *Increased Vehicle Energy Dissipation Due to Changes in Road Roughness with Emphasis on Rolling Losses.* SAE Preprints, 1979(790653).
25. Flintsch, G.W., E.D. León, K.K. Mcghee, and I.L. Al-Qadi, *Pavement Surface Macrotexture: Measurement and Applications.* Transportation Research Record 1860, 2003. **03-3436**: p. 168-177.
26. Mccool, J.I., *Relating Profile Instrument Measurements to the Functional Performance of Rough Surfaces.* ASME J. Tribol., 1987. **109**(2): p. 264-270.
27. Jackson, R.L. and J.L. Streator, *A Multiscale Model for Contact between Rough Surfaces.* Wear, 2006. **261**(11-12): p. 1337-1347.
28. Kogut, L., and Jackson, R. L., *A Comparison of Contact Modeling Utilizing Statistical and Fractal Approaches.* ASME J. Tribol., 2005. **128**(1): p. 213-217.
29. Dawkins, J.J., R.L. Jackson, and D.M. Bevly, *Fractal Terrain Generation for Vehicle Simulation.* International Journal of Vehicle Autonomous Systems. **In Press**.
30. Jackson, R.L., *An Analytical Solution to an Archard-Type Fractal Rough Surface Contact Model.* Trib. Trans., 2010. **53**(4): p. 543 - 553.

31. Majumdar, A. and C.L. Tien, *Fractal Characterization and Simulation of Rough Surfaces.* Wear, 1990. **136**(2): p. 313-327.
32. Mandelbrot, B.B., *The Fractal Geometry of Nature*. 1983, New York, NY: Freeman.
33. Wu, J.-J., *Characterization of Fractal Surfaces.* Wear, 2000. **239**: p. 36-47.
34. Wu, J.-J., *Spectral Analysis for the Effects of Stylus Tip Curvature on Measuring Fractal Profiles.* Meas. Sci. Technol., 2000. **11**(9): p. 1369-1376.
35. Panagouli, O.K. and A.G. Kokkalis, *Skid Resistance and Fractal Structure of Pavement Surface.* Chaos, Solitons & Fractals, 1998. **9**(3): p. 493-505.
36. Sayles, R.S. and T.R. Thomas, *Surface Topography as a Nonstationary Random Process.* Nature, 1978. **271**(2): p. 431-434.
37. Persson, B.N.J., *Theory of Rubber Friction and Contact Mechanics.* Journal of Chemical Physics, 2001. **115**(8): p. 3840-3861.
38. Applied Research Associates Inc., *Life-Cycle Cost 2006 Update: Final Report*. 2007, The Ministry of Transportation (Ontario), Cement Association of Canada, Ontario Hot Mix Producers Association.
39. Mahoney, J.P., C.L. Monismith, J. Coplantz, J. Harvey, V. Kannekanti, L. Pierce, J. Uhlmeyer, N. Sivaneswaran, and T. Hoover, *Pavement Lessons from the 50-Year-Old Interstate Highway System: California, Oregon, and Washington.* Transportation Research Circular, 2007. **E-C118**: p. 88-103.
40. Schmidt, B. and P. Ullidtz, *The Energy Saving Road: Energy Savings in Road Transport as a Function of the Functional and Structural Properties of Road*. 2010, Denmark: NCC Green Road.
41. Eapa/Eurobitume, J., *Environmental Impacts and Fuel Efficiency of Road Pavements.* EAPA Industry Report, 2004.
42. Perriot, A., *Roads and Energy: How Pavements Can Affect Vehicle Fuel Consumption*. 2008, The COLAS Group.
43. Schmidt, B. *Energy Reduction in the Road Infrastructure Network as a Function of Roads Functional and Structural Conditions*. in *16th IRF (International Road Federation) World Meeting*. 2010. Lisbon, Portugal.
44. Ashby, M., H. Shercliff, and D. Cebon, *Materials Engineering, Science, Processing and Design*. 2007, New York: Elsevier.
45. Rhyne, T.B., *Development of a Vertical Stiffness Relationship for Belted Radial Tires.* Tire Science and Technology, 2005. **333**: p. 136-155.
46. Wong, J.Y., *Theory of Ground Vehicles, 4th Ed.* 2008, New York: Wiley.
47. Hill, B.J., *Measurement of Rolling Resistance Using an Eccentrically Weighted Oscillating Wheel*, in *Surface Characteristics of Roadways: International Research and Technologies*, W.E. Meyer and J. Reichert, Editors. 1990, American Society for Testing and Materials: Philadelphia. p. 497-504.
48. Mahoney, J.P., *Study of Long-Lasting Pavements in Washington State.* Transportation Research Circular, 2001. **503**: p. 88-95.
49. Newcomb, D., J.R. Willis, and D.H. Timm, *Perpetual Asphalt Pavements: A Synthesis*. 2010, Asphalt Pavement Alliance.
50. Nielsen, C. and T.D.F. Skibsted, *The Energy-Saving Road: Improving Socio-Economic Conditions by Reducing Rolling Resistance. A Socio-Economic Report*. 2010, NCC Roads A/S: Denmark.

51. Bureau of Transportation Statistics Research and Innovative Technology Administration, *Fuel Consumption by Mode of Transportation*, in *http://www.bts.gov/publications/national_transportation_statistics/html/table_04_05.html*. 2011.