Numerical and Experimental Predictions of Texture-Related Influences on Rolling Resistance

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Abstract
To overcome rolling resistance (RR) a typical vehicle on average consumes 4152 MJ/119 L of fuel annually as a result of both vehicle and pavement factors. A slight improvement in surface texture arrangement may therefore decrease fuel consumption bringing substantial long-term socio-economic benefits. This aligns with ever-tighter limits on CO₂ in the USA (163 g/km until 2025) fostering sustainable construction/exploitation of tires/pavements. This paper describes a multi-scale 3-D numerical methodology to calculate micro-distortional RR and contact indentations of surface aggregates into visco-elastic tread compound accounting for loading, velocity, temperature, and compound properties. It consists of a micro-scale tread block single aggregate model and a macro-scale car tire finite element model, rolling in steady-state mode over a rigid smooth surface. The surface texture is idealized in terms of hemispherical indenters. The micro-distortional RR estimates are based on contact force and energy lost per single stone. The computed contact/normal forces peak significantly due to visco-elastic effects at the beginning of the tire–surface contact phase, followed by a gradually relaxing stress region with a sudden release at the end of the interaction. The contact forces appear to be of a reasonable distribution and magnitude. It is found that micro-distortional RR is higher on a rougher and sparsely packed surface compared with a smoother and more tightly packed case. To determine the total tire-related RR, macro-distortional RR can then be added. The predictions were qualitatively confirmed and adjusted against real bituminous mixes by experimental testing, showing a reasonable agreement.

The harmful influence on the quality of life that stems from our ever-expanding vehicle fleet is well acknowledged by environmental agencies worldwide. This particularly concerns heavily trafficked countries/regions such as the USA and the EU, which have recently made coordinated steps in cutting carbon emissions from cars, vans, and trucks by specifying carbon footprint thresholds (e.g., 95 g/km per car by 2021 in the EU (1); 163 g/mile for both cars and trucks by 2025 in the USA (2)). Even with more fuel-efficient vehicles, low rolling resistance (RR) tires (3) and, since 2014, low RR wearing course (4) being produced to enhance sustainability, little or no progress in reducing carbon footprints has been noted to date (CO₂ has risen by 26% in the past 25 years) mainly because of the continuing increase in vehicle numbers on the roads (5).

Given the fact of air pollution, finite fossil fuel reserves, and that the price of fuel is still increasing, tire and pavement research institutes continually aim at designing and manufacturing tires and highways to be as environmentally friendly and cost effective as modern technologies allow. While the traditional means of minimizing fuel use are to modify aerodynamics, transmission, and tire characteristics, pavements are now seen as a further way of lowering energy consumption. It has been long established that pavements affect fuel consumption just as tires do, through RR, and decreasing RR by 10% may save 1% to 4% of fuel (6).

Generally, RR comprises a set of simultaneous compressive and tangential energy loss mechanisms and varies in magnitude from 25 N to 80 N per car tire. A typical vehicle uses on average 4152 MJ/119 L of fuel per year to overcome RR as a result of both tire and pavement factors, of which weak pavement structure and rough texture have been found to lead to extra fuel consumption.

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Neglecting the aerodynamic drag, the following causes are commonly identified:

- Tire macro-distortional losses (texture-independent);
- Tire micro-distortional losses (texture-dependent);
- Pavement macro-distortional losses.

These mechanisms result in energy dissipation either in the tire/tread compound or the pavement structure, offsetting forward force by asymmetrically spreading contact tread compression, where the leading edge of a contact patch is more markedly deformed than the trailing edge. The energy being dissipated in the pavement is tied with wave propagation along, across, and inside the road structure that brings a deflection asymmetry under the tire. Recent computations (8) have shown that stiffness of the uppermost pavement layer is much more significant than that of underlying layers, meaning that a stiffer upper pavement saves energy. However, replacement of a flexible pavement with a rigid alternative may decrease pavement RR by about 3 N per truck tire at 40 kN vertical load (8). Using a set of falling weight deflectometer (FWD) measurements, Ullidtz compared them with these numerical estimates (11). The results matched quite well at lower deflections, but deviated at larger deflections. Other techniques (e.g., Chupin (9)) have been applied to analyze the pavement-related energy losses, supporting the main findings.

The other two losses take place within the tire. Emergence of macro-distortional energy dissipation is connected with compressive, tangential (micro-slippage and shear-induced inertia), and wave-induced inertial deformations. According to Michelin (3), due to rubber viscosity tread compression and longitudinal shearing contribute the largest amount of energy loss. These texture-independent losses can also be increased by standing waves, centrifugal, and to a lesser degree Coriolis forces.

On the other hand, stone indentations into visco-elastic tread compound induce micro-distortional energy loss. These contact distortions produce local compression which incorporates a visco-elastic and to a smaller extent an inertial component that affect the moment balance in the tire–pavement contact area. Spacing between adjacent aggregates, their size and shape all influence the force level and distribution, having a consequent effect on RR.

Numerous experimental and computational techniques have been employed to study RR. With the help of empirical tests, a clear correlation has been observed between RR and pavement roughness at different scales (7). However, disadvantages are that empirical in-situ testing (e.g., coastdown) takes all energy dissipation mechanisms into account, whereas the laboratory method (drum test) either ignores micro-distortional and pavement-induced effects or includes both macro- and micro-distortional tire energy losses. Regarding other set-ups, a double-wheel test rig has been developed, which measures the contact pressures and indentations per single asperity, but which has not been used to predict dissipated energy (12). These limitations have been in part tackled by modeling an entire tire or a tread pattern that interacts with the road surface.

As far as stone indentation influences are concerned, these have been considered with respect to structural vibration, noise emission, wear resistance, and friction (13, 14). Meanwhile most analytical, numerical, and semi-empirical models have omitted surface roughness and associated interfacial penetrations, emphasising macro-distortional RR (15, 16). Those models that include tread–texture interaction have been built to analyze contact stress distribution, but have ignored energy consumption calculations (12, 13, 17). A few analyses have been carried out to estimate energy losses due to indenting texture (18–20), but not all of these have clearly differentiated micro-distortional from tire macro-distortional losses. For instance, Hoever determined that texture-dependent visco-elastic contributions to RR may amount to 0.1% and 0.75% of total tire load level, for a smooth (stone mastic asphalt) and a rough (surface dressing) texture (19), respectively, which, by and large, aligns with experimental findings that show greater fuel use on surfaces with coarser stone packing (7, 21).

Until now an in-depth texture-dependent RR analysis is still lacking, and there is therefore a need to investigate individual stone effects, namely size/shape-spacing, discerning the visco-elastic and inertial components of micro-distortional RR. So far none of the existing simulations has examined these individual terms, frequently representing indenters as a series of 2-D/3-D linear or non-linear spring-dampers, or through spectral images derived from scanning real-life surfaces.

A reduction of total RR can only be achieved if tire-related characteristics are modified along with the pavement properties. In this respect, wider tires with shorter sidewalls enable lower RR. At the same time, such tire structural configuration leads to aquaplaning. To decrease tire-related RR (non-texture related) without affecting other performance, a new tall/narrow tire size concept has been suggested (22). A methodology that is capable of leading to the design of optimized tire treads, tire material compounds, and road texture for decreased RR, noise, splash, and spray while maintaining adequate drainage, skid resistance (dry, wet, ice, and snow), and ride quality for different operating conditions is therefore badly needed.

The aim of this paper is to suggest an efficient computational multi-scale model for quantification of the
micro-distortional RR caused by macro-texture asperities of wavelength 0.5 mm to 50 mm. The model consists of macro-scale (whole tire) and micro-scale (tread–stone contact) simulations and has been developed utilizing ABAQUS software. Numerical RR predictions have then been validated/adjusted by laboratory testing. Furthermore, application of the testing has enabled an evaluation of the energy consumption with variable textures, explanations of which are given below.

**Numerical Analysis**

**Macro-Scale Model**

A 175 SR14 slick radial Yokohama tire was adopted from ABAQUS open source to conduct the macro-scale 3-D analysis (23). The main purpose of this model was to obtain indentation and release rates to be used in the micro-scale simulation. To model tire free rolling on a smooth and rigid surface, the analysis was broken down into five sequential simulations, namely: inflation, half and full tire stationary footprint, braking/traction, and steady-state rolling. Each successive simulation is dependent on the results transferred from the previous one, and this is performed by means of a built-in transfer capability.

Tire macro-distortion was assessed employing ABAQUS/Implicit (Standard) Steady-State Transport Analysis in a mixed arbitrary Lagrangian eulerian (ALE) formulation, where the deformation is characterized by a Lagrangian method while describing the rigid body rotation in an Eulerian framework. In this analysis the tire was subject to 3300 N load and inflated to a pressure of 200 kPa. To account for large deformation, material, and boundary condition nonlinearities, it was necessary to set the NGEOM function.

Viscous effects, changing geometry, and local instabilities led to a non-convergence problem. To eliminate computational instabilities, a number of techniques was used, namely application of finer mesh, various increment sizes, and global and local stabilization options. After experimentation the time step specified in computation was 1.0 sec; the initial and analysis time increments were taken as 0.001 and 0.01 secs, respectively. The slip tolerance value was set to 0.02 as more relaxed (larger) values help avoid convergence difficulties. The total numbers of elements and nodes in the model were 7,255 and 13,548, respectively. To achieve an efficient runtime and converged solution, a finer mesh was incorporated in the contact region covering 40° of arc and a coarser mesh covering the remaining 320°, as shown in Figure 1, both being discretized with general linear hybrid elements (C3D8H and C3D6H) appropriate for incompressible material. To enforce the constraints strictly, a default hard penalty stiffness contact was adopted with friction defined in terms of a Coloumb law.

The means of arriving at free rolling conditions lay in defining through trial and error the wheel angular velocity (ω2) at the point where the moment balance about the rim center becomes nearly zero (where achievable); macro-distortional RR is then outputted as the reaction force (RF1) in the horizontal direction. In this case, free rolling conditions were found at 72.32 rad/sec angular velocity for a vehicle speed of 80 km/h. Computations of the average RR for the ABAQUS tire matched the results reported in the literature for this tire (24) in spite of imperfect convergence of RR moment about the hub point.

**Tread Compound Properties.** Visco-elastic properties of tread compound were represented in ABAQUS in terms of an assembly of rheological Maxwell elements (springs and dashpots). Description of elastic response was achieved by a reduced polynomial (Neo-Hookean) hyperelastic model applying the HYPERELASTIC capability, where just one parameter was used, being calculated as half of the shear modulus. The contribution of the viscous behavior was idealized by including the VISCOELASTIC capability, which comprises an N-term Prony series expansion of the dimensionless relaxation modulus in the time domain. Consideration of a range of temperatures was based on application of the Williams-Landel-Ferry (WLF) empirical time-temperature superposition principle with a reference temperature of 55°C.

**Micro-Scale Model**

A dynamic 3-D tread–stone contact (Figure 2b) was analyzed using the ABAQUS/Explicit solver to derive
was assumed to be of a hemispherical form. As shown by gathering such data is expensive, the indenter interaction of interlinked influences of stone size and shape, and surface replica in the analysis would not allow the separation of overclosure relationship (i.e. contact stiffness) was established. An optimized high, but computationally stable, level of contact stiffness was then chosen for all analysis steps. A constant friction of 0.7 was adopted, since this was not observed to substantially change contact forces.

**Meshing, Boundary/Contact Conditions and Analysis Steps.** In this configuration, a stationary 45 × 45 mm tread block (i.e. a piece of a tire surface) was used, while the stone penetrated vertically into the elastomeric block. This arrangement of boundary conditions (BCs) enabled consistent normal stresses to be captured in comparison with a fixed stone movable block combination. The surface and sides were left free to move (Figure 2c).

To replicate real-life interactions, three analysis steps were simulated: loading, hold \((V_{\text{hold}} = 0)\), and unloading. The BCs of the stone were described in terms of velocity, which was extracted from the macro-scale model for a series of nodes before and after the vertical velocity becomes zero in the contact area. By assuming that distances between the smooth surface of the macro-scale model pavement and tire surface nodes correspond to indentations caused by texture packing, loading/unloading rates have been generated for a range of tire translational speeds. Durations of time phases have been calculated by summing up the time intervals needed for passage through all internode distances in order to reach a given indentation.

As illustrated in Figure 2b, the block consisted of three discretization layers: bottom (in contact with the stone), middle, and top, with a finer mesh in the bottom layer, applying 40,500 8-node linear brick C3D8R continuum elements with reduced integration and hourglass control. After optimization trials, the selected mesh option gave a good trade-off between accuracy and analysis speed.

In addition, the introduction of mass scaling was found to decrease computational time. However, overly high mass scaling induced significant oscillations compared with the unscaled case. Therefore, by varying mass scaling levels, an optimum value was found to obtain efficient computational speed without sacrificing the accuracy/continuity of contact forces. In addition, to avoid computational problems, a linear soft pressure-overclosure relationship (i.e. contact stiffness) was established at the tread-indenter interface. Numerical overlap between contacting bodies can thus be inhibited. An optimized high, but computationally stable, level of contact stiffness was then chosen for all analysis steps. A constant friction of 0.7 was adopted, since this was not observed to substantially change contact forces.
Methodology to Quantify Micro-Distortional RR. Predictions of micro-distortional RR were estimated from the energy losses for single stones, derived from contact forces and indentations for a given loading; these losses were scaled to give values for the whole wheel. The results from this approach seem to more closely approximate the effects of protruding stones on RR compared with alternative moment-based procedure, explained in (26). Examination of varied texture packings could be accomplished by changing the spacing between indenters along and across the contact allowing both rough and smooth surfaces to be studied.

Description of Packed Indenters Loading Test (PILT)

Adjustment and qualitative confirmation of numerical micro-distortional dissipated energy were achieved with the aid of a packed indenters loading test (PILT) utilizing an Instron 8801 servo-hydraulic machine under load control. Both cored samples and idealized packed spherical surfaces were investigated. In the PILT test, a specimen was placed on a base platform and on top of it a tread pad inserted with the tread pattern facing downwards (Figure 3).

The testing objective was to load the tread pad–texture combination to measure stone penetration into the rubber compound and the force induced. The penetration and force were measured by an internal transducer mounted within a load actuator and a load cell, respectively. The test was conducted at ambient room temperature of 20°C, exposing the specimen to the action of 50 sinusoidal loads at a frequency of 20 Hz. Application of high-frequency cycling was constrained by the limits of the acquisition system and the hydraulic machine. Calculations of energy lost per pad during the 25th cycle were then carried out for a range of tread pads, surfaces, and loading levels. Further, to identify micro-distortional RR per tire, computed energy loss was multiplied by the number of pads in one meter.

Figure 2. A representation of (a) multi-indentation tread–stone model, (b) the adopted mesh and tread–stone configuration, and (c) a schematic sketch of the FE analysis with indicated boundary conditions, where $V_{\text{vert}}$, $F_{\text{vert}}$, $h_{\text{ind}}$, $h_{\text{cont}}$ are vertical velocity, tread height, contact force, indentation depth, and depth of indentation contact zone.

**Qualitative Confirmation and Adjustment of Computational Predictions**

To qualitatively confirm the FE model, numerical computations were compared against the PILT results for a spherical texture of 15.9 mm diameter, both with a tightly packed arrangement and at a spacing of 22 mm. The results from the micro-scale analysis showed good qualitative agreement with the experiments in terms of...
micro-distortional RR and stone indentation as a function of stone spacing. It was found computationally that an increase in stone spacing from 15.9 mm to 22 mm increased both micro-distortional RR and stone indentation by 1.47 and 1.46 times, respectively. These rates matched the PILT data for the same textures quite well. However, in order to carry out a quantitative comparison between the model and PILT data, the impact of rubber bending between spheres, differences in rubber properties, in loading rates and in contact areas all need to be taken into consideration.

An adjustment was also made to convert numerical energy losses for spherical textures to those of conventionally paved surfaces. For this an adjustment factor was employed, which is the ratio between the energy lost for a realistic surface and that for an idealized surface. Stone mastic asphalt (SMA) and hot rolled asphalt (HRA) was tested (PILT) in this work. These ratios amounted to 0.56 and 0.64, respectively, being averaged to account for four loading levels, three rubber types and two artificial manufactured surfaces. These adjustments were only approximate since the PILT loading rate was significantly lower than those applied in the micro-scale modeling to conform to realistic velocities.

Results and Discussion

The effect of stone packing on the contact forces and RR for a range of hemispherically packed textures was assessed using the numerical approach described above. As presented in Figure 4a, indentation of a single 5 mm radius hemisphere by 1 mm into a tread block clearly shows that the tread–stone model distributes compressive forces in the expected visco-elastic fashion.

Figure 4a shows that the presence of damping forces generates asymmetry in the normal forces, whereby the peak force is reached at the beginning of the contact area (i.e. the asperity is fully impressed), followed by a gradual force reduction until the beginning of the release phase where the stone disconnects from the rubber surface. A comparison between these computational predictions and results obtained by Boere and Liu (12, 18) showed a qualitative agreement between them, confirming the general validity of the technique.

It was found that, at the lower loading rate relating to 20 km/h, the rubber has a longer time to relax leading to about 13.33% less force compared with faster loading rates, which is a function of rubber-related stiffening at higher frequencies. In addition, as can be seen in Figure 4a, the normal forces are slightly noisier, being accompanied by distinct ripples at the end of the loading phase and throughout the holding and unloading phases for higher velocities. The ripples are due to two factors: the stiffer rubber and rigid fixing of the base of the block both restrict block movement giving rise to reflective waves within the block.

It should be noted that a larger stone size resulted in a greater contact force, which is justifiable since more resistance would accumulate from the material. Further, removal of rubber density in the model enabled inertial forces to be separated from visco-elastic and frictional forces. In contrast to expectations, observations indicated that inertia makes a negligible contribution to the contact forces and it is thus of secondary importance.
with respect to energy loss. In fact, a reduced density scenario led to a very slight increase in the force. Calculations of micro-distortional RR for a tire under 3300 N load are illustrated in Figure 4b. Regardless of the texture size/packing, the micro-distortional energy losses rise according to a power function as the wheel velocity increases. This is again attributed to the stiffening of the compound; larger indentations appear at a lower velocity producing a lower contact force, while generation of a smaller dent (rubber becomes stiffer) is expected for larger loading rates causing greater forces. For instance, a tight packing of 7.5 mm indenters induced a texture-dependent RR of 7.2 N/tire at 20 km/h and 8.7 N/tire at 100 km/h with corresponding contact distortions reducing from 943 µm to 882 µm, as can be observed in Figure 5a. Overall, for a speed increase from 20 km/h to 100 km/h the variation in RR remained between 11% and 20% for all hemispheres.

Regarding texture packing, a coarser texture caused a larger RR compared with a finer texture, as shown in Figure 4b. Increase of hemisphere radius from 2.5 mm to 20 mm magnified micro-distortional RR by a factor of 3.6, from 3.5 N/tire to 12.8 N/tire for a velocity of 100 km/h. From a qualitative point of view, the tendency for RR to increase with texture depth (assuming the hemisphere radius correlates with the texture depth) is in agreement with the results derived from the coastdown method carried out by Hammerström et al. (7).

Widening the distance between indenters but keeping the same radius of 7.5 mm also showed that a less dense packing results in greater energy consumption. When varying longitudinal spacing alone, the RR rose from 8.2 N/tire for a tight 15 × 15 mm stone pattern to 10.9 N/tire for a looser 20 × 15 mm arrangement. It can be noted that the increase in energy losses from the 15 × 15 mm to 20 × 15 mm pattern appeared to be of approximately same level as for the velocity effect examined under a similar pressure condition. Furthermore, a rise in the RR of 36% was found when the wheel load increased from 1300 N to 4300 N, from 5.5 N/tire to 8.6 N/tire, when rolling over a tight 15 × 15 mm texture pattern. With 18 × 15 mm and 20 × 15 mm arrangements the difference in energy lost amounts to 50% for the same load increase. The less steep increase in the micro-distortional RR for the 15 × 15 mm pattern appears to be a feature of denser texture patterns.

In general, this is related to a larger compression into the compound by the coarser surfaces and is demonstrated in Figure 5a, where a hemisphere radius increase from 5 mm to 10 mm increased contact indentation from 635 µm to 1084 µm. A similar tendency is found for more sparsely packed surfaces. Up to 10 mm radius hemispheres, the indentation levels seem approximately to match the realistic range for asphalt surfaces found experimentally by PILT testing and they agree with the trends and order of magnitude of estimates reported in the literature (27).

To differentiate the effects of rubber material, stiff and soft tires were analyzed. The results obtained showed that the stiffer tire, as expected, resulted in less energy loss than the softer tire, on average, imposing 6.1 N/tire and 6.7 N/tire of RR, respectively, over the 20 to 100 km/h speed range. It should be borne in mind that rubber viscosity and stiffness can play a significant role, potentially affecting contact displacement, forces, and fuel losses.
However, inconsistent results were found for the effect of temperature (°C) variation at 3,300 N load and with tight hemispherical packing of 5 mm radius. At 25°C tire temperature, representing the stiffest case, the micro-distortional energy dissipation decreased as the speed increased, while at temperatures from 45° to 85° there was an increase or a small reduction. The largest effect occurred at 35°, inducing 5.9 N/tire RR, although this differed only marginally from the 45° and 55° scenarios. A temperature of 35° had the greatest effect until 40 km/h, after which the highest losses occurred at 45°. The lowest RR was found at 85° until 60 km/h. The origin of the disordered results is assumed to stem from molecular chain realignment in the rubber under the simultaneous action of frequency and temperature effects.

By adjusting the hemispherical surface of 7.5 mm radius it was predicted that the rougher/looser texture of HRA would induce greater RR as compared with the smoother/tighter texture of SMA. Specifically, the mean values of RR for HRA and SMA for a range of velocities were 5.2 N/tire and 4.5 N/tire, respectively, which is in good agreement with the order of magnitude for various asphaltic surfaces computed by Hoever (19). In comparison with the total RR, including macro-distortional RR of 42.5 N/tire calculated by the macro-scale FE model, these represent 10.9% and 9.7%, respectively. In general, the findings from the PILT experiment qualitatively confirmed that HRA texture gives rise to more energy loss than SMA texture, as well as being consistently/expectedly higher for the softer tread pad.

Assuming 50,000 car passes in a day on a major highway, the energy lost due to HRA and SMA surfaces would equate to 1.04 MJ/m and 0.91 MJ/m, respectively. This means that, taking 40 years as the whole life of the road, these vehicles would burn an extra 434 L/m and 380 L/m of fuel, which is roughly equivalent to emitting 998 kg and 874 kg of CO₂, respectively. The implication is that purely by switching from the rougher to the smoother surface it would save approximately 54 L/m of fuel or reduce by 124 kg the tailpipe CO₂ emissions for cars with 3.3 kN wheel load. Although the predictions are not directly comparable, this is four times larger than the savings deduced to originate from lowering pavement-induced RR as presented by Thom et al. (28) for a traffic flow of 3000 commercial vehicles at 40 kN wheel load, marking it as a substantial source of pavement-related energy loss.

**Conclusions**

A 3-D multi-scale numerical model has been developed to calculate tire–pavement contact forces, stone indentations, and micro-distortional RR. The estimates of texture-related energy loss were experimentally confirmed and adjusted by use of laboratory testing. The influence on micro-distortional RR of six parameters was studied. Velocity was found to increase lost energy by a factor of 1.1 to 1.2 from 20 km/h to 100 km/h, which was observed to equate approximately to a change from a softer to a stiffer tread compound (i.e. this varies from rubber to rubber). A more significant effect on energy loss was identified due to increasing load level. However, the major effect was related to texture size, increasing the energy dissipation by a factor of 3.6 by replacing a finer with a coarser texture. Varying the spacing between stones led to about 1.3 times difference between dense and loose packings. Results for a range of rubber temperatures gave inconsistent trends, but only slight influence.
A comparison between two bituminous surfaces, HRA and SMA, showed that the smoother texture of SMA may save 54 L/m of fuel or lower tailpipe emissions by around 124 kg of CO₂ over 40 years on a heavily trafficked highway. The pavement surface texture was noted to be much more influential on energy loss compared with the pavement structural properties reported in the literature.

Broadly, the model and the experiment can already be implemented into a life-cycle assessment tool for evaluation of different road surfaces. However, in this study, only car tires have been examined; it is necessary to extend the research further to account for truck tires (i.e. the level of loading, rubber properties), for which losses are expected to be higher. An optimization of pavement texture, taking account of drainage, skid resistance, noise, and vehicle maneuverability, is the next logical step, representing a potential means to advance infrastructure sustainability by lowering environmental cost and financial expense.

Author Contributions
The authors confirm contribution to the paper as follows: study conception and design: D. Mansura, N. Thom, H. Beckedahl; data collection: D. Mansura; analysis and interpretation of results: D. Mansura, N. Thom; draft manuscript preparation: D. Mansura. All authors reviewed the results and approved the final version of the manuscript.

References
1. Reducing CO₂ Emissions from Passenger Cars. European Commission, EU Action, 2017. https://ec.europa.eu/clima/policies/transport/vehicles/cars_en. Accessed March 6, 2017.
2. Regulations for Greenhouse Gas Emissions from Passenger Cars and Trucks. US Environmental Protection Agency. https://www.epa.gov/transportation/greenhouse-gas-emissions-passerger-cars-and-trucks. Accessed March 6, 2017.
3. Société de Technologie Michelin. The Tire: Rolling Resistance and Fuel Savings. Michelin, France, 2003.
4. Pettinari, M., B. Schmidt, B. Bo Jensen, and O. Hedeland. New Surface Layers with Low Rolling Resistance Tested in Denmark. Asphalt Pavements, Taylor & Francis, London, 2014, pp. 323–332.
5. Bandivaker, A. Evaluating the Impact of Advanced Vehicle and Fuel Technologies in US Light Duty Vehicle Fleet. PhD thesis, MIT, 2008.
6. Tires and Passenger Vehicle Fuel Economy. Transportation Research Board Special Report 286, National Research Council of the National Academies, Washington, D.C., 2006.
7. Hammarström, U., R. Karlsson, and H. Sörensen. Road Surface Effects on Rolling Resistance-Coastdown Measurements with Uncertainty Analysis in Focus. Research Report, Deliverable 5a. VTI, Sweden, 2008.
8. Lu, T. The Influence of Pavement Stiffness on Vehicle Fuel Consumption. PhD thesis, University of Nottingham, UK, 2010.
9. Chupin, O., J.-M. Piau, and A. Chabot. Evaluation of the Structure-Induced Rolling Resistance (SRR) for Pavements Including Viscoelastic Material Layers. Journal of Materials and Structures, Vol. 46, No. 4, 2013, pp. 683–696.
10. Holmberg, K., P. Andersson, and A. Erdemir. Global Energy Consumption due to Friction in Passenger Cars. Tribology International, Vol. 47, 2012, pp. 221–234.
11. Ullidtz, P. Pavement Deflection and Energy Loss. Green Road Infrastructure Workshop, Denmark, 2014.
12. Liu, S., M. Sutcliffe, and W. Graham. Prediction of Tread Block Forces for a Free-Rolling Tire in Contact with a Rough Road. Wear, Vol. 282–283, 2012, pp. 1–11.
13. Pinnington, R. Tire-Road Contact Using a Particle-Envelope Surface Model. Journal of Sound and Vibration, Vol. 332, 2013, pp. 7055–7075.
14. Sridharan, K., and R. Sivaramakrishnan. Dynamic Behaviour of Tire Tread Block. American Journal of Engineering and Applied Science, Vol. 5, 2012, pp. 119–127.
15. Hall, D., and J. Moreland. Fundamentals of Rolling Resistance. Journal of Rubber Chemistry and Technology. Vol. 74, 2001, pp. 525–539.
16. van der Steen, R. Enhanced Friction Modelling for Steady-State Rolling Tires. PhD thesis, Eindhoven University of Technology, Netherlands, 2010.
17. Kozhevnikov, I., D. Duhamel, H. Yin, J. Cesborn, and D. Anfosso-Lede. A New Algorithm For Computing the Indentation of a Rigid Body of Arbitrary Shape on a Visco-Elastic Half-Space. International Journal of Mechanical Sciences, Vol. 50, 2008, pp. 1194–1202.
18. Boere, S., I. Arteaga, A. Kuipers, and H. Nijmeijer. Tire/ Road Interaction Model for the Prediction of Road Texture Influence on Rolling Resistance. International Journal of Vehicle Design. Vol. 65, 2014, pp. 202–221.
19. Hoever, C. The Simulation of Car and Truck Tire Vibrations, Rolling Resistance and Rolling Noise. PhD thesis, Chalmers University of Technology, Sweden, 2014.
20. Arteaga, I., and H. Nijmeijer. Visco-Elastic Contact Model for the Prediction of Tire/Road Contact Forces and Rolling Resistance. Proc., 18th International Congress on Sound and Vibration, ICSV, Rio de Janeiro, 2011.
21. DeRaad, L. The Influence of Road Surface Texture on Tire Rolling Resistance. SAE Technical Paper 780257. Society of Automotive Engineers, Troy, MI, 1978.
22. Vennebørg, M., C. Strübel, B. Wies, and K. Wiese Low Fuel Consumption Tires for Passenger Cars with CO₂ Emission. ATZ Worldwide, Vol. 115, No. 7–8, 2013, pp. 16–20.
23. ABAQUS On-line Documentation. Dassault Systèmes, Providence, RI, 2014.
24. Behnke, R., and M. Kaliske. Computation of Energy Dissipation in Visco-Elastic Materials at Finite Deformation. Proceedings of Applied Mathematics and Mechanics, Vol. 13, 2013, pp. 159–160.
25. Greenwood, J., and J. Wu. Surface Roughness and Contact: An Apology. Meccanica, Vol. 36, 2001, pp. 617–630.
26. Mansura, D., N. Thom, and H. Beckedahl. A Novel Multi-scale Numerical Model for Prediction of Texture-Related Impacts on Fuel Consumption. *Tire Science and Technology*, Vol. 45, No. 1, 2017, pp. 55–70.

27. Integrated Tire and Road Interaction – Development of a Tire-Road Friction Model. *Specific Targeted Research or Innovative Project. FP6-PL-0506437, Deliverable 5.1.*, Institute for Road and Traffic Engineering, Technical University of Aachen, 2006.

28. Thom, N., T. Lu, and T. Parry. “Fuel Consumption Due to Pavement Deflection under Load.” Paper presented at the 2nd International Conference on Sustainable Construction Materials and Technologies, Ancona, Italy, June 2010. 

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