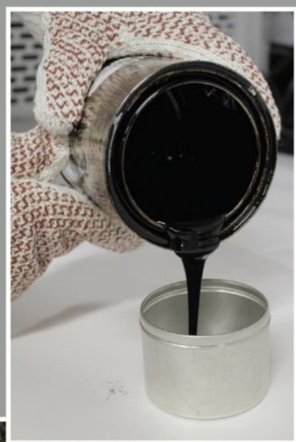

NCAT Report 14-07

EFFECTS OF PAVEMENT PROPERTIES ON VEHICULAR ROLLING RESISTANCE: A LITERATURE REVIEW

By
J. Richard Willis, Ph.D.
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Revised June 2015

National Center for Asphalt Technology
NCAT
at AUBURN UNIVERSITY
277 Technology Parkway ■ Auburn, AL 36830

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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 sponsored agency, the National Center for Asphalt Technology, or Auburn University. This report does not constitute a standard, specification, or regulation. Comments contained in this report 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

GLOSSARY OF TERMS

dB — decibel, an early surrogate measure for the macro-texture of the pavement

deflection — the distance the surface of a pavement compresses due to loading from heavy vehicles and/or passenger cars

L_{MA} — refers to the macro-texture of a pavement (2–50 mm wavelength)

L_{ME} — refers to the mega-texture of a pavement (63–500 mm wavelength)

L_{su} — refers to the smoothness or unevenness of a pavement (630–3,150 mm)

macrotexture — the texture of the pavement as constructed on the roadway measured in wavelengths between 0.5 and 50 mm

megatexture — wave-shaped surface characteristics commonly between 50 and 500 mm which is sometimes associated with pavement damage

microtexture — the texture of the aggregate component of the pavement measured in wavelengths shorter than 0.5 mm

roughness — imperfections in the pavement surface which affect a passenger's perceived ride or drivability

smoothness — see roughness

unevenness — see roughness

ICON GUIDE

The following pictographs are used to denote the method of inquiry for each paper reviewed, as well as the scope of pavement qualities being examined.

METHODS			
Literature Review	Field Tests	Lab Tests	Modeling
			

SCOPE		
Smoothness	Texture	Pavement Type
S	T	P

1 INTRODUCTION

1.1 Background

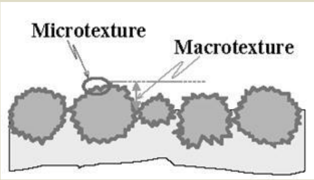
In 2011, approximately 71 percent of the petroleum used in the United States was utilized in the transportation sector, accounting for 27 percent of the U.S. energy demand (1). Despite a 50 percent increase in the overall fuel economy of passenger vehicles between the years 1973 and 2000, the average fuel economy of heavy vehicles has increased less than 20 percent to only 6.2 miles per gallon. In this same time period, the annual mileage driven by heavy trucks has increased by 64 percent (1). Meanwhile, consumers, governments, and state agencies are all seeking ways to become more sustainable.

One focal area in the field of sustainability relates specifically to vehicle fuel economy because it directly impacts all three facets of the triple bottom line sustainability principle: social, environmental, and economic benefits. If the fuel economy of vehicles increase, fewer natural resources will be required to produce fuel, fewer greenhouse gasses will be produced by vehicles traveling on the roadway infrastructure, and money will be saved by consumers who traverse the highway network.

While this might seem like a simple concept, understanding the factors that affect vehicle fuel economy is complex. Rolling resistance, aerodynamic forces, inertial forces when accelerating, internal frictional forces, and gravity when driving on slopes (Figure 1) all must be overcome in order for vehicles to move (2). These forces can be further broken down into rolling resistance, air resistance, inertial resistance, gradient resistance, side force resistance, transmission losses, losses from the use of auxiliary equipment, and engine friction (3). This becomes more complicated when one understands that these components are not isolated parts but rather a system of parts interacting to determine the instantaneous fuel economy of vehicles. While this is a complex phenomenon, this report will focus on just one force that affects vehicle fuel economy — rolling resistance.

Rolling resistance is defined as “the mechanical energy converted into heat by a tire moving for a unit distance of roadway” (4). The sources of energy loss or heat that affect rolling resistance include energy losses in the tires, pavement, bearing friction, tire rotation, aerodynamic resistance, tire drag, and vehicle suspension. In addition, factors such as air temperature, vehicle speed, and tire-inflation pressure also can increase or decrease the rolling resistance of a vehicle and thus could either improve or reduce its fuel economy. Beuving et al. (5) developed an illustration (Figure 2) that graphically represents the effect of vehicle speed on fuel consumption. At 30 mph, rolling resistance consumes approximately 50 percent of the total energy used by the vehicle, while internal friction and air drag each account for 25 percent. If the speed of the vehicle increases to 60 mph, rolling resistance consumes only 30 percent of the total vehicle energy while internal friction and air drag consume 20 and 50 percent, respectively. If the same vehicle were traveling 70 mph on an Interstate, rolling resistance would only account for 20 percent of the vehicle’s energy consumption.

Numerous terms have been used to describe pavement smoothness such as roughness and unevenness. In reality, there is little to no difference in these terms, and they are used interchangeably throughout literature. Texture, on the other hand, is different as it measured using a much shorter wavelength and quantifies imperfection or indentions in both the aggregate (microtexture) or pavement (macrotexture).



Schematic of the Effect of Aggregate on Different Scales of Texture (6)

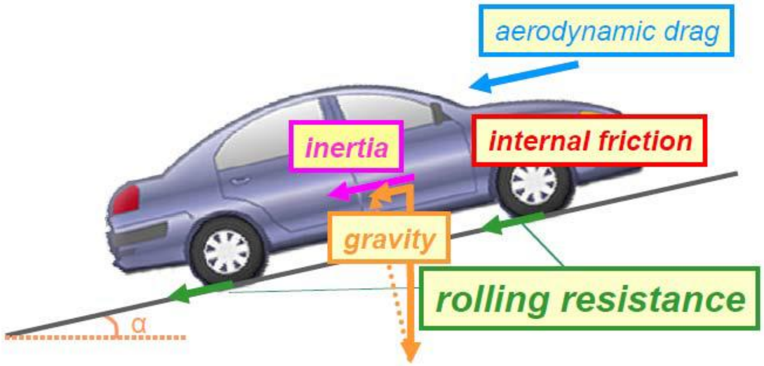


FIGURE 1 Various forces act on a vehicle, which must be overcome to sustain movement (2)

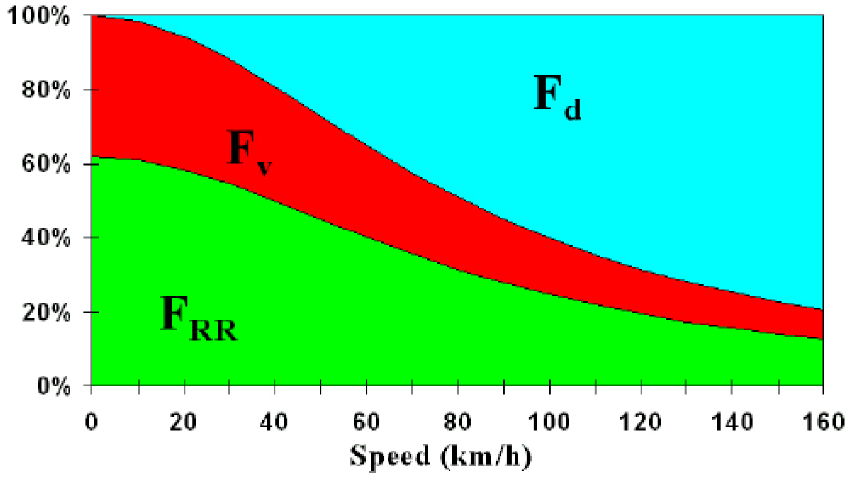


FIGURE 2 Distribution of energy consumption to overcome aerodynamic drag, internal friction, and rolling resistance (5)

While many of the factors that affect rolling resistance are vehicle dependent, pavement properties play a small yet integral role in determining the overall rolling resistance a vehicle must overcome. Three pavement properties commonly thought to affect vehicular rolling resistance are pavement surface texture, roughness (i.e. smoothness), and pavement stiffness.

Surface texture and smoothness create vibrations in the tires and suspensions of vehicles creating vibrations. The vibrations are absorbed by the shock absorbers and tires of the vehicle causing a loss of energy in the overall vehicular system. The surface texture of the pavement induces these vibrations which ultimately affects the fuel economy of the vehicle. The smoothness of the pavement affects the wear and energy lost in the shock absorbers to provide a more comfortable ride to the passenger (7).

Pavement deflection (i.e. pavement type) has been suggested as a possible third pavement property which affects rolling resistance. This theory derives from the idea that when tires and pavement interact, energy is lost due to pavement deflection. This might then affect the fuel economy of the vehicle (8).

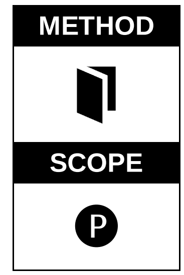
1.2 Objective

The objective of this report is to investigate the influence of pavement type and properties on vehicular rolling resistance. This was completed by reviewing existing literature to assess how pavement properties such as texture, smoothness (unevenness), and stiffness might alter the vehicle fuel economy of both passenger cars and trucks. This effort included a review of both modeling efforts and tests performed in the lab and the field. The literature is primarily presented in chronological order.

2 LITERATURE REVIEW

The following is a literature review of some of the work pertaining to the effect of pavement properties on vehicular rolling resistance. Each study is briefly summarized and some commentary is provided to include limitations and final conclusions. Commentary is separated from the review. Icons are provided to the reader at the beginning of each section to provide information as to the scope (i.e. pavement property studied) and methods used in each study.

2.1 "Energy Losses in Tires" by J.D. Walter and F.S. Conant in Tire Science and Technology, 1974 (9).



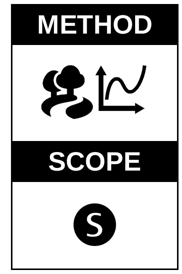
Walter & Conant (9) conducted an early review on the forces that induce energy losses in tires. While the majority of the properties they considered relate to the tire itself, the team suggested that one should consider how much a wheel sinks into the road, as this might affect the energy loss in the tire. For example, they suggested that for every inch the tire sank into the ground, an extra 30 pounds of force would be necessary to move the tire for each ton of load on that wheel. They considered an early study that showed estimates of rolling resistances on different surfaces (Table 1). Based on this table, it was shown that it might take twice as much effort to drive on a gravel road compared to a smooth, hard pavement.

║ Limitations: No structural or material characterization was included in this study.

TABLE 1 Rolling resistance on different road surfaces (9)

Surface	Rolling Resistance, lb/1000 lb vehicle weight
Concrete	10 – 20
Asphalt	12 – 22
Dirt	25 – 37
Sand	60 – 150

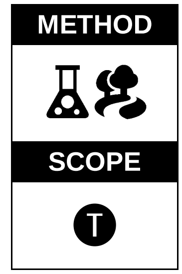
2.2 "Increased Vehicle Energy Dissipation Due to Changes in Road Roughness with Emphasis on Rolling Losses" by S.A. Velinsky and R.A. White, SAE Technical Paper, 1979 (10).



Velinsky & White (10) used vehicle axle acceleration to experimentally study the effect of road roughness on dissipated vehicular energy. Accelerations measured in the field were then correlated to computer simulations. This correlation allowed the research team to develop a deterministic road roughness model that could predict energy losses in both the tire and suspension system of a vehicle. Model inputs included properties such as tire pressure, vehicle speed, and roadway roughness. Using the model, the research team could vary the different inputs to assess the total effect of each property on both rolling resistance and vehicle drag. These models determined that road roughness increased both the rolling and drag losses for vehicles due to dissipation of energy in the tires and suspension. Thus, road roughness must be accounted for in determining vehicle rolling losses. Modeling rough roads showed that the rolling losses could be as great as 20 percent in addition to the aerodynamic losses.

> Limitations: This study used a limited data set for its modeling and did little characterization as to the actual roughness of the road.

2.3 "The Influence of Road Surface Texture on Tire Rolling Resistance" by L.W. Deraad, SAE Technical Paper, 1978 (11).



This report identifies the four major factors that contribute to tire rolling resistance losses:

1) tire design (bias, bias-belted, or radial construction),
2) tire operating parameters (load, speed, inflation pressure, steer, and torque inputs),
3) ambient conditions (precipitation and temperature), and
4) highway design (surface type and aggregate selection).

The experimental study focused on the effect of roadway surface texture on rolling resistance and was completed in two phases. In the first phase, indoor laboratory testing was conducted to include the determination of rolling resistance (addressing only the free rolling case) on a smooth steel surface and on a 3M Safety-Walk surface. Tires with common loading and inflation pressure were tested in 10 different radial passenger car constructions at a speed of 50 mph. Rolling resistance was higher on the textured surface (Safety-Walk) than on the smooth steel drum, with an average difference in rolling resistance reported as 5.3 percent and ranging between 2.5 and 11 percent.

The second phase of the work included outdoor testing. This was conducted on six different surfaces using 10 various passenger car tire constructions; one tire was tested in each construction. Tires selected included multiple manufacturers and were mostly radial tires but also included bias and bias-belted tires. A heavy-duty pickup truck with a cantilevered single wheel was fixed to the rear of the bed. Rolling resistance was measured in the free-rolling case at a speed of 30 mph over six different surfaces. The surfaces included polished concrete, new concrete with texture ("similar to a newly constructed burlap-dragged freeway surface"), asphalt (considered an "average type asphalt highway"), asphalt with less rounded exposed aggregate, asphalt with slightly more exposed aggregate, and asphalt covered with a sealcoat "of sharp aggregate."

Rolling resistance was found to increase with increased texture. Rolling resistance was normalized to the new concrete surface and it was found that there was an 8 percent difference in rolling resistance between the new concrete surface and the most textured asphalt surface. The polished concrete showed a 12 percent reduction in rolling resistance over the new concrete surface. Although an 8 percent difference was reported, the difference between the average asphalt highway (surface 3) and new concrete (surface 2) was one unit of rolling resistance. Thirty percent differences were reported for "hard-surface public roads," referring to the asphalt covered with coarse sealcoat. The author recognized the importance of surface texture for wet traction performance and suggested that surface texture consider both rolling resistance and the need for safety during wet traction performance.

Commentary and Limitations: This study reinforces the importance of texture on rolling resistance. However, only two of the surfaces were concrete, both of which had a smooth macrotexture, whereas all of the asphalt surfaces had, at minimum, a medium macrotexture. The vehicle speed on this study was also below standard highway speeds (30 mph in the outdoor phase and 50 mph in the indoor phase). This report identifies the importance of tire design and operating parameters, but does not account for the differences in tire design relative to rolling resistance measured on various highway surfaces.

2.4 "The Influence of Tyre and Road Surface Design on Tyre Rolling Resistance" by A.R. Williams, Institute of Petroleum Monograph, 1981 (12).

METHOD

SCOPE

P

In the United Kingdom, Dunlop Tires became interested in assessing what it could do to reduce the rolling resistance of tires in the early 1980s. The research group fitted replica road surfaces onto a drum and assessed the rolling resistance of five different tires. While the primary intent of the experiment was to characterize how the tires influenced rolling resistance, by fitting multiple surface types to the drum Williams was also able to assess the interaction of tire type and pavement type on rolling resistance. When comparing the extremes (smooth steel to surface dressing) there was a 15 percent difference in the rolling resistance of a single tire type; however, when comparing the other pavement types, the differences were not as noted.

Limitations: Statistical analyses were not completed to see if any of the results were statistically significant.

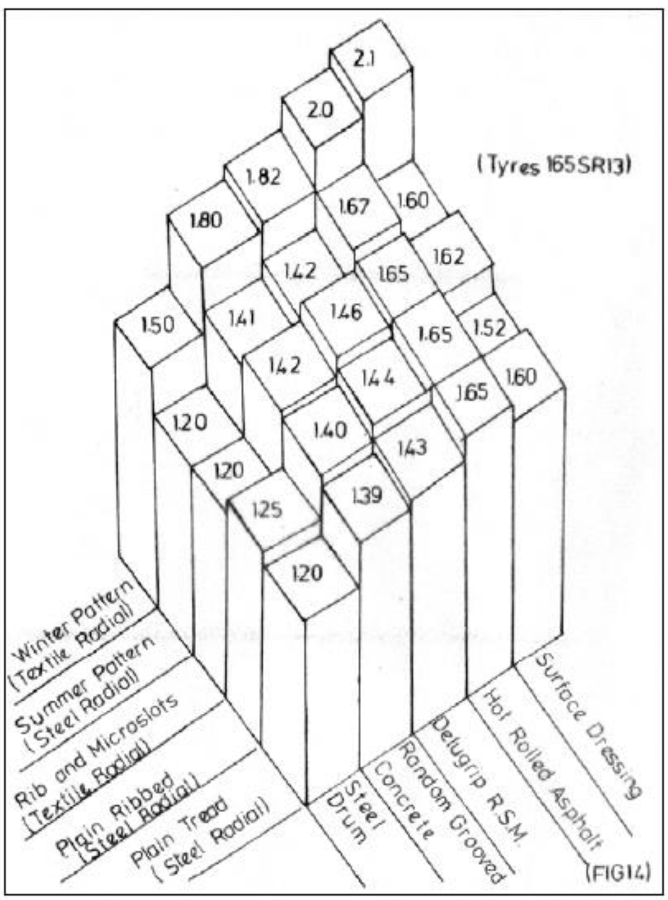


FIGURE 3 Relationship between rolling resistance coefficient and type of tire and road surface, at various points measured on a drum facility having various replica road surfaces (12)

2.5 "Effect of Pavement Type and Condition on the Fuel Consumption of Vehicles" by C.J. Bester in *Transportation Research Record 1000*, 1984 (13).

METHOD

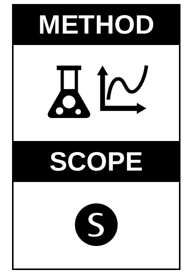
SCOPE

P S

Bester completed one of the earliest experiments specifically developed to assess how pavement type and roughness affect rolling resistance. Bester used an experimental coast-down method to measure the rolling resistance of passenger cars and trucks on eight different surfaces: asphalt (2), concrete (1), surface treatment (4), and unsurfaced (1). His study determined that pavement type (asphalt vs. concrete) had only a small effect on rolling resistance. Both the asphalt and concrete roads had lower rolling resistance values than surface treatments. The roughness had an effect on the rolling resistance as smoother roads had lower rolling resistance values.

> Limitations: Little pavement or material characterization took place in the analysis. Additionally, only eight test sections were used to develop trends, and no statistical analysis was included in the study.

2.6 “Effects of Road Roughness on Vehicular Rolling Resistance” by X.P. Lu in ASTM STP 884, 1985 (14).



Using spectral density functions, Lu modeled the effects of road roughness on vehicular rolling resistance. Like many other studies, this experiment focused on a singular property (roughness) and its effect on rolling resistance. Using the spectral density functions and developed models, the research team was able to compare the effect of road roughness on rolling resistance for a quarter car. As the roughness of a road increased, the rolling resistance became exponentially greater. For example, the amount of force required to keep the vehicle moving on a good road in one condition was 300 N. If the same roadway were in a poor condition, 10 percent more energy (330 N) would be required to keep the car moving. A road in a very poor condition would increase the rolling resistance by 40 percent (420 N).

These models also showed that roughness and vehicle speed interact to affect rolling resistance. When a vehicle is traveling at a slower speed, the roughness of the road does not affect rolling resistance as much as if the vehicle were traveling quickly.

> Limitations: This model has not been validated using field data at this time. Additionally, limited pavement parameters (only roughness) were used in the modeling.

2.7 "Computation and Analysis of Texture-Induced Contact Information in Tire-Pavement Interaction" by T.G. Clapp and A.C. Eberhardt in *Transportation Research Record 1084*, 1986 (15).

METHOD

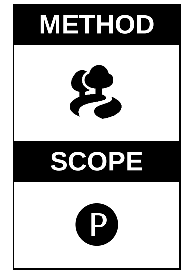
SCOPE

T

Theoretical computations using numerical analysis were completed to assess how texture could influence fuel consumption. Based on the tire-induced contact determined in the models, the team determined that texture could affect fuel consumption by determining contact area with the tire based on textural patterns.

Limitations: This model is currently unverified using field data.

2.8 "Effect of Pavement Surface Type on Fuel Consumption" by J.P. Zaniewski, Portland Cement Association, 1989 (16).



The objective of Zaniewski's research was to assess how pavement surface type affects fuel consumption. Fuel consumption data were collected for multiple vehicle types on 12 different highway sections, which included asphalt concrete, portland cement concrete, asphalt surface treatments, and gravel roadways. While rough pavements were included in the study, the report focused on smoother and intermediate smoothness pavements. Vehicle speeds ranged from 10 to 70 mph in 10 mph increments.

Overall, statistical analyses did not provide any meaningful data to show differences between pavements when assessing all of the cars, speeds, and pavement conditions. For automobiles, some asphalt pavements showed better fuel consumption than concrete pavements; however, the converse was also shown to be true. On the other hand, trucks consistently had better fuel economy on concrete pavements compared to asphalt pavements. For a semi-truck, the difference in fuel consumption between asphalt and concrete pavements was roughly 1 percent.

> Limitations: The pavement structures were not characterized in this study to determine if they were equivalent designs. Additionally, the only pavements used in the analysis were in good condition.

2.9 "The Influence of Pavement Evenness and Macrotexture on Fuel Consumption" by R. Laganier and J. Lucas in ASTM STP 1031, 1990 (17).

METHOD

SCOPE

T S

Laganier & Lucas (17) conducted three phases of research to assess how pavement evenness (i.e. smoothness) and macrotexture both affected fuel consumption. Phase one was completed in a laboratory while phases two and three were completed on a test track and open road respectively. In the laboratory experiment, unevenness was simulated using a vibration bench, which acted like the profile of the road; however, this test commonly underestimates the effects of roughness due to its elimination of draft coefficient changes. On the test track and open roads, evenness was characterized using the longitudinal profile analyzer while macrotexture was measured using a mini-texture meter (MTM) so that rolling resistance could be compared to these pavement properties.

In all three cases, both texture and smoothness affected the fuel consumption results (Figures 4–6). On the Nantes Test Track, surface textures ranged from 0.3 to 3 mm. In addition, the unevenness of the open roads and test track varied so that correlations between rolling resistance and smoothness could be developed. The authors concluded smoothness was as important as the textural component.

> Limitations: The methods and units used for measuring texture and smoothness are non-standard today.

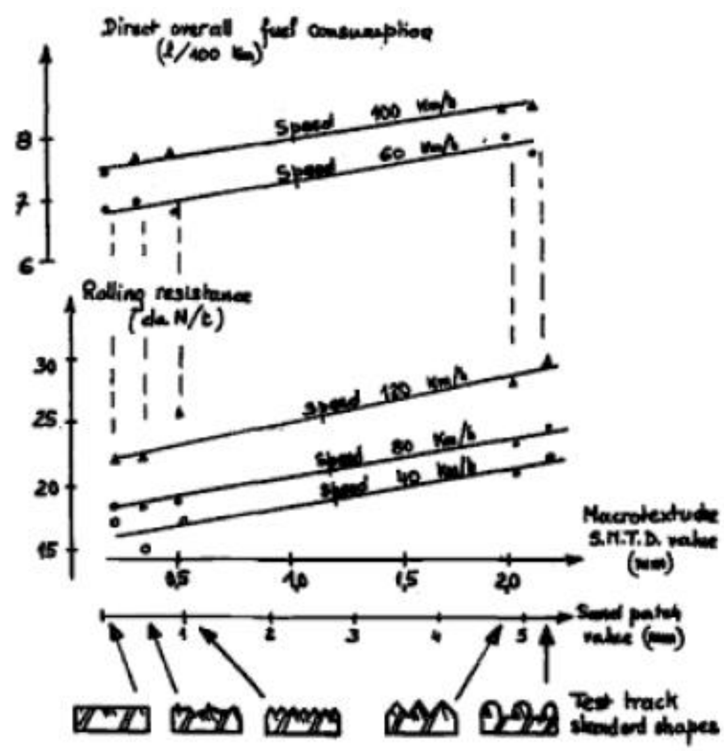


FIGURE 4 Effect of macrotexture on fuel consumption (17)

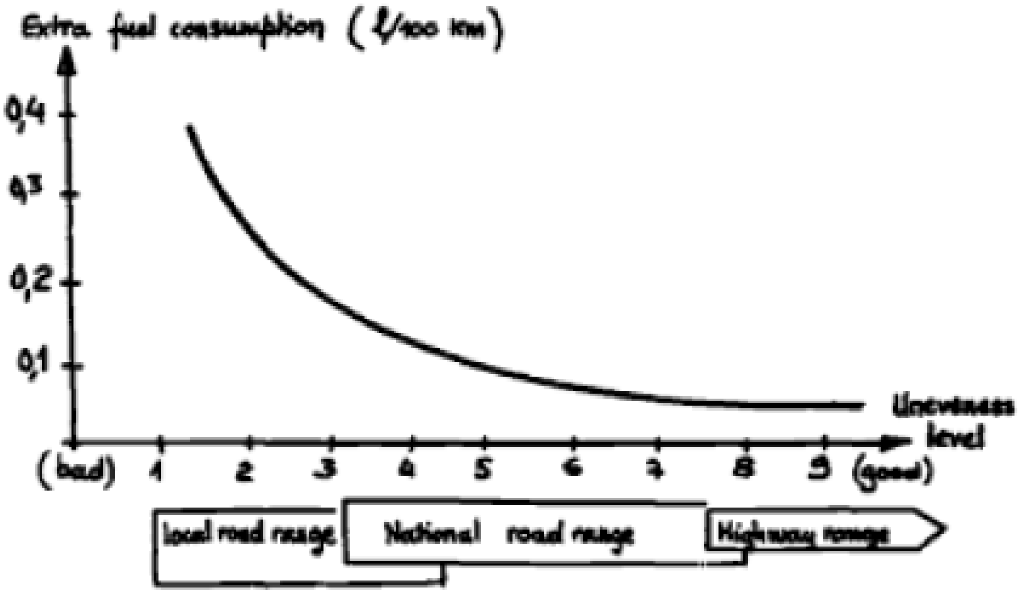


FIGURE 5 Extra fuel consumption, open-road test: effect of unevenness level, for mixed three-wavelength ranges using the longitudinal profile analyzer (17)

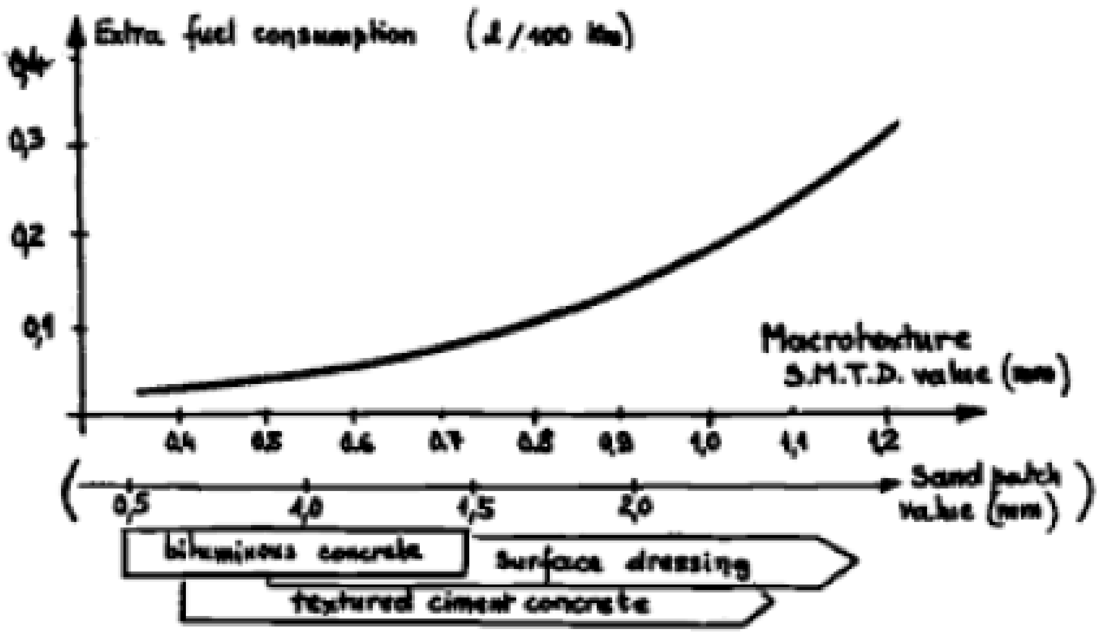


FIGURE 6 Extra fuel consumption, open-road test: effect of macrotexture level (standard shape) (standard mean texture depth) (17)

2.10 "Road Macro- and Megatexture Influence on Fuel Consumption" by U.S.I. Sandberg in ASTM STP 1031, 1990 (18).

METHOD

SCOPE

T S

Sandberg conducted vehicle fuel economy studies on 20 different road surfaces that had different textures (18). He conducted the testing at 50, 60, and 70 km/h. These surfaces ranged from standard asphalt mixtures to chip seals and unpaved roads. Texture and unevenness were measured using a laser profilometer attached to a Volvo 242 passenger car. The data for each speed were averaged and compared to the profile textures.

Sandberg concluded that fuel consumption could vary by 11 percent from the smoothest to roughest road, comparing textures on a 0.6 to 3.5 m wavelength (L_{SU}) (i.e., megatexture and roughness) (Figure 7). If the 2 to 50 mm (L_{MA}) wavelength was considered, texture could cause a 7 percent change in fuel consumption. The correlations were strong (R^2 = 0.90) (Figure 8) when wavelengths greater than 0.6 m were compared; however, the correlation was not as strong below 0.6 m wavelengths, showing that macrotexture was not as influential as megatexture and unevenness.

The results of the study demonstrate that road surface quality has a great impact on fuel consumption, and the largest potential for improvements can come from controlling megatexture and roughness. Macrotexture was only important when cars were traveling greater than 60 km/h. The roughness of the road could affect fuel consumption by up to 12 percent for the large range of smoothness values tested and texture could affect fuel consumption by 7% when comparing a rough macrotexture to a smooth macrotexture.

Limitations: Concrete was not tested as part of the project scope. Additionally, the units used for texture are no longer commonly used today.

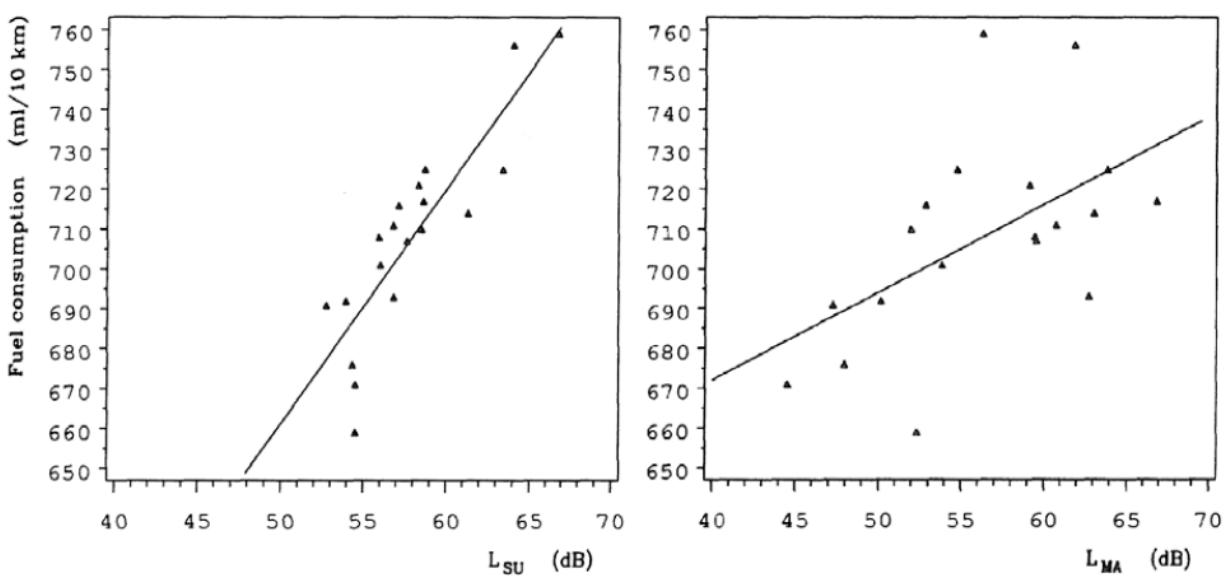


FIGURE 7 Effect of texture and roughness on fuel consumption (18)

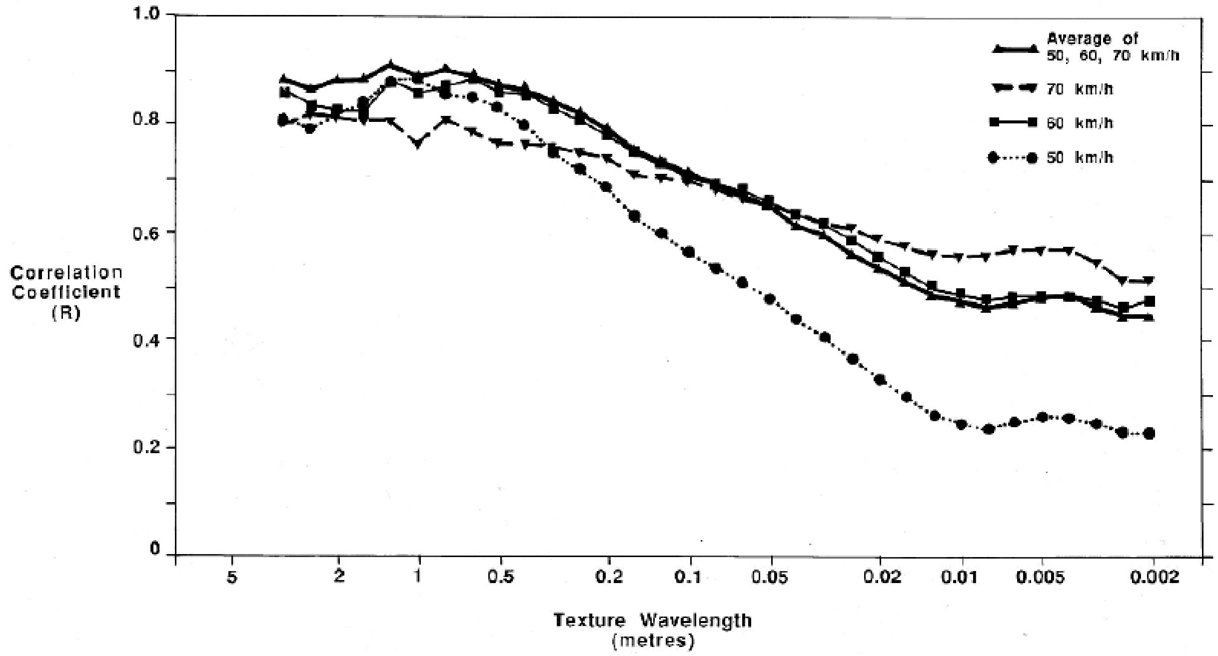


FIGURE 8 Fuel consumption versus road texture levels (18)

2.11 "Road-surface Influence on Tire Rolling Resistance" by G. Descornet in ASTM STP 1031, 1990 (19).

METHOD

SCOPE

T

Using a Belgian Road Research Centre rolling resistance trailer and a profilometer for texture and unevenness, Descornet measured the effect of megatexture, and macrotexture on rolling resistance using a patternless Michelin SB 14-inch tire. This testing was conducted on 37 different test sections, which included all the common pavement types in Belgium. The figure does have an error in the rolling resistance coefficient (C_R), which should be 0.0021. This suggests that the rolling resistance coefficient increases by 0.0021 for each millimeter of texture. The study concluded that megatexture was the most influential property, but one should also realize that macrotexture was important when disregarding sections that were transversely grooved. The combination of mega- and macrotexture could influence rolling resistance by almost 47 percent, which could then save 9 percent on fuel consumption.

Limitations: No statistical analyses were conducted in this analysis.

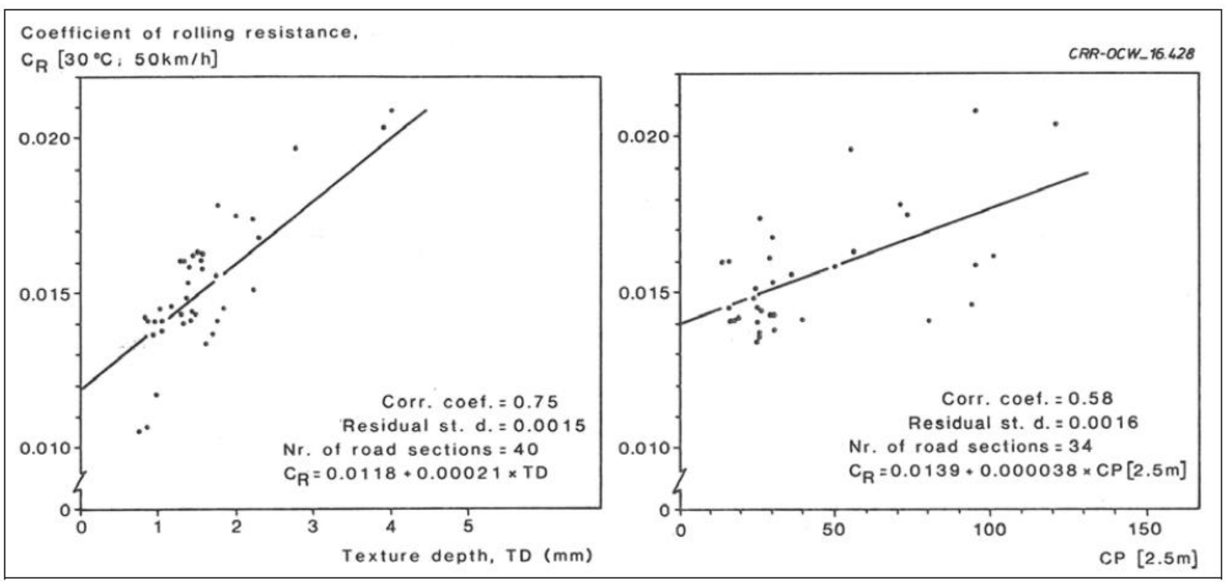


FIGURE 9 Relationship between C_R and (mean) texture depth (at the left) and between C_R and roughness amplitude at 2.5 m texture wavelength (at the right) (19)

2.12 "Fuel Consumption of Vehicles as Affected by Road-Surface Characteristics" by H.W. du Plessis, A.T. Visser, and P.C. Curtayne in ASTM STP 1301, 1990 (20).

METHOD

SCOPE

T S

The research team developed a comprehensive experiment to investigate the effect of road-surface conditions and characteristics on fuel consumption for South African settings using a passenger car, two medium-sized trucks, and two buses using coast-down tests. This experiment was designed to assess rolling resistance over a series of roads and pavement conditions common to the local environment.

Using 77 observations on 26 different test sections, the research team discovered that increases in tire temperature, decreases in road roughness, and textural decreases all decrease the rolling resistance of the pavement for passenger cars.

When compiling all of the data, they drew conclusions that given a level road, road-surface properties might increase rolling resistance by up to 7 percent at 100 km/h for passenger cars (Figure 10). For medium trucks and busses, the road roughness and tire pressure are significant in assessing rolling resistance (Table 2).

Limitations: No statistical analyses were completed in this study.

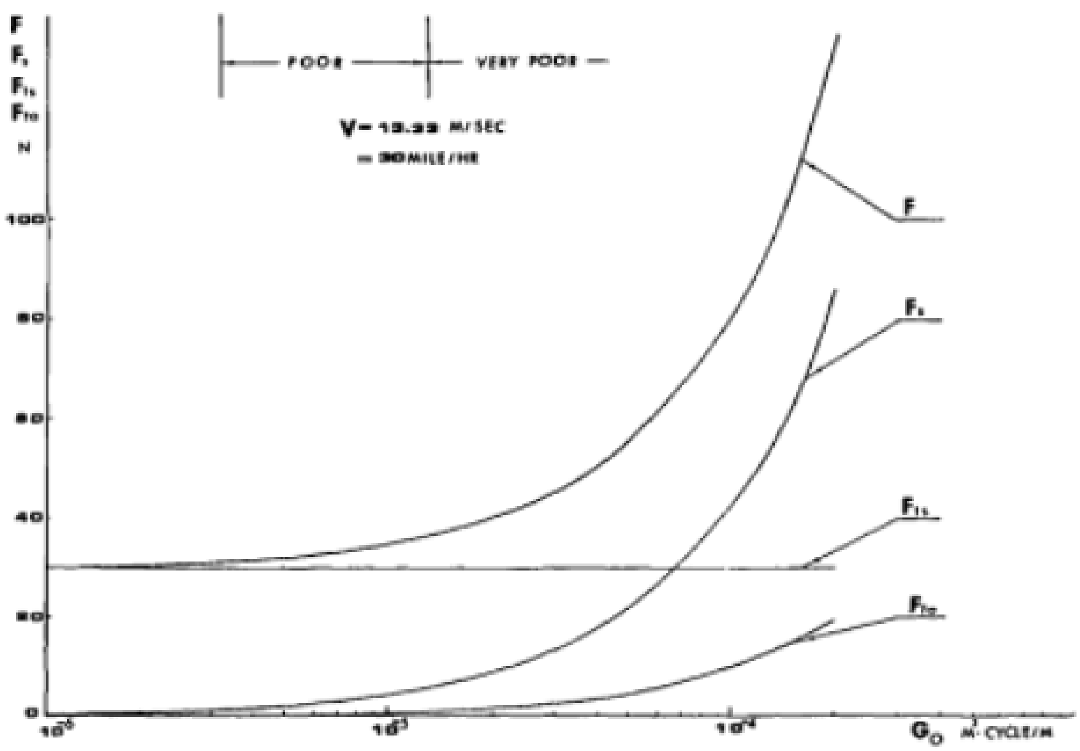


FIGURE 10 Rolling resistance versus the road roughness coefficient (20)

TABLE 2 Calculated value of the vehicular rolling resistance force rate for different levels of road roughness (20)

Road Class	Geometric Mean of $s_z(\gamma_0)$	G_0, m^2 cycle/m	F, N	Rate, %
Very good	4	0.101×10^{-6}	298	…
Good	16	0.405×10^{-6}	300	100
Average	64	0.162×10^{-5}	306	102
Poor	256	0.640×10^{-5}	331	110
Very poor	1024	0.259×10^{-4}	434	145

2.13 "The Influence of Pavement Evenness and Macrotexture on Fuel Consumption" by Y. Delanne in ASTM STP 1225, 1994 (21).

METHOD

SCOPE

T S

This paper assessed how pavement smoothness and macrotexture affect the fuel consumption of light vehicles on paved roads. Practical tests were carried out at the Nantes Test Track and by Michelin in France using hydraulic bench tests, test track measurements on rolling resistance, and fuel consumption measurements on approximately 10 different sections of roads. The relationships (Figures 11–13) developed between these pavement properties and fuel consumption showed that increasing both texture and unevenness could exponentially increase vehicle fuel consumption. The pavements with the most texture were either surface dressings or textured concrete pavements. One might see as much as a 50 percent increase in rolling resistance for an additional 1.5 mm of texture. Specifically, up to a 6 percent increase in car fuel consumption can be caused by smoothness and 5 percent by macrotexture standard mean texture depth (S.M.T.D) (0.5 to 2.5 mm).

Limitations: No statistical analyses were given in the analysis.

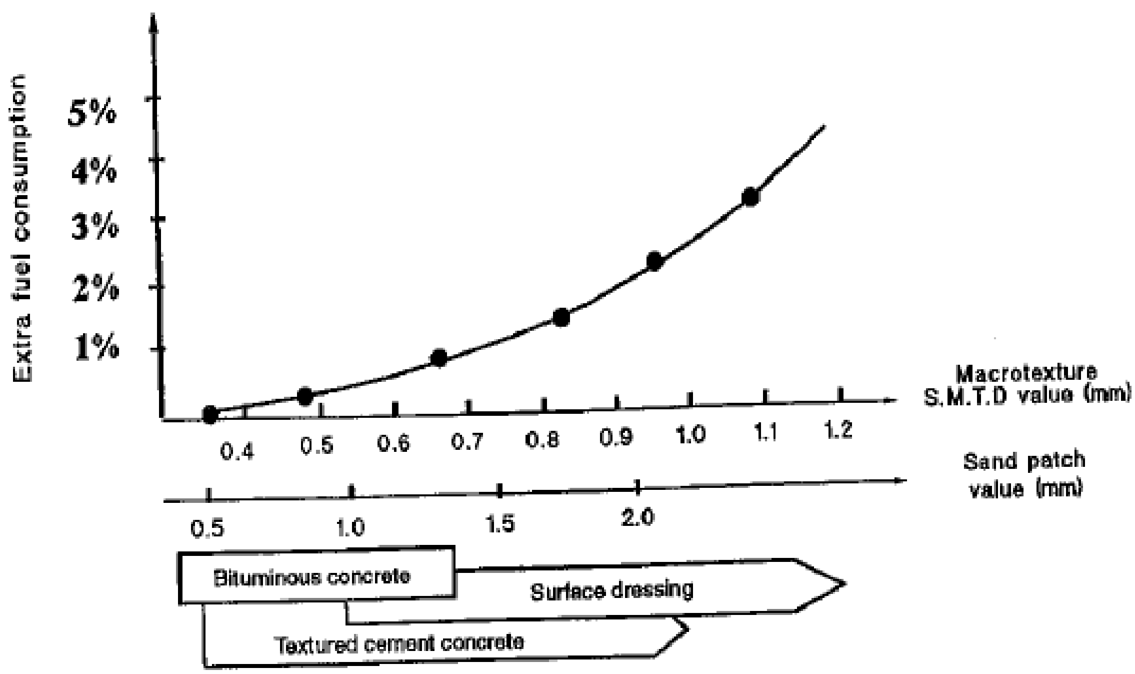


FIGURE 11 Texture and extra fuel consumption (21)

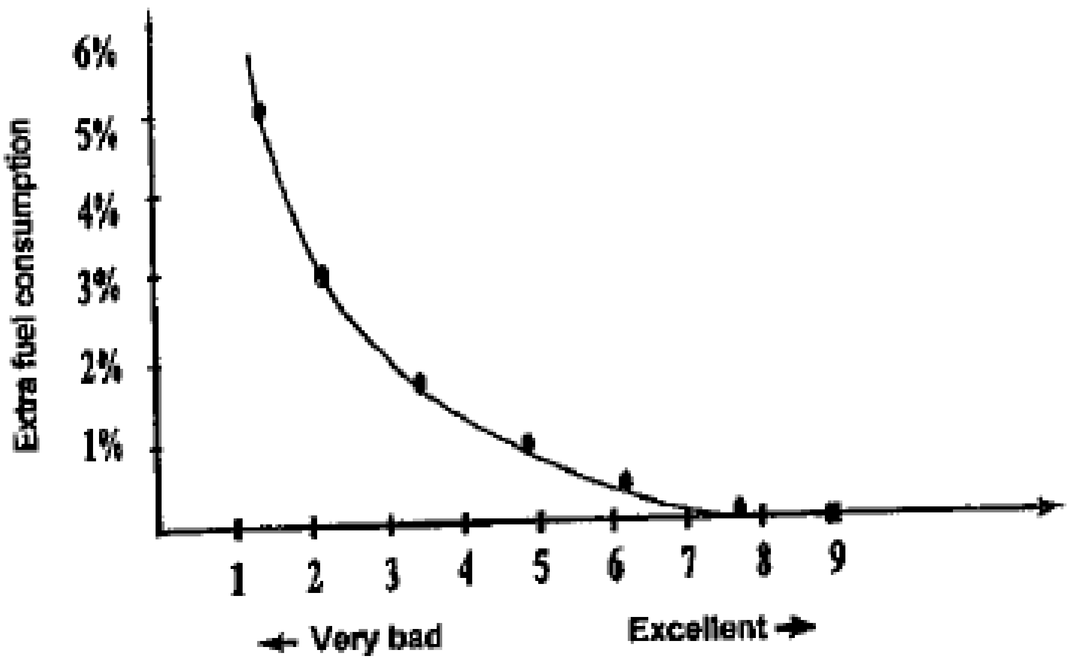


FIGURE 12 Unevenness and extra fuel consumption (22)

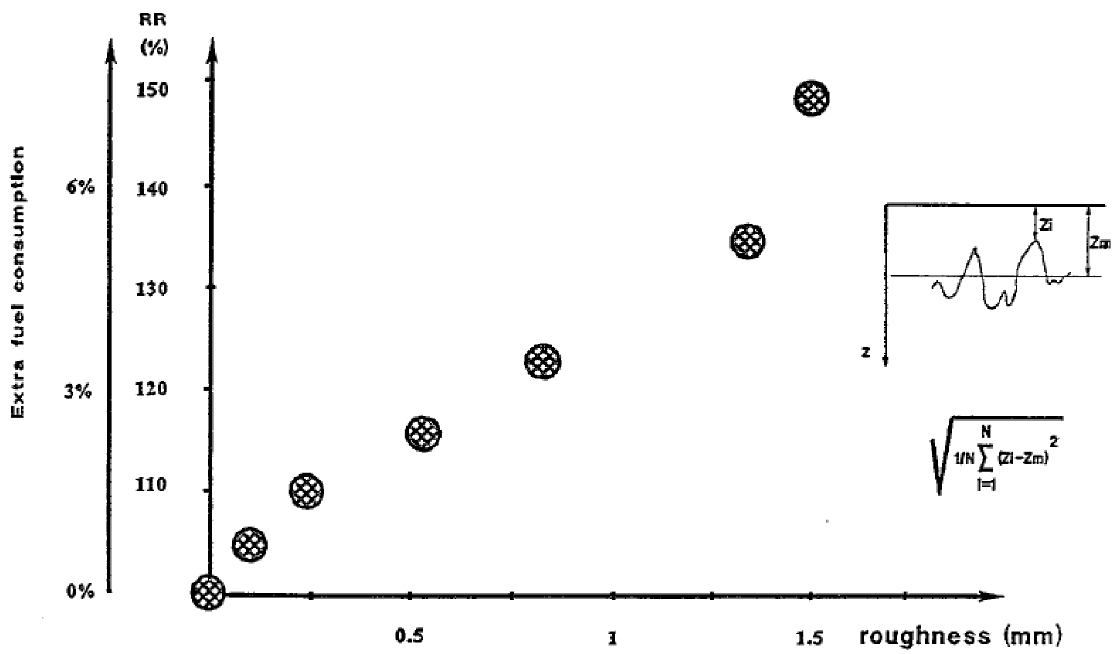


FIGURE 13 Roughness and extra fuel consumption (22)

2.14 "Rolling Resistance Characteristics of New Zealand Road Surfaces" by P.D. Cenek in ASTM STP 1225, 1994 (23).

METHOD

SCOPE

T S

The steady state torque method of measuring rolling resistance was developed in New Zealand in the 1980s and 1990s. The methodology for conducting this test involved driving a car at a constant speed of either 20 or 75 km/h. While driving, the torque of one tire, wind speed, and direction were measured. In addition to measuring torque, suspension losses, which affect rolling resistance, were also quantified.

Using these measurements, Cenek found a 55 percent difference in the rolling resistance of the best and worst pavements. Texture values and smoothness values ranged from 0.6 to 2.7 mm and 1.4 and 2.3 m/km. After developing an equation that assessed change in rolling resistance due to texture (Figure 14) and smoothness, he calculated that increasing 1 mm of texture could increase rolling resistance by 44 percent when the smoothness was 1 m/km; however, the equation was not linear in nature and a 2 mm increase in texture was even more drastic. If one assumed the texture of the pavement was 1 mm, changing the smoothness of the pavement from 0.5 to 2.5 m/km would result in an 18 percent increase in rolling resistance. This shows that neither smoothness nor texture should be ignored in the analysis of rolling resistance.

Limitations: The pavement structures were not characterized in this analysis.

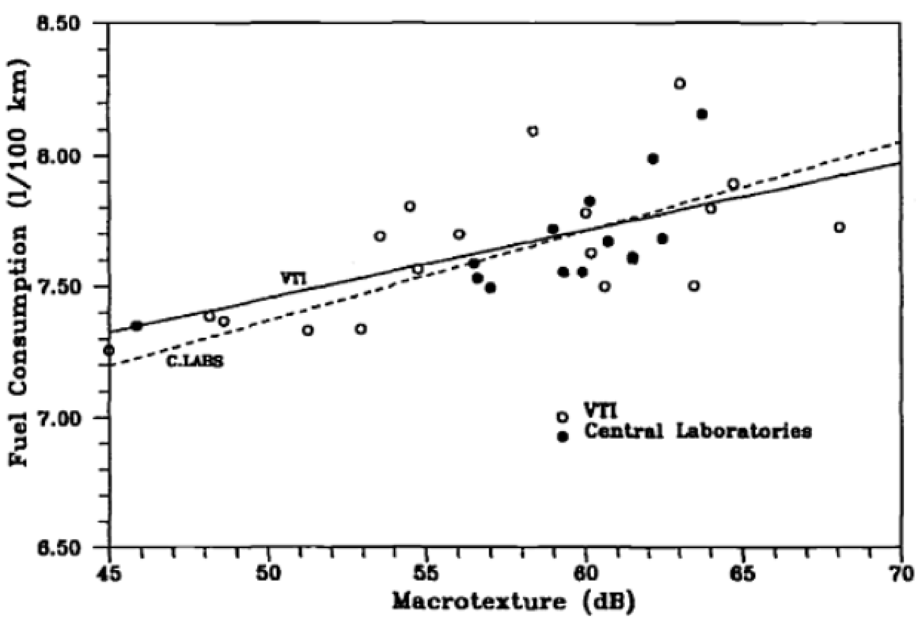


FIGURE 14 Macrotexture versus fuel consumption (23)

2.15 "Rolweerstand van ZOAB — een pilotstudie" (Dutch Report: Rolling Resistance of Porous Asphalt — A Pilot Study) by D.F. de Graaff, Report No. M+P.MVM.97.2.1 rev. 2, M+P, 1999 (24).

METHOD

SCOPE

T P

A fully fueled and instrumented Volvo V70 car with two passengers traveled 90 km/h over test sections. The fuel consumption of the vehicle on each pavement type was then correlated back to a dense-graded mixture (Table 3). This study showed that there were little to no statistical differences between porous and dense-graded mixtures, as the positive effects of texture could be completely dissipated by other negative pavement properties. In addition to assessing differences in texture, there were statistically no differences between the rolling resistance of concrete and asphalt pavements. It is important to understand that this limited study was conducted using passenger cars instead of heavily loaded vehicles.

Limitations: No structural characterization was completed on these pavements.

TABLE 3 Fuel consumption at 90 km/h on different types of road pavement relative to dense asphalt concrete 0/16 (24)

Road Surface Type	Fuel Consumption Relative to Dense Asphalt Concrete 0/16, %
Dense asphalt concrete 0/16	0
Porous asphalt 6/16	- 0.0 (±3.5)
Stone mastic asphalt 0/16	+3.4 (±3.6)
Double-layered porous asphalt 4/8 + 11/16*	+1.2 (±3.3)
Cement concrete, broomed transversely	+0.4 (±3.4)
Cement concrete treated with a surface epoxy durop	+2.7 (±4.5)
Brick-layered pavement	+5.3 (±6.6)

***new road surface bitumen still present**

2.16 “Effects of Pavement Surface Type on Vehicle Fuel Consumption — Phase II: Seasonal Tests” by G.W. Taylor, P. Marsh, and E. Oxelgren, 2000 (25) & “Additional Analysis of the Effect of Pavement Structure on Fuel Consumption” by G.W. Taylor, P. Farrel, and A. Woodside, 2002 (26).

METHOD

SCOPE

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The National Research Council of Canada’s Centre for Surface Transportation Technology conducted an experiment to assess the effect of pavement structure on fuel consumption using heavy trucks. The overall aim of the study was to assess how factors such as pavement structure, roughness, vehicle speed, vehicle configuration, vehicle load, and ambient air temperature affected fuel consumption.

The scope of this research used two concrete pavements, three asphalt pavements, and one composite pavement. Each pavement was trafficked by three types of trucks (tractor semitrailer, straight truck with tandem rear axle, and a B-train). The study suggested that there was as much as 11 percent higher fuel consumption on Ontario Highway 417’s asphalt pavement compared to Québec Autoroute 440’s concrete pavement at different vehicle speeds for a semi-trailer.

> Commentary: One should note that inconsistencies in the trends on the other pavements and load conditions were observed, but the causes of these inconsistencies were not identified by the authors.

G.W. Taylor Consulting conducted additional statistical analyses in 2002 to correct the range of fuel consumption differences to 4.1–4.9 percent on asphalt compared to 11 percent in the previous study. The overall conclusions again suggested that concrete was more fuel efficient than asphalt; however, upon further evaluation of the data, only one asphalt pavement of the three had higher fuel consumption than concrete pavements. This pavement averaged between 4 and 7 percent greater fuel consumption. In addition, it was only in the case where the loading was completed with a semitrailer that this increase in fuel consumption was noticed.

> Limitations: Differences in surface roughness, short pavement test sections, and differences in air temperatures plagued the validity of these statistical results. Little pavement characterization in terms of structure and texture was included in the study.

2.17 "VEROAD® Calculations. Maximum Energy Dissipation When Driving on Asphalt Pavement Versus Driving on Rigid Cement Concrete" by Netherlands Pavement Consultants, 2002 (27).

METHOD

SCOPE

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In 2002, Netherlands Pavement Consultants published a report citing the theoretical maximum energy dissipations which can occur when driving on asphalt pavements compared to concrete using VEROAD® Visco-Elastic ROad Analysis Delft software. Using average seasonal air temperatures to determine pavement temperature and pavement material properties from laboratory studies, two different loadings (100 and 130 kN) were applied with 0.75 MPa of pressure at either 50 or 80 km/h. The outputs of this modeling exercise were energy per dual-tire wheel per meter of road, energy per axle per 100 km of road, energy per vehicle per 100 km of road, and fuel per vehicle per 100 km. The results are given in Table 4. The average fuel consumption differences between asphalt pavements in the spring and fall was modeled to be 0.16 percent. In the summer, this was approximately 0.88 percent. Using these simulations, they concluded that the energy dissipation from the pavement might cost the user 0.05 percent additional fuel per year driving on asphalt compared to concrete.

> Limitations: The pavements were only modeled for the summer and spring conditions. Additional modeling should have been completed to fully characterize seasonal changes.

TABLE 4 Calculation of dissipated energy in asphalt pavement due to its viscous behavior (27)

Time of Year	Axle Load, kN	Speed, km/h	Energy per dual tyre wheel per meter of road, J/m	Energy per axle per 100 km of road, MJ	Energy per vehicle per 100 km of road, MJ	Fuel per vehicle per 100 km (14 MJ/l), l
Summer	100	50	5.21	1.04	3.34	0.24
Summer	100	80	3.52	0.70	2.25	0.16
Summer	130	50	6.96	1.39	4.46	0.32
Summer	130	50	6.96	1.39	4.46	0.32
Spring	130	50	1.27	0.25	0.81	0.06
Spring	130	80	0.93	0.19	0.60	0.04

2.18 "Effect of Road Roughness on the Vehicle Ride Comfort and Rolling Resistance" by A.M.A. Soliman, SAE Technical Paper, 2006 (28).

METHOD

SCOPE

In 2006, Soliman conducted a study to assess the effect of road roughness on rider comfort and rolling resistance (28). Using a quarter car model, if one assumes the vehicle is a rigid body with the mass of the wheel concentrated in its center, no slippage occurs between the tire and pavement. If the road is rigid, one can assume the relationship between rolling resistance is linear with vehicle speed.

Two typical roads were chosen to model the effects of ride on rolling resistance. Using the quarter car model coupled with rolling resistance models, it was shown that rolling resistance increases as roughness increases. An average of 38.7 percent difference was seen between the rolling resistances of the smoothest and roughest roads in the study (Figure 15). A more common comparison of a good to a rough road would show almost a 12 percent difference in rolling resistance. These values were all modeled at 10 m/s. When vehicle speeds were increased from 10 to 15 m/s, the rolling resistance coefficients increased by 11 percent, showing that roughness is even more important when a vehicle is traveling at highway speeds (Table 5).

Limitations: Only two roads were used in the modeling effort.

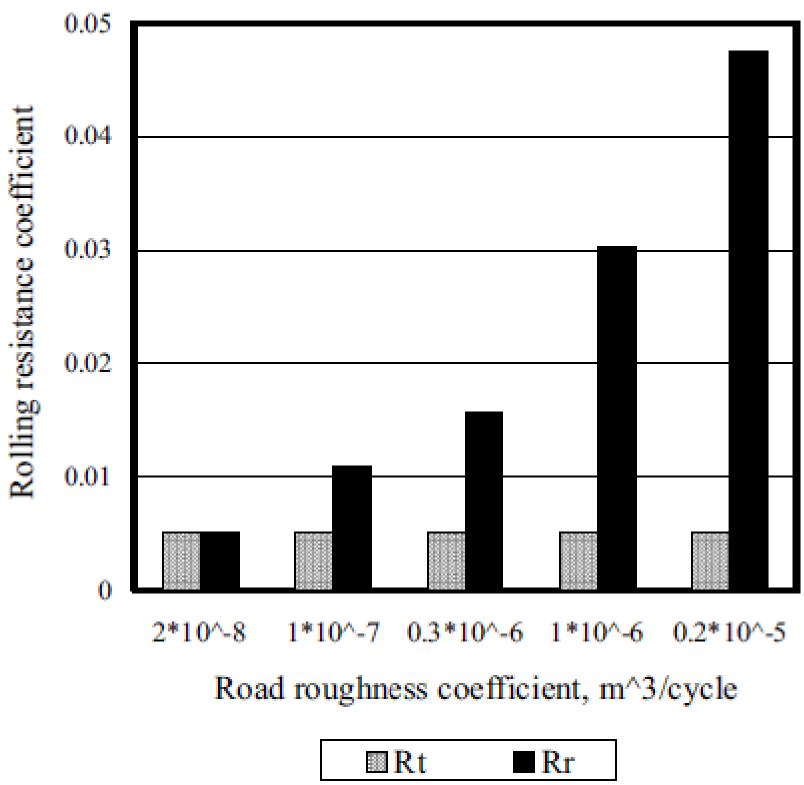

FIGURE 15 Effect of road roughness coefficient on vehicular rolling resistance force (28)

TABLE 5 Rate of rolling resistance force for different road roughness (28)

Road Class	R_c, m^3/cycle	F, N	Rate, %
Minor road	3×10^{-6}	297.2	100.00
Rough road surface	0.2×10^{-5}	332.6	111.90
Roughest road surface	0.8×10^{-5}	412.3	138.70

2.19 "Pavement Smoothness and Fuel Efficiency: An Analysis of the Economic Dimensions of the Missouri Smooth Road Initiative" by D. Amos, 2006 (29).

METHOD

SCOPE

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As part of its smooth ride initiative, the Missouri Department of Transportation conducted a study that compared the differences in dump truck fuel economy on a pavement before and after it was resurfaced. Four dump trucks were used as a substitute for 18-wheel tractor-trailers on a 22-mile loop of I-70 in Lafayette County, Missouri. Each vehicle traveled more than 2,000 miles on the test loop at approximately 60 mph before pavement resurfacing to assess fuel economy. After the resurfacing project was completed, the fleet of trucks made the loop again to see how fuel consumption changed.

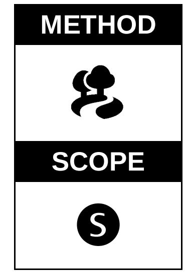
An Automated Road Analyzer (ARAN) van was used to measure pavement smoothness as IRI. An IRI of 130 in/mile was measured before resurfacing. Resurfacing the roadway reduced the IRI to 60 in/mile (Figures 16 and 17). This improvement in fuel consumption resulted in a 2.46 percent improvement in the fuel economy for the dump trucks.

> Limitations: Only drumptrucks were used in this study, and no statistical analyses were conducted.

FIGURE 16 Interstate 70 pavements before and after pavement resurfacing (29)

FIGURE 17 Close-up of pavements before and after resurfacing (29)

2.20 "NCAT Fuel Economy Research Overview" by M. Heffernan, Master of Science thesis, Auburn University, 2006 (30).



During the initial 2000 NCAT Pavement Test Track cycle, fuel consumption of the pavements were measured over a two-year period. As the asphalt became rougher (i.e., a higher IRI), the fuel economy of the vehicles on the track decreased (Figure 18). This trend was noticed along a limited IRI range of about 65 to 75 in/mile. The basic trend showed an increase in fuel economy of over 0.5 miles per gallon by just increasing the smoothness of the road by 10 in/mile. This common trend was seen throughout the Test Track cycle.

> Limitations: Very unique truck trafficking was used for this study. Additionally, all the test sections on the 2000 Test Track were more than 20 inches thick. Therefore, limited pavement structures were available.

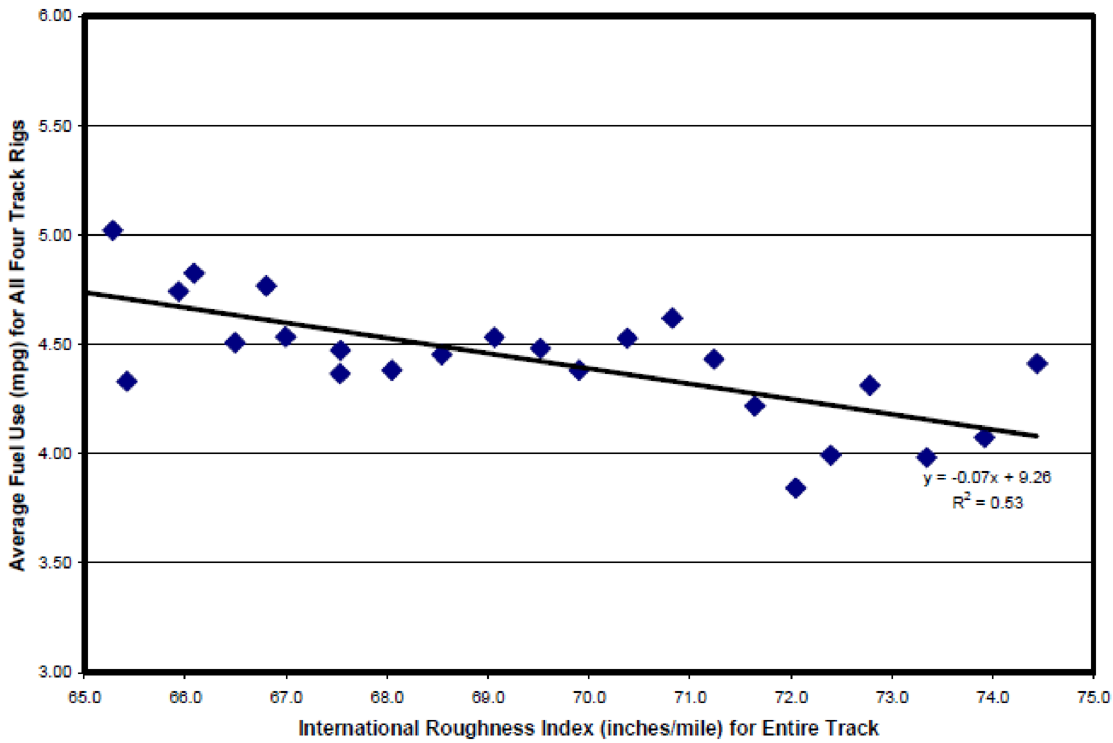


FIGURE 18 IRI versus fuel economy (30)

2.21 "Effects of Pavement Structure on Vehicle Fuel Consumption — Phase III" by G.W. Taylor and J.D. Patten, 2006 (31).

METHOD

SCOPE

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In 2006, Taylor & Patten conducted a study to assess the effect of pavement structure on vehicle fuel consumption. A highway tractor with a tandem drive pulling a van semitrailer was driven over concrete, asphalt, and composite paved roads to detect if fuel savings could be attributed to pavement surfaces. These tests were conducted in winter, spring, summer night, summer day, and fall at 60 km/h and 100 km/h using three different weights in the trucks on open roads in Ontario and Québec. All the roads used in this study were in good condition and surface wear, tining, friction, and cross-section irregularities were not considered. All pavements with an IRI greater than 1.6 m/km were removed from the analysis.

The study found that on smooth roads at 100 km/h, concrete roads reduced fuel consumption between 0.8 and 1.8 percent. These differences were statistically significant for all seasons except for summer nights, where the differences were only 0.4 percent. The report shows multiple results for concrete versus asphalt pavements for a fully loaded truck at 60 km/h; however, both sets of results suggest concrete to be more efficient. In addition to cruising tests, coast-down tests from 30 to 10 km/h were used to assess differences in fuel efficiency of pavement types. These tests showed no difference between the asphalt and concrete pavements.

> Limitations: One limitation of this study is a lack of information as to the complete structure and stiffness of the pavements during testing. The influence of the smoothness was also marginalized because all the roads were in good condition.

2.22 "Mätning av bränsleförbrukning på asfalt- och betongbeläggning norr om Uppsala" (Swedish Report: Measurement of Fuel Consumption on Asphalt and Concrete Pavements North of Uppsala) by P. Jonsson, and B.-Å Hultqvist, Swedish National Road and Transport Research Institute (VTI), 2008 (32).

METHOD

SCOPE

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The Swedish National Road and Transport Research Institute (VTI) was commissioned to investigate the difference between asphalt and concrete pavements in relationship to fuel consumption. These measurements were taken on a section of road north of Uppsala, Sweden, where both pavement types were located. Before testing, the methodology was calibrated and showed differences between concrete and asphalt pavements using a Volvo 942. The vehicle recorded time, speed, road distance, fuel consumption, and fuel temperature. The vehicle weight was also kept constant between the test sections by keeping the same driver and a full gas tank.

The research team discovered during the pilot study that measurements needed to be kept on stretches of road less than 1 km, as traffic levels affected the fuel consumption. Properties of the four pavements are shown in Table 6. The texture on the asphalt pavement is representative of a stone-matrix asphalt (SMA) pavement.

TABLE 6 Surface characteristics (32)

Parameter	Concrete North	Concrete South	Asphalt North	Asphalt South
Rut depth (mm)	2.4	2.6	3.2	3.1
IRI (mm/m)	1.22	1.17	0.79	0.67
MPD (mm)	0.48	0.51	0.99	0.86
Gradient (%)	-0.27	+0.43	-0.28	+0.44

When comparing fuel consumption of the asphalt to concrete pavement, there was 1.1 percent less fuel consumed on the concrete road. A 95 percent confidence interval showed the range would fall between 1.7 and 0.5 percent. The average results are provided below (Table 7). When looking at the measured fuel consumption and comparing it to the VETO fuel model commonly used in the Nordic countries, concrete had about 1 percent less fuel consumed than asphalt pavements (Table 8).

TABLE 7 Average fuel consumption (32)

Fuel Consumption	Asphalt	Concrete
Average (g/m)	0.0597	0.0591
Standard Deviation	0.0039	0.0041
Average (l/10 km)	0.807	0.798

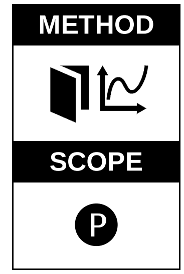
TABLE 8 Measured and calculated fuel consumption (32)

Fuel Consumption	Concrete North	Concrete South	Asphalt North	Asphalt South
Actual (l/10 km)	0.747	0.849	0.757	0.857
Calculated VETO (l/10 km)	0.758	0.825	0.772	0.862

The study also assessed how the pavements would be affected by using a heavy vehicle that weighed about 60 tons at a constant speed of 80 km/h. These results showed that the asphalt pavement consumed approximately 0.290 liters per 10 km more than concrete pavements. These tests were conducted on a hot summer day. The results showed that fuel consumption increased when both headwind increased and the surface temperature of the asphalt mixture increased.

> Limitations: The asphalt mixtures had double the texture and more rutting on the pavement. The wind could have been an issue during testing.

2.23 “Roads and Energy: How Pavements Can Affect Vehicle Fuel Consumption” by A. Perriot, Colas Group, 2008 (33).



This report is a critical review of existing literature claiming that less fuel consumption is incurred on portland cement concrete pavements than asphalt concrete pavements.

Perriot identifies four factors that influence rolling resistance:

1) “Energy dissipation through friction between the tire and pavement”
2) “Energy dissipation caused by deformation of the tire”
3) “Energy dissipation due to the shock absorbers”
4) “Dissipation as a result of the viscoelasticity of the pavement”

Furthermore, Perriot identifies two categories for pavement properties that are responsible for dissipation: surface characteristics (due to friction and deformation of the tire and shock absorbers) and structural properties (due to viscoelastic dissipation in the pavement). Perriot acknowledges the difficulty in evaluating the influence of these factors:

- There are parameters of the pavement such as the surface texture or mechanical properties that cannot be selected in advance. This makes it difficult “to decouple the effects of the different parameters in a systematic way.”
- Rolling resistance is not dependent on pavement alone, but rather is also affected by vehicle parameters (tires, load, and shock absorbers).

Literature pertaining to the influence of surface state on rolling resistance was reviewed, as well as the influence of pavement nature. Perriot summarizes the influence of surface state based on previous literature, stating “surface properties, from megatexture to evenness, play a major role in vehicle fuel consumption and can lead to difference of roughly 10 percent (17, 18, 19).” Perriot notes that although the role of macrotexture has not been as well established, the effect may lead to changes in fuel consumption of less than 5 percent based on work by Laganier & Lucas (17), as well as Sandberg (18).

In reviewing previous literature on the influence of pavement nature, Perriot categorizes it by viscoelastic dissipation, structure stiffness and the average excess consumption of a bituminous pavement. The following is a summary of Perriot’s discussion on the influence of these three categories of pavement nature.

<u>Viscoelastic Dissipation</u>: The author identifies four studies that the concrete industry used to support their claims of rigid pavements resulting in a reduction in fuel consumption of 15 percent (reported in (33) and summarized in (34)) and provides a critical review, summarized herein. In the first study (35) it was reported that changing from an AC to PCC pavement resulted in a 20 percent increase in fuel consumption for a given truck. However, as Perriot points out, the same author reported in a study published the following year (36) that fuel consumption differences between sections of concrete and bituminous pavements were not statistically significant: “Measurements were taken on PCC, AC, ST, and gravel sections to

determine if surface type had an influence on fuel consumption. […] In general, there were no statistically significant differences at 95 percent level between fuel consumption on the paved sections." Perriot points out that in the second study (24), which was conducted in three phases, reported in phase two that fuel consumption of a loaded semitrailer could be 11 percent higher on AC than on PCC pavements. However, as Perriot reports, a joint study by the Asphalt Institute and Ontario Hot Mix Producers Association (37) showed that the AC pavement used in phase two had a surface state in much worse condition and therefore introduced bias. In phase three, a reduction in fuel consumption of 0.8 to 1.8 percent was reported for concrete roads versus asphalt (30). As reported by Perriot, in his summary of the phase three report, it is concluded that the differences between phases two and three "stem primarily from the collected data themselves." The third study cited by the concrete industry was an Indian study (38) "that appears to be unobtainable." The fourth study (39) utilizes data from the first two studies (16, 24). A theoretical study (37) reported results that agree with the results from (30) that appear to be obtained from reliable measurements. As Perriot reports, the theoretical study reported an increase in fuel consumption on AC pavements in summer conditions due to viscoelastic dissipation is of the order of 0.88 percent, consistent with phase three of the Canadian study (30).

<u>Structure stiffness</u>: Perriot argues that the common belief that vehicular loss of energy due to greater deflections in asphalt pavements is invalid. Rather, Perriot makes the case that the dissipation of energy is due to the viscoelasticity of bituminous pavements rather than their compliance. This indicates that the only effect of compliance is the influence on tire-pavement contact area, such as the more flexible the pavement, the larger the contact area and more energy dissipated in the tire. The author examines this relationship and concludes "the greater flexibility of bituminous mixes leads to virtually no difference in the dimensions of the contact area. This effect is therefore negligible."

<u>Evaluation of the order of magnitude of the average excess consumption on AC</u>: Perriot looks at the effect of higher fuel consumption on AC pavements on a broader scale by pointing out that the four aforementioned studies looked at the excess consumption for trucks, which only make up approximately 15 percent of the traffic mix. In applying the worst-case scenario (0.88 percent excess fuel consumption in summer conditions (30)) and assuming a sedan weighs 32 times less than the vehicles used in the previous study (30), the author determines that the "relative excess fuel consumption due to the use of bituminous materials as being of the order of 0.004 percent." Furthermore, considering the proportion of trucks in the traffic mix and the different fuel consumption of trucks and light vehicles, the author states, "considering the mean consumption of traffic on the road, an increase of 0.48 percent in fuel consumption" is due to the use of bituminous mixes. The author also states that this effect is "much less than that brought about by a reduction in the quality of evenness (18)."

The author closes this critical review by stating: "It seems that in order to limit the rolling resistance of a pavement we should target the quality of small wavelength evenness rather than engage in more dubious speculation about the nature or stiffness of pavement materials."

2.24 "Numerical Simulation of the Influence of Pavement Stiffness on Energy Dissipation" by T. Lu, N.H. Thom, and T. Parry in *Proceedings of the International Conference on Computing in Civil and Building Engineering*, 2010 (40).

METHOD

SCOPE

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In 2010, Lu et al. conducted a study for the International Conference on Computing in Civil Engineering and Building Engineering. The University of Nottingham in the United Kingdom used a 3D Finite Element (FE) model to simulate energy dissipation between tires and the pavement. This methodology allowed the research team to assess how speed, tire loading, and pavement stiffness all affected energy dissipation. Using the ABAQUS FE modeling package, a 26-meter-long and 10-meter-deep pavement was created. These parameters allowed the rolling tire and pavement to be in a fairly steady-state condition at speeds up to 130 km/h.

When changing the stiffness of the pavement between 1,000 and 11,000 MPa, it was determined that the stiffness of the pavement was influential on energy dissipation. Using a 16-ton vehicle with four single rolling tires, this would result in about a 0.12 percent loss of kinetic energy per kilometer. This is relatively small, and the researchers suggested this would be relatively minor compared to potential gains from engine efficiency, aerodynamics, or tire design. However, they still suggested that this should be included in modeling. The researchers concluded that stiffness was important if the modulus of the pavement fell below 3,000 MPa.

> Limitations: One should note that the study was limited to only assessing how one pavement property affects rolling resistance. Pavement thickness, texture, and smoothness were not included in the study to determine if stiffness was a primary or secondary effect based on this type of modeling.

2.25 "Energy Reduction in the Road Infrastructure Network as a Function of Roads Functional and Structural Conditions" by P. Ullidtz, B. Schmidt, and O. Neilsen, in *Proceedings of the 16th International Road Federation World Meeting*, 2010 (41).

METHOD

SCOPE

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NCC Roads initiated a research project to evaluate the importance of structural pavement characteristics on energy consumption. To assess this, energy losses under a heavy falling weight deflectometer (FWD) were evaluated using a hysteresis loop, as shown in Figure 19.

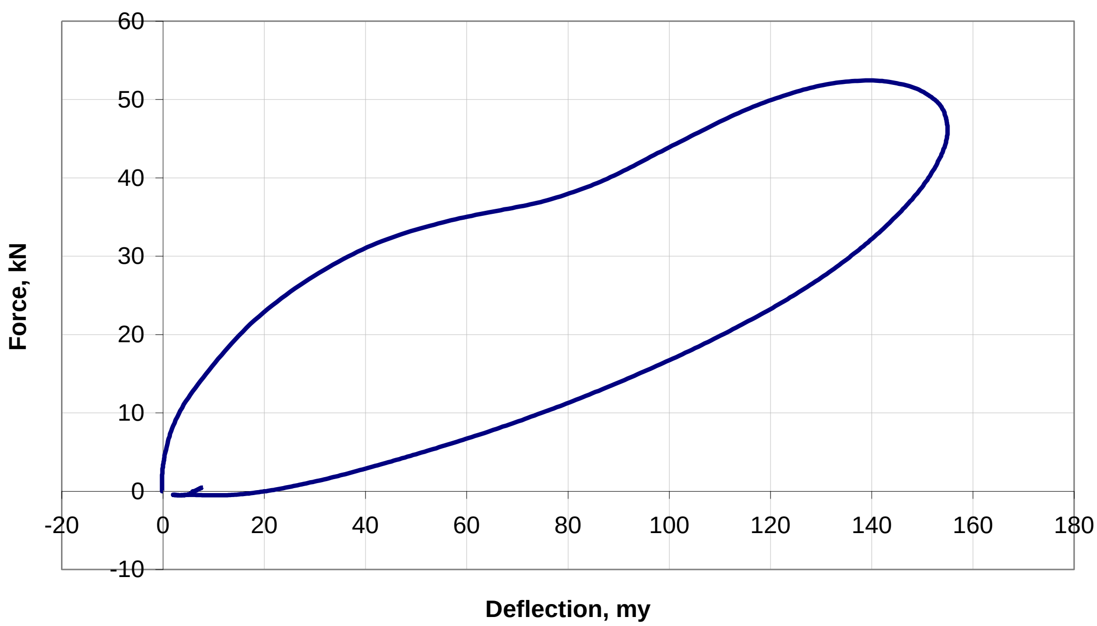

FIGURE 19 Hysteresis curve (41)

FWD testing was conducted on a normal highway pavement, two high-modulus asphalt pavements, and a pavement with a cement-treated base layer using three drop heights which correlate to 30, 50 and 70 kN. No further details regarding pavement structure or properties were given. While the research team admitted it was impossible to translate energy loss from an FWD to rolling resistance of a moving wheel, an upper limit could be obtained by distributing the loss over the diameter of the plate. The rolling resistance might then be between 70 and 80 percent of that upper limit. This study suggested that the rolling resistance might be 35 percent less using a cement-treated base compared to a normal asphalt pavement (Table 9).

TABLE 9 Energy loss measured with FWD on four pavements (41)

Section	δ (50 kN)	Energy loss (J)	Rolling resistance (N)	Coefficient
HM2	150	4.2	14.0	0.000280
HM1	183	4.7	15.5	0.000310
CTB	140	3.6	12.2	0.000243
Normal	233	5.7	18.9	0.000378

After conducting the tests using a FWD, the rolling resistance was measured using two different tires on the equipment from the Technical University of Gdańsk (TUG) at speeds of 50 and 80 km/h. Rolling resistance was higher by 2 to 10 percent at higher speeds. It was also found that the total coefficient of rolling resistance decreased with increasing contribution from the deflection (Figure 20). For example, the cement-treated base (CTB) section had the lowest deflection, but the highest rolling resistance.

The mean pavement depth or texture was also measured and correlated to rolling resistance, showing that an increase of 0.5 mm of textures would increase the rolling resistance by about 10 percent (Figure 21). Overall, the research saw that the deflection of the pavement affected the rolling resistance of trucks by at most 4 percent and even less for passenger cars.

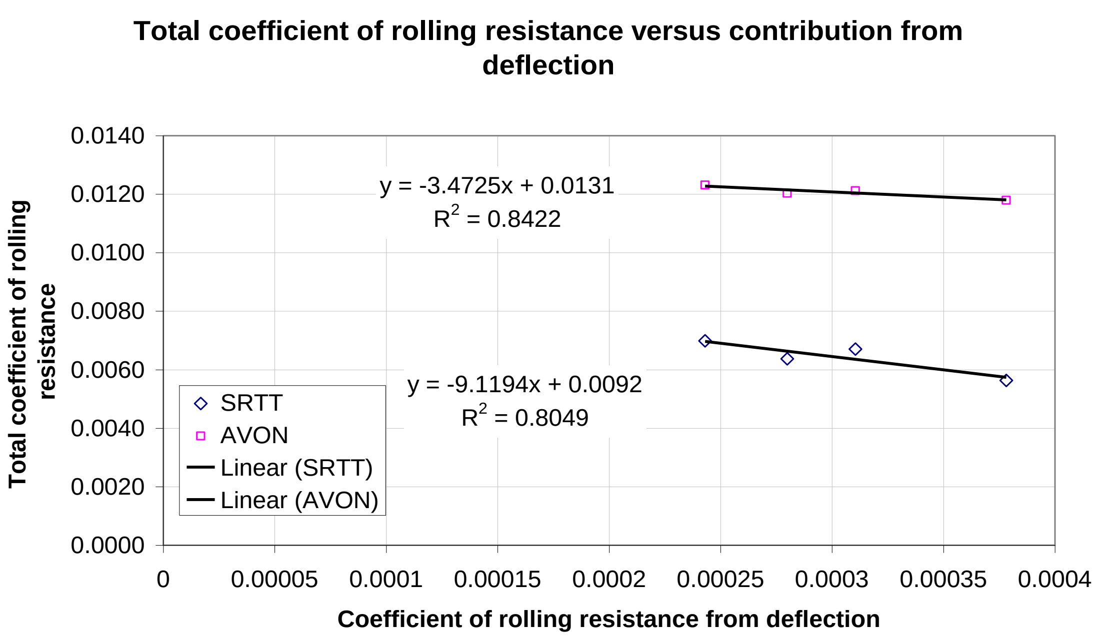

FIGURE 20 Relations between total coefficient of rolling resistance and contribution from deflection (41)

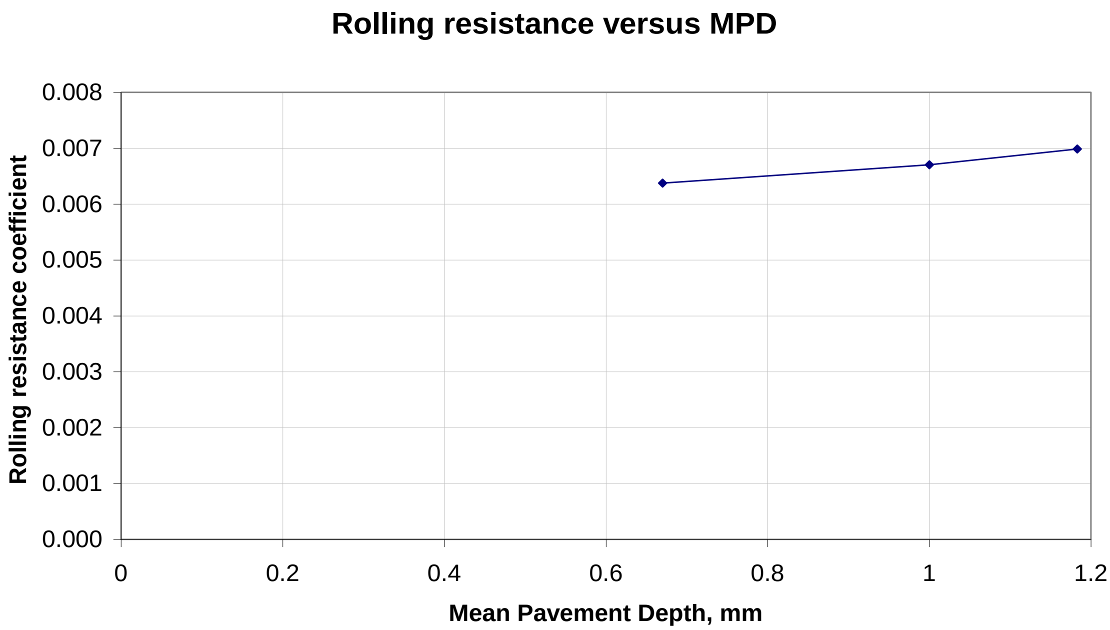

FIGURE 21 Increase in rolling resistance with increase in Mean Pavement Depth (MPD) (41)

Limitations: This study was conducted with limited data, and the model is yet to be verified in the field. While texture was captured in the pavement, little data are provided related to the pavement structures used in the study.

2.26 "Fuel Consumption Due to Pavement Deflection Under Load" by N.H. Thom, T. Lu, and T. Parry in *Proceedings of 2nd International Conference on Sustainable Construction Materials and Technologies*, 2010 (42).

METHOD

SCOPE

P

This study assessed how pavement stiffness affected vehicle fuel consumption by using a 3D finite element analysis to model a pavement 10 meters deep using viscoelastic boundary elements as shown in Figure 22. The model was validated using falling weight deflectometer (FWD) data. Despite the differences between FWD loading and moving wheel loading, this allowed the research team to assess the ability of the model to deal with inertial effects of loading the pavement.

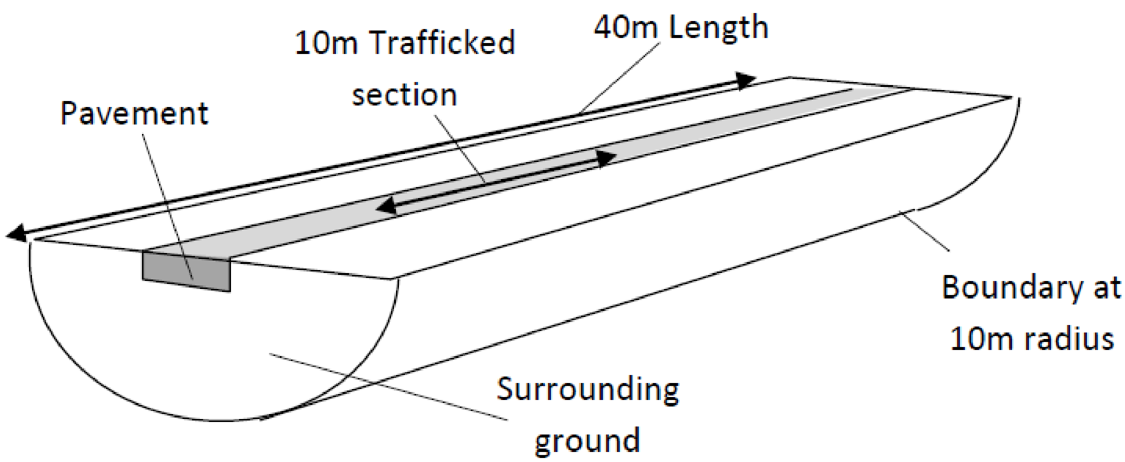

FIGURE 22 Finite element model (42)

The simulated pavement had four layers of 140, 200, and 300 mm thickness, respectively, while the fourth layer was infinite in its thickness. Layers two and three had stiffness values of 7,000 MPa and 2,400 MPa, representing strong and weak cement bound layers. The upper layer varied between 1,500 and 110,000 MPa, which could account for changes in temperature or material quality. The fourth layer ranged from 20 to 150 MPa to account for variability in material quality.

Figure 23 shows the effects of material stiffness on a 40 kN vehicle traveling 90 km/h. As can be seen, the subgrade effect was secondary. The surface stiffness showed large proportional differences between energy losses due to pavement stiffness; however, the true total affect is dependent upon traffic level.

> Limitations: This research noted that only pavement deflection was considered and tire deflection, tire contact area due to tread, and pavement texture may have, at the least, equal influence.

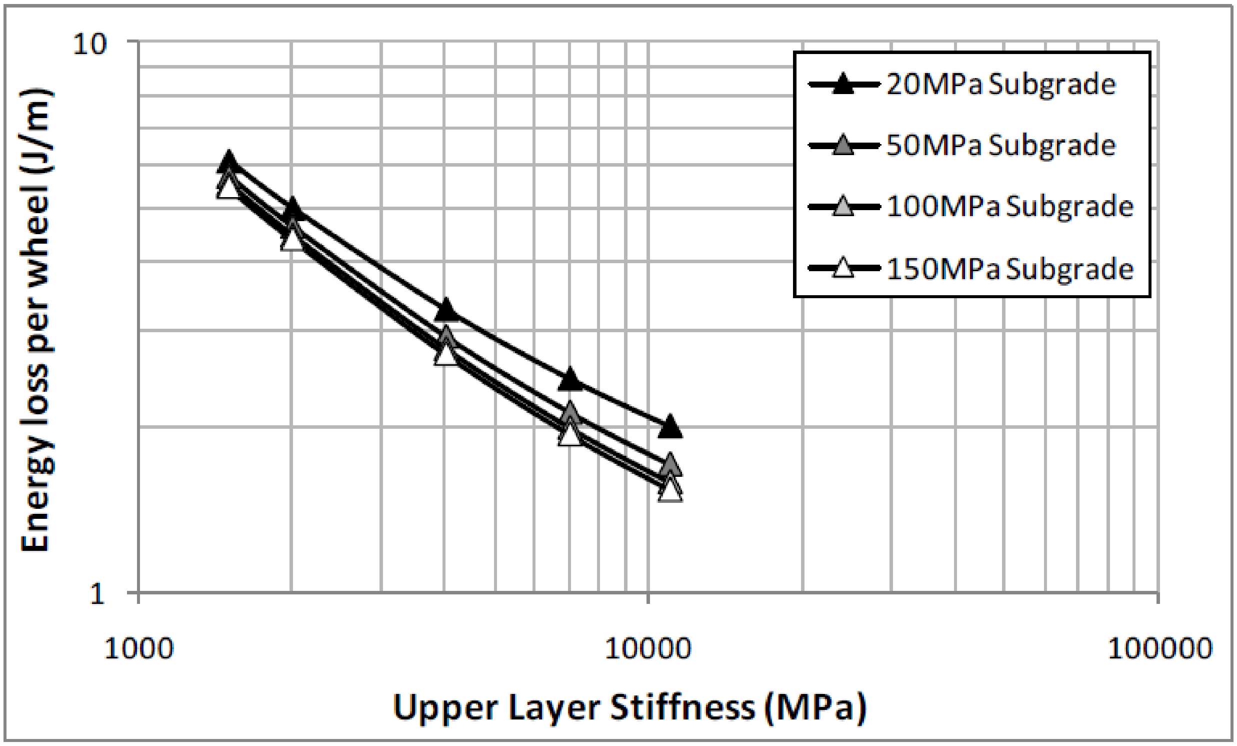

FIGURE 23 Stiffness versus energy loss (42)

2.27 "Effect of Pavement Type on Fuel Consumption and Emissions" by P. Sumitsawan, S.A. Ardekani, and S. Romanoschi in *Proceedings of the 2009 Mid-Continent Transportation Research Symposium*, 2009 (43).

METHOD

SCOPE

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The goal of this study was to investigate the effect of pavement type on fuel consumption and emissions. Its emphasis was on urban driving cycles at non-highway speeds, as more than half of vehicular fuel consumption in the United States is due to urban driving. If significant differences in fuel consumption and emissions rates were to be observed across various pavement surface types, they may result in substantial differences in the total energy consumption and carbon footprints during the design life of roadway facilities. As such, those differences should be considered in life-cycle cost analyses of alternative pavement designs.

In achieving the research objectives, fuel consumption measurements were made using an instrumented vehicle driven over two types of pavement surfaces (PCC and AC) under two driving modes (constant speed and acceleration) (Table 10). In order to isolate the effect of pavement type on fuel consumption, attempts were made to either control or record all other key variables that might influence fuel consumption. These included vehicle weight, tire pressure, wind speed and direction, ambient temperature, atmospheric pressure, humidity, elevation, roadway gradient and curvature, and smoothness The two sections selected had similar geometric characteristics and differed only in the type of pavement. One should note that while the pavements had similar IRI values; both values were fairly high for new pavements. The PCC pavement had an IRI of 174.6 in/mile while the asphalt pavement had an IRI of 180.6 in/mile. No notation of the pavement structure is given in the article.

TABLE 10 Average fuel consumption rates for PCC versus AC sections (43)

Pavement	Average Fuel Consumption (10^{-3} gal/mile)	Testing Parameters
PCC, Constant speed	40.7	Date: 11/7/2008
		Temp: 69 °F
AC, Constant speed	42.7	Wind: 7 mph W (tailwind)
		Engine: Warm
PCC, Acceleration	236.4	Tire Pressure: 50 psi
		Tank Level: Full
AC, Acceleration	236.9	IRI (in/mi): 174.6 (PCC) 180.6 (AC)
		Longitudinal Slope: +1.2%

It was determined statistically that concrete had a greater fuel economy at 30 mph at the 10 percent level of significance; however, there was no statistical difference in the acceleration mode.

Limitations: All the differences are attributed to differences between concrete and asphalt; however, the total pavement structure is not considered. Stiffness and structure are both part of pavement deflection, and this is not addressed.

2.28 "Road Surface Influence on Tyre/Road Rolling Resistance" by U. Sandberg, A. Bergiers, J.A. Ejsmont, L. Goubert, R. Karlsson, and M. Zöller, Report MIRIAM_SP1_04, Swedish National Road and Transport Research Institute (VTI), 2011 (44).

METHOD

SCOPE

T

The Technical University of Gdańsk measured the rolling resistance of multiple road surfaces in Sweden and Denmark over five years using the TUG trailer. Table 11 presents the pavement surfaces assessed. Age and condition of the pavements varied within the project. The macrotexture (MPD) data were plotted against rolling resistance in this study as regression diagrams for testing conducted at 80 km/h (Figure 24). One should note that the exposed aggregate cement concrete (EACC) pavement falls on the same trend line for rolling resistance as the asphalt pavements. This suggests there might not be difference related to pavement type in rolling resistance. These early measurements were made before TUG had fitted an enclosure around the test tire to eliminate air-flow resistance.

TABLE 11 Pavement types tested (44)

11	Dense asphalt concrete, max aggr. sizes 6, 8, 11, 16 mm
9	SMA (stone matrix asphalt), max aggr. sizes 6, 8, 11, 16 mm
1	Hot rolled asphalt (HRA), UK type, max aggr. size 16 mm
3	Dense-graded asphalt rubber (Arizona type adapted in Sweden). Max aggr. size 11, 16 mm
1	Open-graded asphalt rubber (Arizona type adapted to Sweden), max aggr. size 11 mm
3	Porous asphalt concrete, single-layer, max aggr. size in top layer 8, 11 mm
3	Porous asphalt concrete, double-layer, max aggr. sizes in top layer 8, 11 mm
2	Chip seals (surface dressings), single layer, max. aggr. size 11 mm
6	Thin asphalt layers (dense), max aggr. sizes 6, 8, 16 mm
1	Exposed aggregate cement concrete, max aggr. size 16 mm
1	SMA, max aggr. size 16 mm, medium texture but very uneven

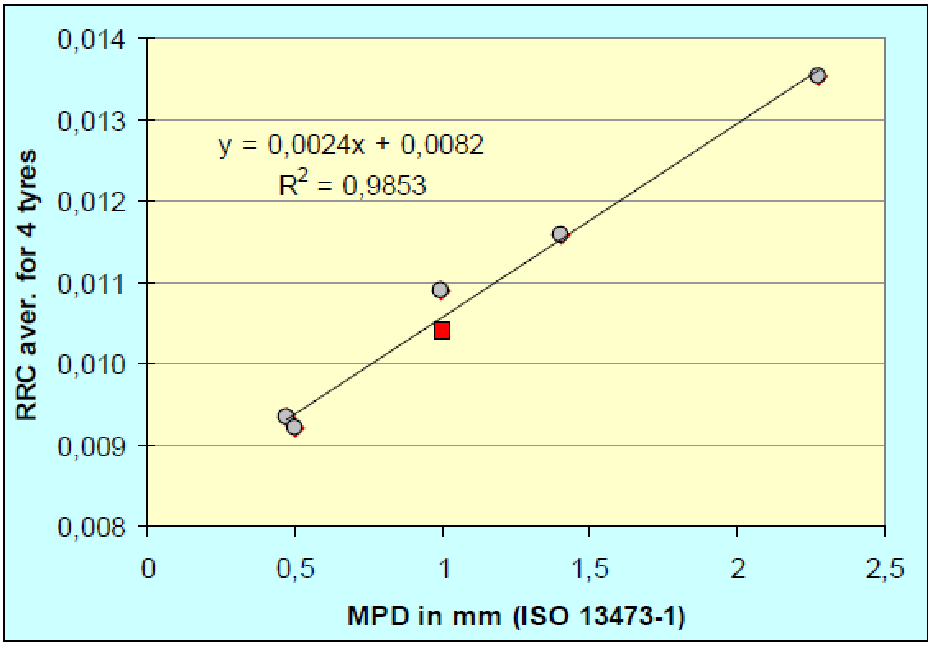


FIGURE 24 Rolling resistance coefficient plotted against macrotexture (MPD) for measurements 2005 and 2007. The round (grey) symbols are for dense asphalt, and SMA pavements and an extremely rough-textured chip seal (the highest point); while the square (red) symbol is for an EACC (cement concrete). (44).

Additional testing was conducted from 2009–2010 using the enclosed tire. Testing was conducted at both 50 and 80 km/h, and speed did not greatly affect the results. The lack of correlation seen in this figure is relative to the time when measurements were taken. Differences in temperature, tire pressure, and tire temperatures made a difference in the rolling resistance coefficient. When the measurement series were considered, the relationships between texture and rolling resistance were more aligned (Figure 25–26).

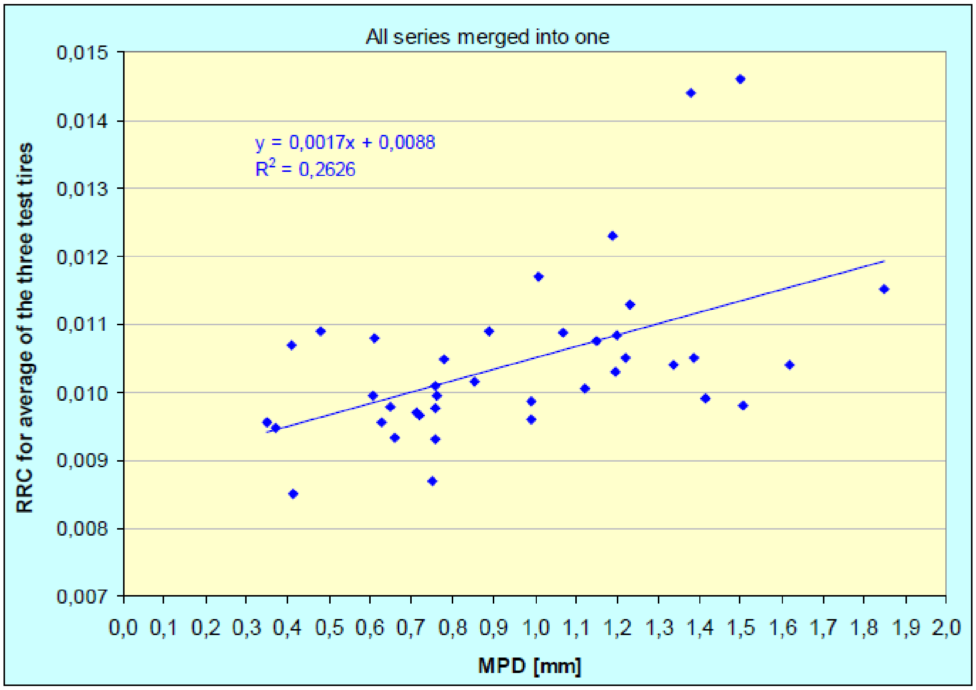


FIGURE 25 Rolling resistance coefficient plotted against macrotexture (MPD) for measurements 2005 and 2007. The round (gray) symbols are for dense asphalt, and SMA pavements and extremely rough-textured chip seal, while the square (red) symbol is for an EACC for all data (44).

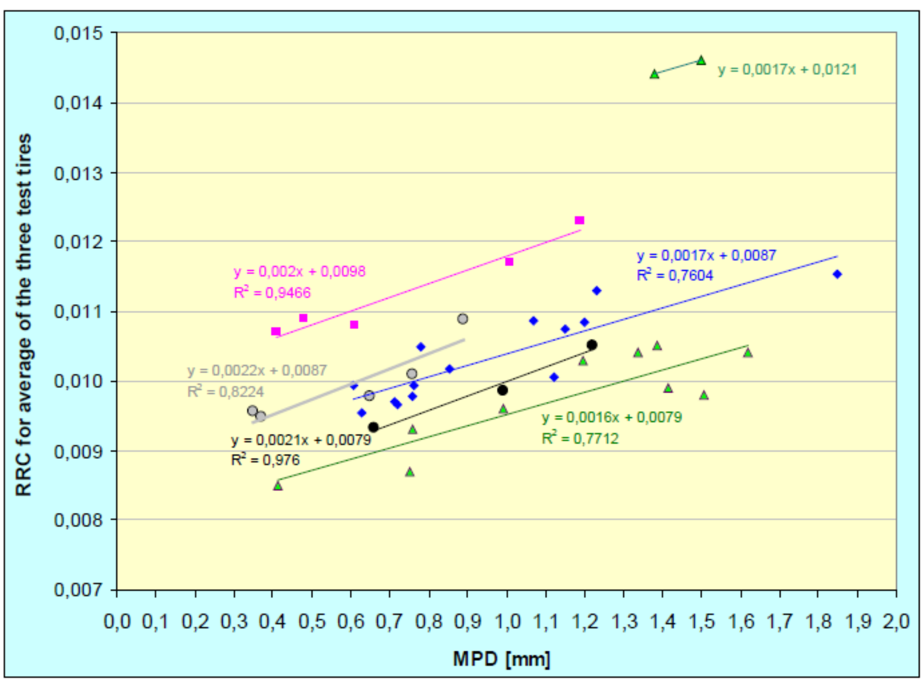


FIGURE 26 Rolling resistance coefficient (RRC) plotted against macrotexture (MPD) for measurements 2009 and 2010 (44)

Previously, Sandberg suggested that pavement stiffness cannot be excluded as an important factor in rolling resistance and should be included as part of the Models for rolling resistance in Road Infrastructure Asset Management systems (MIRIAM) Project. However, it was still unknown as to what extent stiffness should be considered. In 2011, a TUG trailer was used to measure 1 km of a concrete and asphalt road in Sweden. The asphalt pavement was an SMA. Both mixtures used a 16 mm stone and were approximately four years old. Table 12 provides the rolling resistance data. It seems the concrete pavement had slightly less rolling resistance for the three tires; however, this is due to lower texture and not stiffness.

TABLE 12 Comparison between a cement and a stone mastic asphalt surface (44)

Tested Surface	Average RRC for the three tyres	MPD (mm)	IRI m/km
EACC 0/16	0.00130	0.55	1.2
SMA 0/16	0.0135	0.80	0.7

MIRIAM also conducted round robin tests to assess the repeatability of rolling resistance devices, correlation between devices, and influence of texture and tire type on rolling resistance. For this report, relationship between texture and rolling resistance will only be considered. After testing pavements with the TUG, the most important texture range for rolling resistance was between 20 to 500 mm, which included all of the megatexture range and the rougher macrotexture. Below 20 mm, the data are not valid due to the enveloping procedure used to analyze the data (Figure 27).

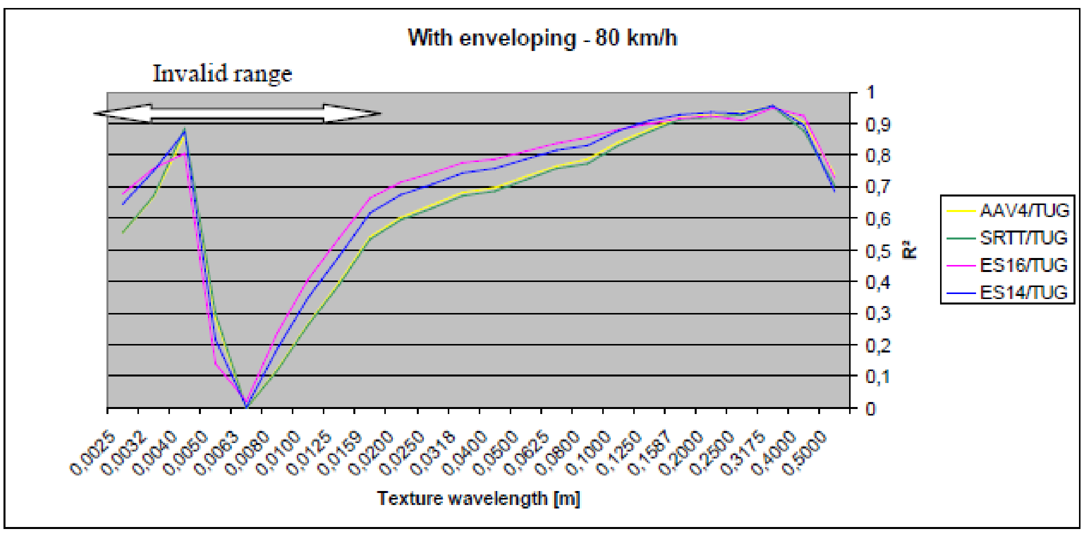


FIGURE 27 Texture wavelength versus fit with enveloping at 80 km/h (44)

An example of the correlations between texture and rolling resistance is given in Figure 28 using a standard tire. It appears that despite only having one data point with a high texture value, the correlations between texture and rolling resistance were strong.

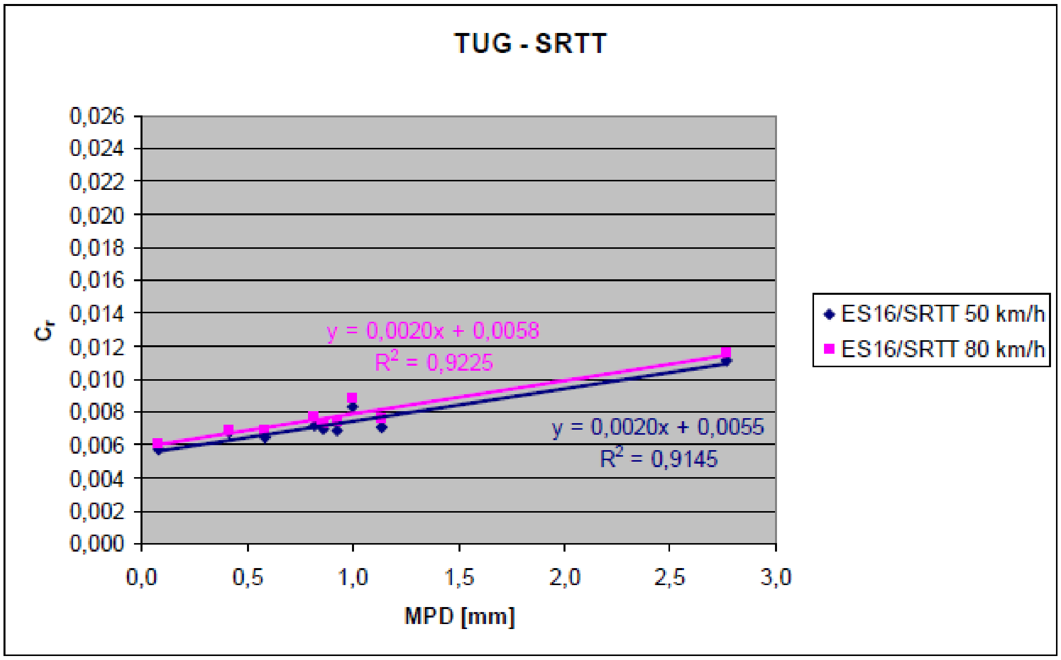


FIGURE 28 Correlation between MPD and C_R, for the TUG/SRTT tire (no enveloping) (44)

Limitations: Did not assess how stiffness or pavement type affected rolling resistance beyond the one exposed aggregate cement concrete section.

2.29 “A Field Investigation of the Effect of Pavement Surface Conditions on Fuel Consumption” by I. Zaabar and K. Chatti in *Proceedings of the TRB 90th Annual Meeting,* 2011 (45) & *NCHRP Report 720: Estimating the Effects of Pavement Condition on Vehicle Operating Costs* by K. Chatti and I. Zaabar, 2012 (46).

METHOD

SCOPE

T S P

Five different vehicles were used in this study to assess fuel consumption relative to pavement type, vehicle speed, road roughness, and surface texture. Only flat and smooth pavement sections were used in order to determine the direct effect of pavement surface texture and type on fuel consumption. Five different locations in Michigan were selected for testing with a medium car, SUV, van, light truck and (articulated) heavy truck. However, it is unclear if a 2005 9200 6×4 International tandem-axle tractor with a flatbed is truly representative of all heavy trucks. Fuel consumption was measured as testing was conducted in winter (wet conditions) and summer (dry conditions) and at three speeds (35, 45 and 55 mph). Five sections each of asphalt concrete (AC) and portland cement concrete (PCC) pavements were identified for testing, although it is not stated what type of PCC pavements (jointed plain concrete pavement, continuously reinforced concrete pavement, etc.) were included. Raw profile and texture data were collected by the Michigan Department of Transportation. The IRI on these pavements ranged between 0.8 and 6.0 m/km for AC pavements and 0.8 and 2.5 m/km for PCC pavements, while the texture ranged from 0.23 mm to 1.96 on the AC pavements and 0.23 to 2.7 mm on PCC pavements.

Using an analysis of covariance (ANCOVA), the authors estimated the effect of roughness on fuel consumption, as well as the effect of surface texture on fuel consumption. A regression and lack of fit analysis were conducted to determine the effect of surface texture on fuel consumption. The authors summarized that grade and IRI were each statistically significant and although surface texture was found to be statistically significant at 35 mph, it was not statistically significant at 45 and 55 mph.

To determine the effect of pavement type on fuel consumption, the authors took a subset of the data that was tested on sections considered to be smooth and flat. The selected roadway sections were further divided into 100-foot subsections from which 138 subsections were selected that met the following criteria: IRI of 1m/km ±10 percent; mean profile depth of 0.5 ±20 percent; and slope in the range of ±0.1 percent. The selected 100-foot subsections were then grouped by pavement type (AC or PCC). A univariate analysis with IRI as the covariate and pavement as a fixed factor was conducted for the data from all five vehicles at three speeds. Based on this analysis, the authors reported that for both light and heavy trucks in summer conditions, the mean difference between asphalt and concrete pavements is statistically significant at 35 mph, although at higher speeds (45 and 55 mph) it was not found to be statistically significant. For winter conditions the authors reported that the “mean difference of fuel consumption between asphalt and concrete pavements is statistically not significant.” It was concluded that differences in fuel consumption were statistically significant for loaded light and heavy trucks at low speeds (35 mph) and summer conditions, and that under these conditions, trucks driven over AC pavements will consume about 4 percent more fuel than when driven over PCC pavements.

> Limitations: The approach of selecting 100-foot sections of pavement that were considered smooth (1 m/km±10 percent), resulting in 138 sections, seems valid as it attempts to hold many known variables constant. The downside is that it is unclear how many of these 138 sections were AC and how many were PCC. Given that the AC pavements selected as a whole had higher IRI than the PCC pavements, the selection process may have resulted in less available AC sections for the analysis.
>
> It is noted that "fuel consumption for heavy trucks in winter was not available," thus, conclusions were drawn by evaluating pavements in the worst-case scenario for AC (summer, heavy loading, and slow speed (56 km/h)). This is acknowledged, however increased deflections in AC pavements in the summer is named as the culprit:
>
>> "For winter conditions, the mean difference of fuel consumption between asphalt and concrete pavements is statistically not significant. However, it should be noted that heavy (articulated) truck was only tested in summer. These observations could be explained by the viscoelastic behavior of asphalt pavement. Since in summer AC pavements are more viscous, trucks will cause more deflection on flexible pavements than on rigid pavements. Therefore, trucks need more power to overcome the traction caused by the deflected pavement; thus, more fuel is required to drive on flexible pavements. However, in winter, the power required to overcome the deflected AC pavement will be similar to rigid pavements."

2.30 ***Model Based Pavement-Vehicle Interaction Simulation for Life Cycle Assessment of Pavements* by M. Akbarian and F. Ulm. Concrete Sustainability Hub, 2012 (47).**

METHOD

SCOPE

P

The objective of Akbarian and Ulm's research, conducted at the Concrete Sustainability Hub at the Massachusetts Institute of Technology, was to use a mechanistic approach to develop a relationship between pavement structural and material properties with its deflection. Once this relationship was created, the team desired to link the stiffness of the pavement to the impact on PVI using a simplified model for predicting pavement deflection.

The authors used the Federal Highway Administration's (FHWA) Long-Term Pavement Performance (LTPP) program as the sole data source for the pavement deflection model. These FWD datasets were used to calibrate the model, using 4,564 datapoints for flexible pavements and 1,079 datapoints for rigid pavements. The model calibration was done using wave propagation methodology based on time history for the deflection measurements. The pavements were modeled as infinite beams on viscoelastic foundations being loaded by non-deformable tires. Calibration was only done on the deflection under the load and at the furthest point to calculate *E* and *k*. Model validation was completed using deflections at various distances from the load using a limited dataset. Given a pavement of known stiffness, the model would then be used to predict the deflection of the pavement. The authors propose that the more a pavement deflects, the more fuel is consumed because the vehicle is constantly having to drive uphill on the slope of the pavement deflection.

After the model was developed, Akbarian and Ulm then applied it to the entire LTPP database to determine the overall effect of pavement stiffness on PVI and fuel consumption. This network application was completed by calculating the average and standard deviations for pavement thickness and layer stiffness for all rigid or flexible pavements in the LTPP dataset. The authors used Monte Carlo simulations to develop cumulative distributions for pavement deflections by pavement type for the database. The authors then concluded that using stiffer or rigid pavements could result in fuel savings of approximately 4 percent for the network.

> Limitations: The authors commonly refer to *k* as both the modulus of subgrade reaction and the subgrade modulus, and it leaves the reader wondering which was actually used. These two terms have different meanings. The primary subgrade input for rigid pavement design is the modulus of subgrade reaction, *k* (pci). Westergaard (48) used this term to describe the support the subgrade provides to a concrete slab. By considering a liquid foundation (commonly referred to as a Winkler foundation), the slab is on an infinite number of springs, such that the volume displaced is proportional to the applied load, where *k* serves as a spring constant. In past versions of the AASHTO Flexible Pavement Design Guide, the subgrade was characterized by the resilient modulus (psi) in design nomographs. Other tests such as the California Bearing Ratio (CBR) and Resistance value (R-value) have been used as surrogates for determining the material's resilient modulus. In the current Mechanistic-Empirical pavement

design methodology, the elastic modulus of a pavement's subgrade is used for design. Both elastic and resilient modulus vales are measures of material stiffness.

The authors chose "the beam on a viscoelastic foundation model" to represent both flexible and rigid pavements (*47*). This approach is not appropriate for asphalt pavements because while concrete pavements are sometimes constructed directly on subgrade, asphalt pavement structures commonly contain a granular base material between the asphalt layer and subgrade. This is due to fundamental differences in the way flexible and rigid pavements carry loads. In a flexible pavement, the base material is meant to distribute the load to the subgrade; however, the more rigid PCC layer facilitates "slab action" and the stresses transmitted to the subgrade are relatively small in the center of the slab. The load and stress distribution changes as loading approaches joints. Therefore, using one generic model to understand the effect of stiffness on the way a pavement deflects oversimplifies reality, making comparisons between the pavement types difficult or inappropriate.

In addition, the authors consider the elastic modulus of the surface layer (without considering asphalt viscoelasticity) and the modulus of subgrade reaction but make no mention of any material properties for the base layer. It is later mentioned in the Chapter 4 summary that "the impact of the base layer on pavement performance is not included" (*47*). Flexible pavement deflections are sensitive to thickness and moduli of the various material layers, including the asphalt surface, base, and the subgrade (*48*). Failure to include the base materials in the asphalt pavement structure will result in increased deflections.

Furthermore, the tire considered in the model is infinitely stiff. By using an infinitely stiff tire, this model does not account for the energy transfer into the tire that would cause it to deform. When considering the stiffness of both the pavement and the tire, the stiffness of the pavement is two to three orders of magnitude greater than that of the tire; therefore, the energy lost from the pavement deflection should be much less than that lost from tire deflection. This would reduce the impact the pavement has on fuel consumption (49).

The accuracy of the model is questionable. When Akbarian and Ulm validated the model, the model provided errors in the top layer modulus up to 40 percent and 30 percent in the subgrade modulus. These values seem to be high and not within a reasonable range for accuracy. Ultimately, these errors could be compounded when Akbarian developed distributions of top-layer modulus, subgrade modulus, and thickness across 1,079 concrete sections and 4,564 asphalt test sections to assess how fuel efficiency could be affected across the entire network. Monte Carlo simulations can be used to compare data if the pavements are of equivalent design. All the pavements were presumed to be designed to carry highway traffic; however, the data do not suggest this is the case. In this case, the average concrete pavement is almost five times stiffer than the average flexible pavement. Using the table in the report, the coefficient of variation is 51.6 percent for flexible pavements compared to 20.4 percent for rigid pavements. Using this average and standard deviation, it would be possible in Monte Carlo simulations to get stiffnesses that would be unrealistically low, even approaching zero. Similar results are seen

for pavement thickness. The average flexible pavement was less than 6 inches thick while the average concrete pavement was over 9 inches thick.

2.31 “Viscous Energy Dissipation in Asphalt Pavement Structures and Implication for Vehicle Fuel Consumption” by S. Pouget, C. Sauzéat, H. Di Benedetto, and F. Olard in *Journal of Materials in Civil Engineering*, 2012 (50).

METHOD

SCOPE

P

In this study, finite element modeling was used in conjunction with a linear viscoelastic (LVE) model for asphalt concrete materials. A typical French pavement section was modeled to determine the energy dissipation under a rolling load representative of a 40-ton truck which could then be correlated to fuel consumption. As the authors state, this study “proposes a scientific method to access fuel consumption excess due to viscous energy dissipation, which proves to have a small influence compared to evenness and roughness in flexible and rigid pavements.” In this investigation, material response was determined by moduli measured using the push-pull test and applied to a previously developed 3D isotropic LVE model, the Di Benedetto-Neifar (DBN) model. This model was used in a finite element model (FEM) (software was COMSOL) to calculate stress and strain in a typical French pavement cross-section under a rolling load. The cross-section consisted of 0.06-meter polymer-modified asphalt wearing course atop a combined 0.16 meters of AC base course (two AC base layers were considered with total thickness varying from 16 to 28 centimeters), on top of a 1-meter soil subbase. The slab considered for the FEM was 2 meters long by 1 meter wide. Load was modeled as a wheel at constant speed in the longitudinal direction with a normal pressure of 0.67 MPa on a square area (0.22 × 0.22 meters), consistent with a French standard.

Dissipated energy was determined in each bituminous layer at the time of the passing load and then compared with the total energy consumed to make the 40-ton truck move (engine efficiency was not considered). The fuel consumption excess was determined by taking the ratio of dissipated energy due to the moving load over the pavement structure to the total energy to move the truck. This work assumed perfect bond between layers. Fuel consumption of a 40-ton truck was 60 l/100 km, and the caloric value of fuel was 40 MJ/l. Assuming a constant speed of 100 km/h, the dissipated energy was reported to peak at 63°C (which represents summer conditions), corresponding to an excess fuel consumption of approximately 5.5 percent. In considering the mean reference temperature for pavement design in France, 15°C, the increase in fuel consumption at 100 km/h was found to be 0.25 percent. The authors conclude that in general “at very low temperatures (<15°C) and at very high temperatures, where bituminous material can be considered as purely elastic in a first approximation, fuel consumption excess is negligible (<0.25 percent).”

> Limitations: The authors acknowledge that further work is necessary and that this work may be improved by “considering more realistic conditions (evolution of temperature with depth, influence of dual wheel or tandem axle).”

2.32 "Evaluation of the Structure-Induced Rolling Resistance (SRR) for Pavements Including Viscoelastic Material Layers" by O. Chupin, J.-M. Piau, and A. Chabot in *Materials and Structures*, 2013 (51).

METHOD

SCOPE

P

This article addressed whether the viscoelasticity of an asphalt pavement impacted the rolling resistance of a pavement. The research team used a theoretical approach by computing the structure-induced rolling resistance (SRR) for a response of a viscoelastic pavement under a moving tire. Using a structure-induced power dissipation model, the structure-induced dissipation from the deflection of the pavement was obtained. This approach was applied to a thick pavement to allow the SRR to be evaluated as a function of both temperature and vehicle speed. The team also used non-dimensional analysis to extend the results to other contexts. One drawback of this approach was that only the viscoelastic effects of the pavement were considered without the effect of texture or pavement smoothness.

The research team concluded that the SRR of an asphalt pavement increases with temperature and decreases with speed. However, even under unfavorable conditions such as high temperatures (40°C) and heavier trucks at a speed of 20 m/s, less than 0.5 percent of the total energy is available in the fuel. This suggests that when the pavement structure is thin, trucks are heavy, and speeds are slow, one might see a 1–2 percent difference based on viscoelasticity. However, this will not be the case as pavements with higher truck traffic will be thicker. In addition, it is estimated this effect will be about 30 times less when passenger cars are considered in place of trucks.

Limitations: Additional properties need to be considered beyond material dissipation.

2.33 "Fuel Efficiency Study of Concrete Pavements" by R. Stubstad, Presented at the 2009 California Pavement Preservation Conference, 2009 (52)

METHOD

SCOPE

P

In 2008, the California Department of Transportation (Caltrans) conducted a study to measure and compare fuel economy of vehicles traveling on different pavement types. Vehicles on concrete pavements had 2 percent less fuel consumption. Other studies showed a 1 percent difference between asphalt and concrete fuel consumption. A summary is presented in Table 13.

Limitations: Pavement texture was not considered in this study.

TABLE 13 Factors influencing vehicle fuel consumption (49)

Test Performed		Fuel Savings (approximate)
Effect of vehicle speed on PCC		6.5% (for every 5 mph decrease in vehicle speed)
AC vs. PCC	Fuel efficiency van on I-80	1.9% to 3.2% (in favor of PCC)
Diamond grinding PCC pavements that result in a significant improvement in IRI		1.8 % to 2.7 % * (for every IRI decrease in IRI of 50 in/mile)
Effect of tire pressure on PCC and AC pavements, respectively		1.0 % to 1.7 % (for every 4 psi increase in tire pressure)
AC vs. PCC	Fuel efficiency van on I-5	−0.1 % to 0.8 % (however no statistically significant differences were noted)

* Still unsubstantiated level of fuel savings through diamond grinding pending further testing on additional test sections.

2.34 *Rolling Resistance – Basic Information and State-of-the-Art on Measurement Methods* by U. Sandburg, 2011 (53).

METHOD

SCOPE

T

Testing was conducted on a rolling resistance drum on approximately 100 car tires. The drum had either a smooth surface or a surface dressing with 11 mm chips. The smooth surface had a texture of 0.12 mm (far below what most textures should be for safety) and 2.4 mm for the surface dressing (Figure 29). Measurements were made at three different speeds (80, 100, and 120 km/h). A multiple regression analysis showed that texture and vehicle speed had almost no relationship. The coefficient of the term in the regression linking texture to speed was statistically zero. Thus, texture was either weakly or not related to speed when assessing rolling resistance between 80 and 120 km/h.

Limitations: This is based only on laboratory testing.

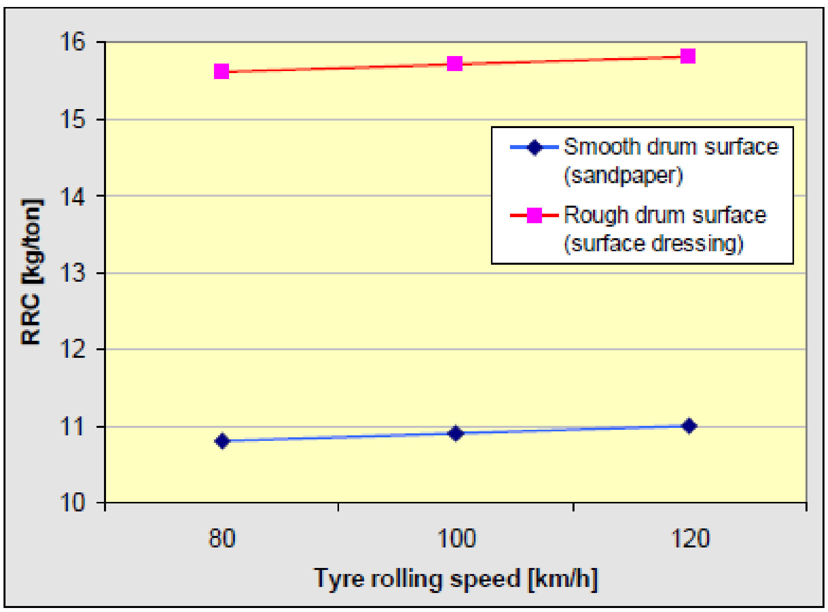


FIGURE 29 Speed versus RRC (50)

2.35 *Comparison of Fuel Consumption on Rigid Versus Flexible Pavements along I-95 in Florida* by M. Bienvenu and X. Jiao, 2013 (54).

METHOD

SCOPE

P

In 2013, Bienvenu and Jiao conducted a study on I-95 in Brevard County, Florida, to compare the fuel consumption of passenger vehicles and tractor-trailers. The asphalt pavement in this study was 9.25 inches thick, which included a 0.75 inch open-graded friction course, on 5 inches of limerock base and 12 inches of stabilized subgrade. The IRI of the pavement was 48 inches per mile. The concrete pavement was 13 inches of plain jointed portland cement concrete and 1 inch of asphalt concrete over 4 inches of asphalt-treated permeable base. The IRI of the road was 46 inches per mile.

Instantaneous gas consumption was recorded using the on-board data collection capability of the vehicles. Tables 14 and 15 show the results of the study. Overall, the report suggests that passenger cars and tractor-trailers were 3.2 and 4.5 percent, respectively, more fuel efficient on concrete pavements compared to asphalt pavements.

TABLE 14 Comparison Results from Monthly Data Collection for Passenger Vehicle (51)

Date	Air Temperature/Wind Velocity	Miles per Gallon (MPG) Difference (Rigid minus Flexible)	MPG % Difference	Gallons per 100 Miles (GPHM) Difference (Flexible Minus Rigid)	GPHM % Difference
11/23/12	62 F/11 mph NW	1.5	4.5%	0.130	4.3%
12/12/12	76 F/6 mph S	1.0	2.8%	0.078	2.8%
1/13/13	72 F/11 mph SE	1.3	4.2%	0.131	4.0%
2/27/13	68 F/4 mph W	1.1	3.8%	0.124	3.7%
3/9/13	49 F/ 4 mph NNW	0.6	2.1%	0.072	2.0%
4/18/13	79 F/10 mph WSW	1.0	3.4%	0.109	3.2%
5/10/13	80 F/10 mph SW	1.0	3.4%	0.110	3.2%
6/13/13	84 F/4 mph E	0.8	2.5%	0.080	2.5%
Overall Average	—	1.0	3.3%	0.104	3.2%

TABLE 15 Comparison Results from Monthly Data Collection for Tractor-Trailer (51)

Date	Air Temperature/Wind Velocity	Miles per Gallon (MPG) Difference (Rigid minus Flexible)	MPG % Difference	Gallons per 100 Miles (GPHM) Difference (Flexible Minus Rigid)	GPHM % Difference
5/10/13	84 F/9 mph SE	0.31	3.8%	0.53	4.1%
6/15/13	84 F/13 mph E	0.33	4.5%	0.68	4.7%
1/13/13	82 F/6 mph E	0.30	4.1%	0.63	4.5%
Overall Average	—	0.31	4.1%	0.61	4.5%

Commentary: The study links these results back to previous work to show that pavement stiffness and deflection were the cause of these differences; however, there are some inconsistencies in this logic. If pavement stiffness was the reason for differences in fuel consumption, why were the differences between the asphalt and concrete pavements less when it was 84°F outside compared to test dates at 62, 76, 72, 68, 79, and 80°F. This could have been a confounding variable of the wind; however, the authors make no note of this anomaly.

Additionally, the authors only tested using the tractor-trailer from May to July and did no further testing during the colder months. The ambient air temperature only varied by 2°F during these months. However, the research team extrapolated the 4.5 percent fuel savings across the entire year, which is inappropriate.

Ultimately, while these pavements may have been designed for the same annual average daily traffic and truck percentages, they probably did not have the same design lives or structural capacity. Additionally, using an open-graded friction course would have changed the texture of the pavement, thus, impacting fuel economy. These factors were overlooked by the authors of this report.

3 SUMMARY OF FINDINGS

More than 30 studies were presented in this literature review. Tables 15-17 provide summaries of the findings in the literature reviewed in this report broken down by pavement property. Each study was developed to assess how pavement type or properties affect rolling resistance and pavement-vehicle interaction. Studies which evaluated multiple pavement properties are included in multiple tables. The following statements reflect the state-of-the-science.

Megatexture has negative impact on rolling resistasnce. Megatexture can affect the rolling resistance in a negative way. The greater the texture of the pavement, the greater the rolling resistance. Numerous studies analyzed texture as a singular property to determine its effect on rolling resistance. In many cases, texture could change the rolling resistance of pavement by 5 to 10 percent. Some studies suggested this value was even greater. However, it is difficult to quantify what realistic changes in texture occur in the field under trafficking or due to rehabilitation. Tining in concrete pavements can greatly affect its texture, while mixture design might have the greatest influence on texture for asphalt pavements. It is also important to consider that while early research linked texture with speed, current science shows that speed and texture are not correlated in pavement-vehicle interaction.

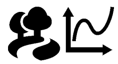
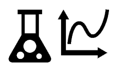
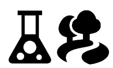
Smooth roads decrease vehicle fuel consumption**.** Every study that assessed the effect of unevenness or smoothness on pavement vehicle interaction showed that smoother pavements reduced rolling resistance. The more smoothness is improved, the greater the reduction in rolling resistance. The example was given in a real world study from a Missouri rehabilitation project showing that reducing the IRI of a pavement from 130 to 60 in/mile could save 2.46 percent fuel. Other studies such as WesTrac show this could be as high as 4 to 4.5 percent. Studies have also suggested that the effect of smoothness changes with speed.

Pavement type and stiffness studies have not consistently shown how this impacts PVI. Multiple studies suggest that overall, concrete pavements might be more fuel efficient than asphalt pavements in either high temperature or heavily loaded situations. However, other studies suggest this may not always be the case. It is difficult to make direct comparisons to the fuel consumption of an asphalt pavement to that of concrete due to inherent differences in pavement texture, structural capacity, or smoothness. While the effects of texture and smoothness on pavement vehicle interaction are well-established, the results from studies on the effects of pavement stiffness and type have been inconsistent; thus, more work needs to be completed to further develop and determine the interaction of pavement stiffness and vehicle fuel economy.

Conclusions. One study has yet to grasp how all three pavement components (texture, stiffness, and smoothness) all contribute to rolling resistance simultaneously. Most models have not been developed to handle all three pavement components either. However, while these three properties may be independent of each other in their contribution to rolling resistance, it is true that singling out only one or two properties in a field study without controlling the other properties could allow one to attribute too much importance to a singular pavement property.

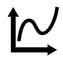
Currently, we understand that pavement smoothness typically has the greatest influence on rolling resistance. The effect of texture is smaller on well-maintained pavements, and no real consensus has been determined as to the effect of pavement stiffness on vehicular rolling resistance.

TABLE 15 Effect of Smoothness of Pavement-vehicle interaction

Study	Method	Scope	Findings	Limitations
2.2 Velinksy & White, 1979		S	• Smoothness losses could account for 20 percent of energy loss	• Limited data
2.5 Bester, 1984		P S	• Smoothness had effect on rolling resistance values	• No statistics. Limited data. • No pavement characterization.
2.6 Lu, 1985		S	• Smoothness and vehicle speed interact to affect rolling resistance. • Smoothness affected more at higher speeds.	• Model not validated. • Limited pavement properties.
2.9 Laganier & Lucas, 1990		T S	• Smoothness as critical as texture for fuel consumption.	• Non standard smoothness and texture measurements
2.10 Sandberg, 1990		T S	• Smoothness affect as high as 12 percent fuel consumption	• Non standard texture measurements
2.12 du Plessis et al., 1990		T S	• Road surface properties could affect cars by 7 percent fuel consumption	• No statistics
2.13 Delanne, 1994		T S	• Smoothness could influence fuel economy by up to 6 percent	• No statistics. • Non standard smoothness measurement
2.14 Cenek, 1994		T S	• Non-linear relationship between smoothness and texture	• No pavement characterization

2.18 Soliman, 2006		S	• Commonly saw 12 percent as difference between rolling resistance of a good and rough road.	• Limited pavement structures
2.19 Amos, 2006		S	• Resurfacing improved fuel consumption for dump trucks by 2.46 percent.	• Limited data. • No statistics
2.20 Heffernan, 2006		S	• Improved fuel economy on smoother pavements	• Texture not considered
2.29 Zaabar and Chatti, 2011		T S P	• Concrete was more fuel efficient on hot days with slow speeds	• Limited temperatures for testing
2.29 Chatti and Zaabar, 2012				

TABLE 16 Effect of Texture of Pavement-vehicle interaction

Study	Method	Scope	Findings	Limitations
2.3 Deraad, 1978		T	• Rolling resistance is higher on textured surfaces	• Limited speeds. • Limited textures.
2.7 Clapp & Eberhardt		T	• Increased texture increases rolling resistance	• Model unverified.
2.9 Laganier & Lucas, 1990		T S	• Increase in texture increased rolling resistance	• Non standard texture and smoothness measurements.
2.10 Sandberg, 1990		T S	• Textural affect as high as 7 percent fuel consumption	• Non standard texture measurements. • No concrete.
2.11 Descornet, 1990		T	• Texture could influence fuel consumption by 9 percent	• No statistics available
2.12 du Plessis et al., 1990		T S	• Road surface properties could affect cars by 7 percent fuel consumption	• No statistics available
2.13 Delanne, 1994		T S	• Texture changes from 0.5 to 2.5 mm could influence fuel consumption by 5 percent	• No statistics available
2.14 Cenek, 1994		T S	• Non-linear relationship between smoothness and texture	• No structural characterization
2.15 de Graaff, 1999		T P	• Effects of texture can be washed out by other effects	• No structural characterization
2.28 Sandberg et al., 2011		T	• Texture had impact on fuel economy	• Did not assess structure

2.29 Zaabar and Chatti, 2011 2.29 Chatti and Zaabar, 2012		T S P	• Concrete was more fuel efficient on hot days with slow speeds	• Limited temperature variation
2.33 Sandburg, 2011		T	• Texture can reduce rolling resistance by 30 percent in extreme cases	• Limited data

TABLE 17 Effect of Pavement Type of Pavement-vehicle interaction

Study	Method	Scope	Findings	Limitations
2.1 Walter & Conant, 1974		P	• Twice the rolling effect on gravel compared to smooth, hard pavement	• No pavement characterization. • Smoothness and texture not considered.
2.4 Williams, 1981	B	P	• Rolling resistance was numerically higher on asphalt compared to concrete	• No statistical analyses. • Smoothness and texture not considered.
2.5 Bester, 1984	C	P S	• Pavement type had small effect on rolling resistance	• No structural or material characterization. • Limited data. • No statistics.
2.8 Zaniewski, 1989	C	P	• Inconclusive results for autos, but concrete had 1 percent better fuel consumption for trucks (no statistical differences)	• No pavement characterization. • Only pavements in good condition.
2.15 de Graaff, 1999	C	T P	• No statistical difference between concrete and asphalt in passenger car	• No structural characterization.
2.16 Taylor et al., 2000	C	P	• Concrete more fuel efficient than asphalt	• Study discounted
2.16 Taylor et al., 2002	C	P	• Concrete more fuel efficient than asphalt	• Study discounted
2.17 NPC, 2002	E	P	• Concrete 0.05 percent more fuel efficient	• Modeled only spring and summer
2.21 Taylor and Patten, 2006	C	P	• Little difference between concrete and asphalt	• Pavement characterization is limited

2.22 Jonsson and Hultqvist, 2008	C	P	• 1 percent savings on concrete pavement	• Asphalt had double the texture and more rutting
2.23 Perriot, 2008	D	P	• Pavement type makes little difference on rolling resistance	• Model not verified
2.24 Lu et al., 2010	E	P	• Stiffness had relatively little effect on energy dissipation	• Thickness, texture, and smoothness not included in study. • Model not verified
2.25 Ullitdz et al., 2010	C	P	• Deflection only modestly affected rolling resistance	• Model is not verified • Limited sections • Pavement structure undefined
2.26 Thom et al., 2010	E	P	• Energy loss is associated with pavement stiffness	• Tire deflection, contact area, texture, and smoothness not considered
2.27 Sumitsawan et a., 2009	C	P	• Concrete more fuel efficient than asphalt at 30 mph but not in acceleration mode	• Pavement structure not considered
2.29 Zaabar and Chatti, 2011 2.29 Chatti and Zaabar, 2012	C	T S P	• Concrete was more fuel efficient on hot days with slow speeds	• Heavy truck only tested in summer

2.30 Akbarian and Ulm, 2012	E	Ⓟ	• Pavement deflection due to material stiffness could impact fuel economy by 4 percent.	• No field validation • Non-deformable tire • Asphalt modeled like concrete • Confusion on *k* • Monte Carlo simulations with exaggerated results
2.31 Pouget et al., 2012	E	Ⓟ	• Increase of fuel consumption by 0.25 percent based on dissipated energy	• Few limitations
2.32 Chupin et al., 2013	E	Ⓟ	• Less than 0.4 percent change in fuel on hot days, heavy loads, and slow speeds	• Only material dissipation considered.
2.33 Stubstad, 2009	C	Ⓟ	• 0–3 percent less fuel on concrete	• Texture, and pavement structure were not considered
2.35 Bienvenu and Jiao, 2013	C	Ⓟ	• Concrete 3.2–4.5 percent more fuel efficient	• Pavement structures were not equivalent. • Texture was not considered.

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