TRUCK TIRE ROLLING RESISTANCE IN REAL USAGE

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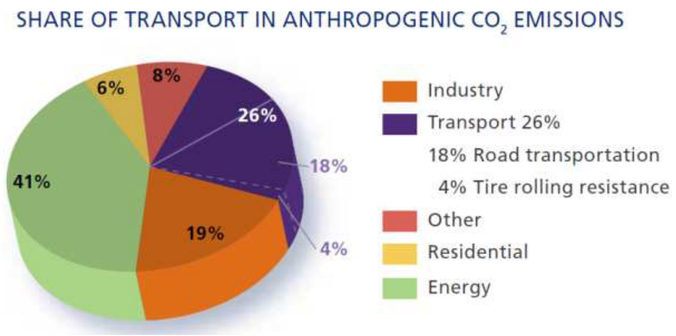
Abstract
The tire rolling resistance has a significant impact on the fuel consumption of trucks, then their CO2 emissions. Various schemes are enforced in more and more countries to reduce the CO2 emissions of trucks and the tire rolling resistance coefficient (RRC) is considered through its value in specific nominal ISO conditions. The purpose of this paper is to discuss the impact of the real usage parameters that impact the RRC through calculations and measurement. It also shares an order of magnitude of this effect on actual fuel consumption. The focus is done on a European use case.

Keywords: tire, rolling resistance, real usage, Heavy Vehicles, CO2 emissions

1. Introduction and Context

Transportation is responsible for ¼ of worldwide human CO2 emissions and the major part (18% of total) comes from road transport. The rolling resistance accounts for 4% of total CO2 emissions.

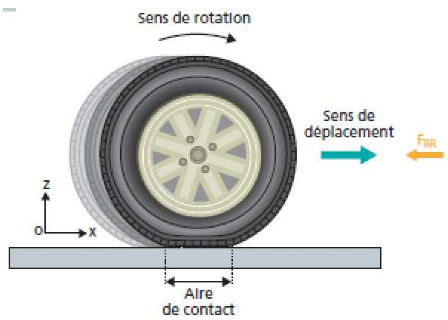


To master the CO2 emissions, more and more countries are voting regulations on fuel economy, like VECTO in Europe, GEM in the US, or other ongoing deployment schemes in China, India, Brazil, ...
The scheme to reduce truck CO2 emissions in Europe, engaged with the Vecto approach, requests the truck OEMs to reduce the average CO2 emissions of their sales by 15% in 2025 versus 2019 and 30% in 2030. Enforcing this change, a heavy penalty of 6800 € per g CO2/t.km will be applied by the European Commission for each gram of CO2, per truck sold above this limit.
Some technologies are necessary to achieve that goal and low rolling resistance tires have the advantage of being a plug and play solution aspart of the improvement.

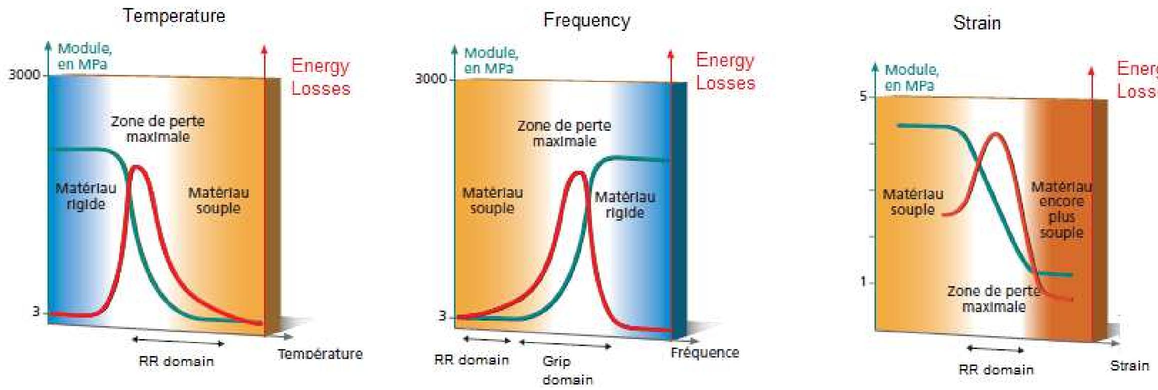
2. Tire RRC impact on CO2 emissions and fuel consumption

2.1 What is tire rolling resistance

The rolling resistance of a tire is the consequence of energy losses in the tire. It is characterized by the rolling resistance coefficient (RRC), which stands for the rolling longitudinal resistive force due to the tire divided by the load carried by the tire. When the tire is rolling, it generates heat because it is made of rubber materials that are stressed and have viscoelastic properties. This heating is the consequence of a loss of energy that creates the resistance force at the wheel center.



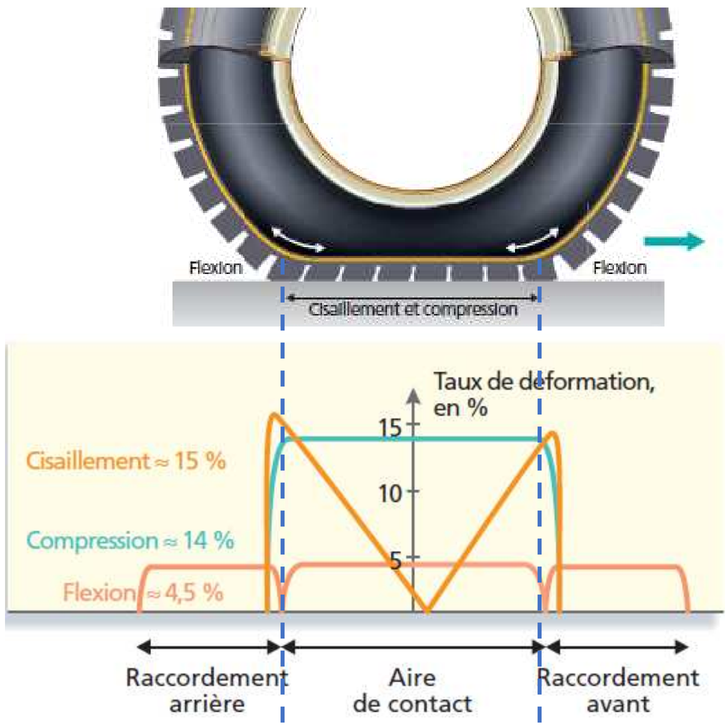
The dissipation of viscoelastic materials is highly dependent on many parameters : temperature, frequency, strain; so it is not so easy to model actual rolling resistance as it can vary a lot depending on usage conditions.



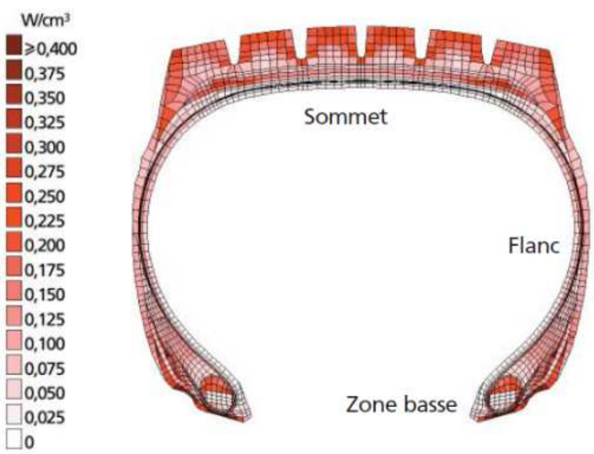
The rolling resistance is driven by several mechanisms, each one leading to specific design levers for RRC reduction. For truck tires, we can consider the 3 following mechanisms:

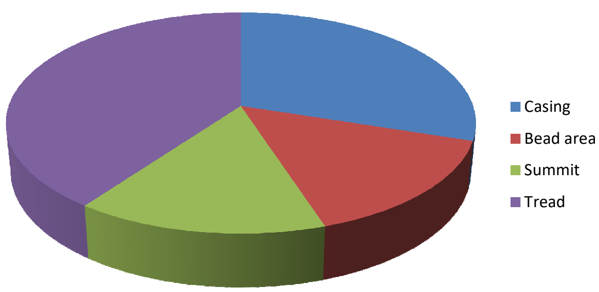
- Shear
- Compression
- Flexion

The strain rates plotted on the opposite figure explain why the tread compression and shear are identified as the main contributors to rolling resistance.



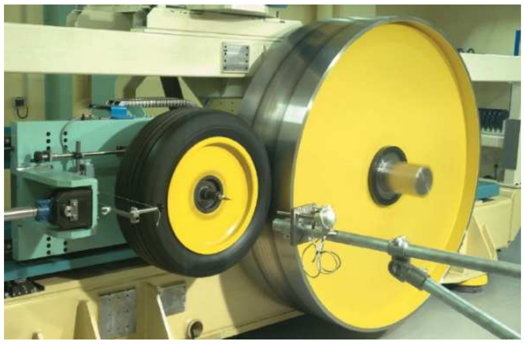
The results of a thermomechanical FEM calculation gives the energy dissipated per tire zone and confirms that the main contributor to the RRC is the tread; there is thus a big compromise to tune through the tread volume between RRC and tire mileage.





The RRC is a parameter that is measured on a test drum following a standard procedure and standard conditions (ISO28580), for a truck tire:

- Speed = 80kph
- Load = 85% of load index
- 3 hours warm up phase
- Ambient temperature = 25°C
- Pressure = nominal pressure as per tire markings
- Smooth steel drum as opposite

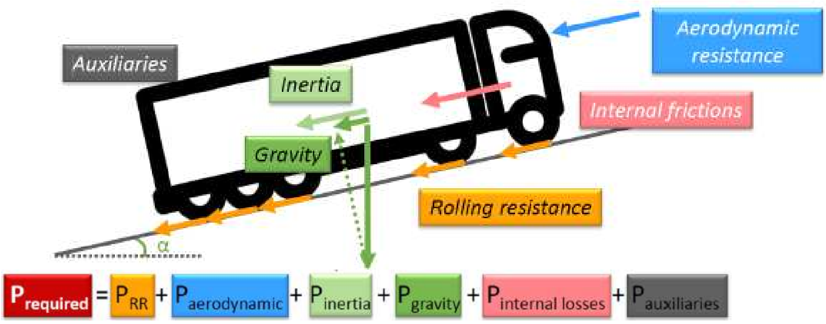


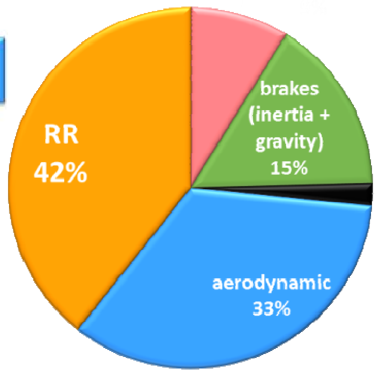
The RRC is then measured with a standard test in analytical laboratory conditions, but the reality is a bit different since:

- The actual load on the tire differs from the 85% of load index that is applied in the ISO test conditions;
- The pressure recommendations are sometimes different from the maximum pressure of the test to fit with the actual load and optimize the tire mileage with the most even wear;
- The speed of the test (80kph) is not far away from the trucks' average commercial speed in Europe (75kph);
- The actual average ambient temperature (15°C for Europe in average) is highly different from the test conditions (25°C) and it has a very significant impact on the RRC;
- The transient RRC before the tire reaches a stabilized thermal state must be considered as well;
- Real road roughness and flatness differ from the smooth steel drum.

2.2 Rolling resistance weight in fuel consumption and CO2 emissions

RRC is one key parameter to consider when assessing the CO2 emissions and the fuel economy of a truck. For example, for a European truck combination tractor 4x2 and semitrailer in long haul usage at 40t GCW, P required accounts for 30% to 45% of fuel consumption:





Michelin has defined a simple estimating equation to predict FC gain due to RR reduction:

$$\Delta FC = \alpha \times M \times \Delta RRC$$

ΔFC: Fuel consumption difference, in L/100 km

α: Coefficient, in L/100km/kg in range and [0.033-0.053] for heavy trucks

ΔRRC: Difference of rolling resistance (ISO 28580), in kg/t
M: Vehicle mass, in ton

The alpha coefficient is the sensibility of fuel consumption with respect to RRC and is defined by the following equation:

$$\alpha = \frac{g}{\eta_{trans} \cdot \eta_{th} \cdot PCI_f \cdot \rho_f} \cdot \frac{d_{mot}}{d} \cdot 100.$$

g = gravity acceleration [m/s²]
d_{mot} = distance traveled under engine torque [km]
η_{trans} = transmission efficiency
η_{th} = engine thermodynamic efficiency
PCI_f = fuel energy [kJ/kg]
ρ_f = fuel density [kg/L]
All these parameters are highly impacted by the usage and the truck typology.

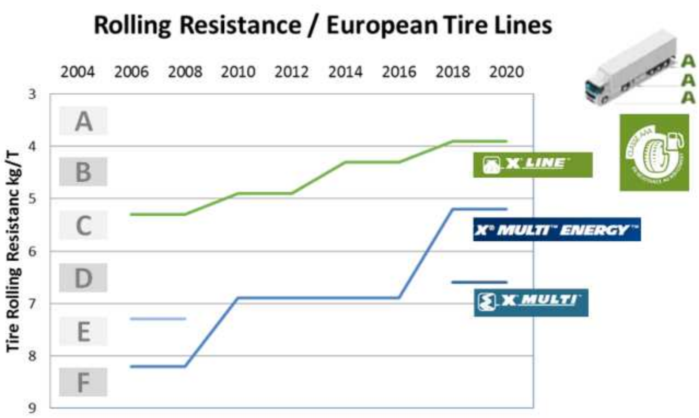
For a 40t European truck combination this theoretical equation gives a fuel consumption reduction of 2l/100km for -2kg/t RRC on all 12 tires of the convoy, which is not far away from what VECTO calculates or from what we can measure in analytical fuel consumption tests.
We understand then how powerful this lever is and why the race to low RRC tires is important!

2.3 Consequences on tire product segmentation and design strategy

We have seen that the tread is a big contributor to rolling resistance, then it is quite easy to reduce rolling resistance sacrifying the tire mileage by reducing the tread volume, but such an approach would lead to end user dissatisfaction and raw material waste because lots of casings would be scrapped to achieve the expected mileage.

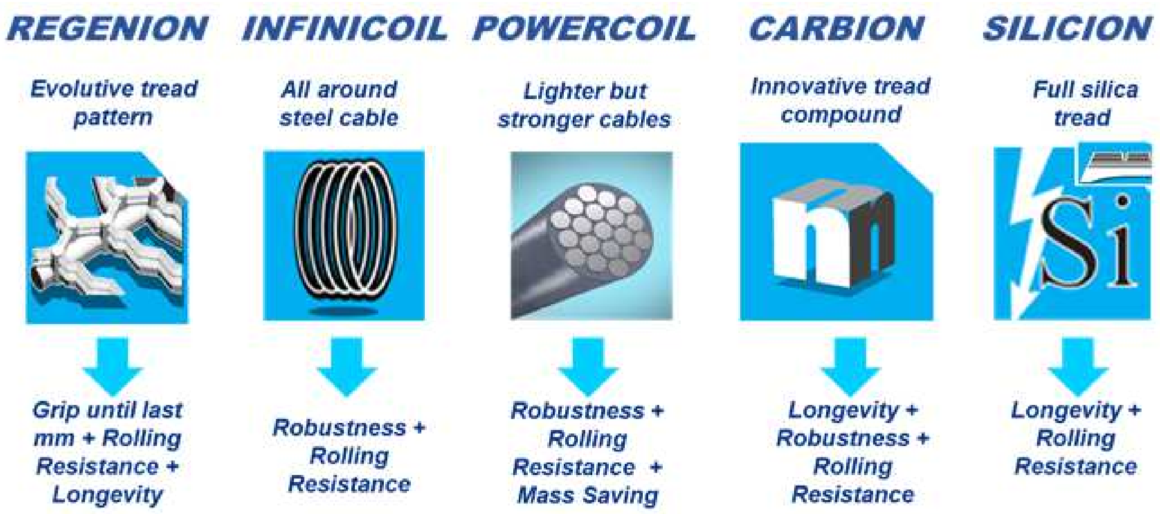
To reconciliate the OEM expectation (RRC for fuel consumption and CO2) and the various end user expectations (RRC, mileage, uptime, …) due to their transport vocations, most tire manufacturers propose two kinds of tire lines for on road purpose:
- one for aggressive usage regarding wear / traction needs : regional tire line;
- and one for softer wear usage, more oriented to fuel consumption: long haul tire line.

Each tire line has an adapted tread design and rubber to fit with the expectations of the usage.
Both tire lines have been constantly improved in their rolling resistance. Michelin has constantly improved the RRC of the new tire models launched on the market keeping and even improving mileage.
It took 15 years after first low rolling resistance long haul tires to reach the RR label A < 4kg/t.

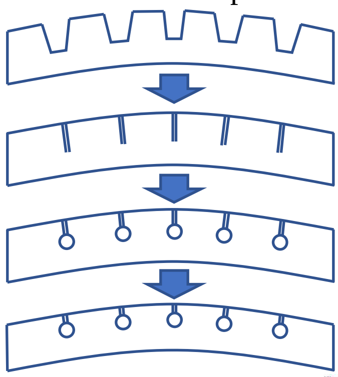


Furthermore, an intermediate tire line has been introduced on the market to realize the impossible wedding of RRC and mileage: Michelin X Multi Energy. This new tire line brings a significant improvement in rolling resistance and therefore in fuel consumption without any tradeoff on mileage.

As there is a strong tradeoff between wear lifetime and rolling resistance performance, the solution to maintain the mileage at a good level and reduce rolling resistance is to implement smart technologies in the tire design like tread material, tread geometry, casing architecture.

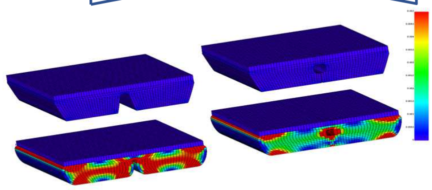


The tread pattern Stiffness is a key parameter for Tire Wear: the first mm of tread pattern is worn much faster than the last one. Regenion is a smarter way to solve RRC wear antagonism.



The new state tire void volume is over designed since it is designed to have enough void in a worn state, thus, to unmold the tire it is necessary to have clearance angles in the groove geometry.

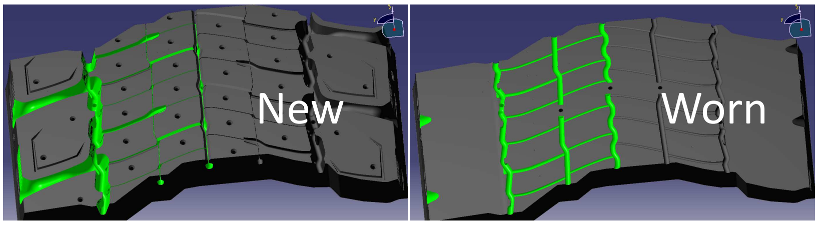
To improve wear rate, it is powerful to increase tread stiffness, which could be done by more compact tread design, but would impact the wet grip performance because there will be less void volume to store the water in the contact patch.



To optimize tread compacity with respect to void volume for water storage, the best option is to place the void volume in the last part of the tread height and connect it to the surface at the new state.

The useful void volume will then appear at the end of life being always active through the connection channels.

This leads to a very complex tread design and therefore mold design that needs new technologies to manufacture 3D printed molds.



Following this strategy leads to a reduction in tread depth to convert wear rate improvements into rolling resistance improvements at the same wear level.
Michelin started to develop this approach 15 years ago and it is now applied in most of the new products that are introduced into the market.
More than 100 granted patents protect this technology and the first granted patent has been awarded European inventor award in 2018.

3. Real usage impact on rolling resistance

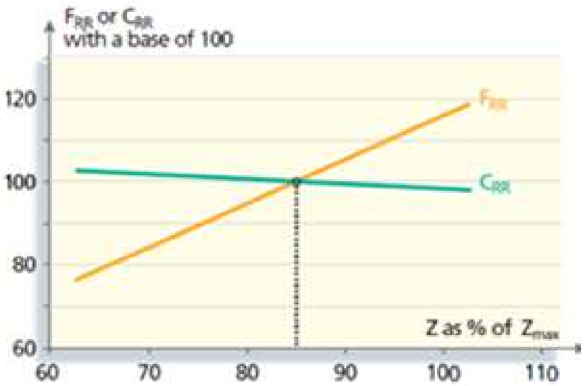
In real usage of the tire, many parameters differ and can affect significantly the RRC:

- The almost flat ground on real road differs from drum curvature leading to a reduction in the RRC on real flat road since the strains are lower. The Clark formula describes this and tries to compensate the drum curvature to align the RR machines between themselves (nevertheless, it is more accurate for drum radius normalization than for flat road transposition):

$$CRR_{road} = CRR_{drum} \cdot \frac{1}{\sqrt{1 + \frac{R_{tire}}{R_{drum}}}}$$

- Road roughness increases the RRC measured on smooth steel surface by changing the local scale deflections in the tread materials. This is a significant aspect of real usage that affects the RRC.

- When the load increases, the tire deflection increases, then the mechanical losses in the casing are higher but the tread compression driven by tire inflation pressure is the same. Therefore, when tire load increases, the RRC decreases as well.



- Inflation pressure has also a significant impact on RRC since it influences the tire deflection:

$$CRR_{Stab}(\mathrm{Z,P}) = CRR_{ISO} \cdot \left(\frac{P}{P_{ISO}}\right)^{\alpha} \cdot \left(\frac{Z}{Z_{ISO}}\right)^{\beta}$$

Where good orders of magnitude are α = -0.2 and β = 0.9

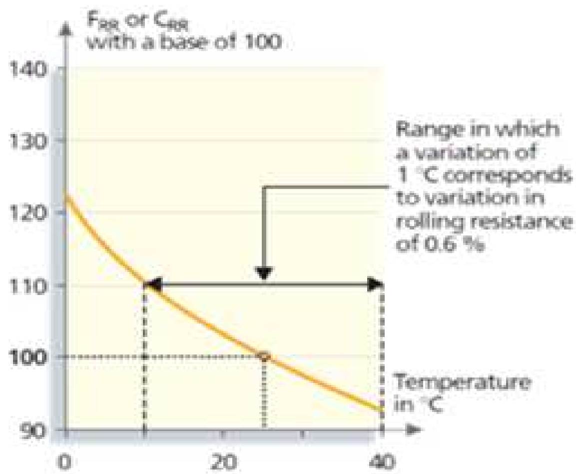
- The real usage velocity changes the strain frequency of materials in the tire, which we can model through a polynomial dependency:

$$CRR_{Stab}(\mathrm{V}) = CRR_{ISO} \cdot \left[1 + b \cdot \left(\frac{V - V_{ISO}}{V_{ISO}}\right) + c.\left(\frac{V - V_{ISO}}{V_{ISO}}\right)^{2}\right]$$

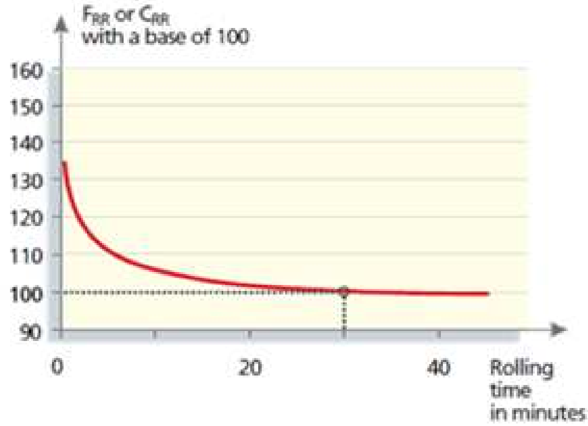
where b = 0.05 and c = 0.1

- Ambient temperature modification with respect to the measurement cell for ISO test changes the heat transfers between the tire and the environment and hence the tire temperature, then consequently the viscoelastic materials' temperature and dissipation. The ISO standard 28580 defines a formula to take into account this effect:

$$CRR_{Stab}(T_{amb}) = CRR_{ISO} \cdot [1 + K \cdot (T_{amb} - T_{ISO})]$$ where K = 0.06



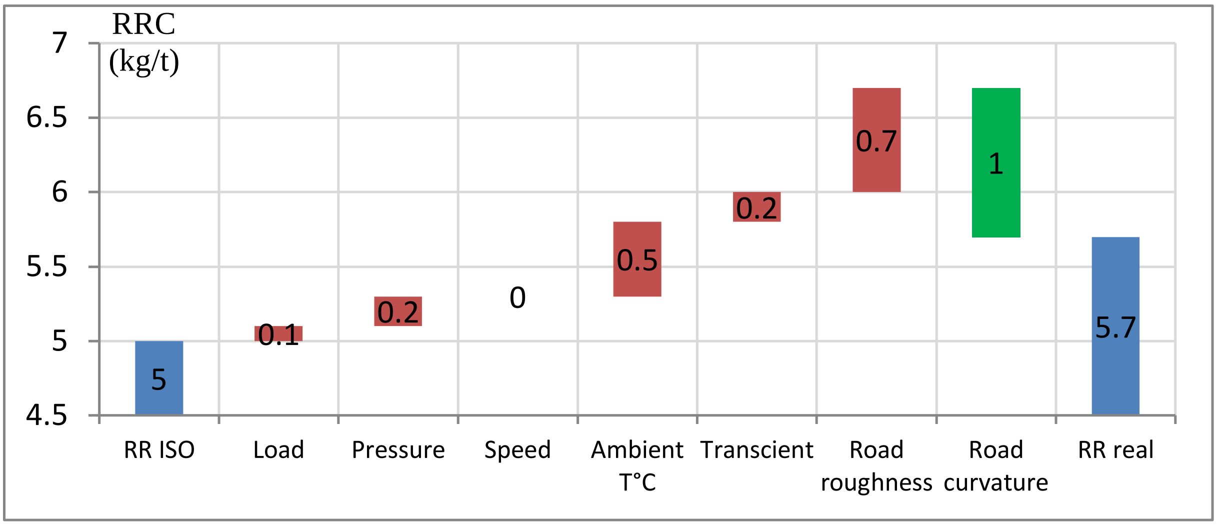
- In a turn for a given speed, the tire is under lateral force then there is a slip angle that appears. This creates a lateral force projection along longitudinal axis of the vehicle, increasing slightly the rolling resistance.



- The ISO standard test is done at a constant speed after a warm up time assuring a stabilized thermal state, but in real usage the speed profile puts the tire in a constant non stabilized state changing the heat exchanges then the tire temperature impacting the RRC.

- The last real-life impact on RRC is the wear level of the tire itself. Indeed, as the tread contributes a lot to RRC, if the tire is worn, the RRC decrease significantly.

If we consider realistic values for all the parameters described above, we can expect from an European drive tire to have a real RRC value increased by 0.7kg/t from the ISO value at 5kg/t for a new tire, and this decomposes as follow :



If this bias must be considered for all tire positions, that would represent a fuel consumption increase by 5% or 1.5L/100km for a 40t truck combination.

Conclusion

This study gives some good values to consider when assessing the impact of rolling resistance on diesel trucks' fuel consumption. It also explains what deviation to consider for real usage.

Some measurements and models are presented to enable the extrapolation of the ISO standard value for a better understanding of fuel consumption performance.

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