

Reducing Tire Rolling Resistance to Save Fuel and Lower Emissions

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ABSTRACT

In a context of a renewable and sustainable progress in the automotive industry where fuel and respect for the environment are in the middle of all concerns, energy efficient tires could play a significant role in saving money, limiting greenhouse gases and contributing to reduced local pollution. Using simulation, this paper establishes a simple law to predict fuel savings between two tire configurations, which appear to be almost independent of the usage and which depend on the difference of rolling resistance coefficients, the actual weight of the vehicle and the fuel type. This approach has been evaluated in practice for passenger car tires fitted on one gasoline and one Diesel Midsize car by performing rolling resistance tests, coast down tests, fuel consumption tests at constant speed and emissions recorded on a test bench. Even more than just validating the fuel savings prediction law, the test results also show how low rolling resistance tires can help to decrease CO₂ emissions and local pollutants such as CO emissions for gasoline engines and NO_x emissions for Diesel engines. This conclusion of simultaneous CO₂ and NO_x reduction has also been proven at constant speed on a heavy duty vehicle equipped with a gas analyzer.

INTRODUCTION

BACKGROUND

While environmental concerns continue to grow, the steady increase in greenhouse gas emissions related to the development of road transport, which already dumps in the atmosphere more than 5Gt/year of CO₂ [1] causes sharp discussions on the ways to approach the fight on this issue. Indeed, according to the International Energy Agency, road transport represented already in 2003 around 18% of worldwide carbon dioxide emissions produced by the human activity. Moreover, if fuel prices remain at a sustained high level, which is expected if oil resources become scarcer, every effort to improve fuel economy will be well appreciated as a mean to limit functioning costs.

As engine design often requires compromises between pollutant levels and specific fuel consumption at a given operating point, it may be interesting to focus on the strategies to limit power requirements, since vehicle

emissions are ultimately a function of the power output of the engine. In this context, tires could have a meaningful effect. As tires roll under the vehicle's weight, their shape is being deformed and their rubber compounds, which are also designed to ensure traction and comfort, dissipate energy that turns into heat. To overcome this lost energy, additional fuel must be expended.

Rolling resistance is defined as the energy consumed by a tire per unit of distance travelled. As this force F_{RR} is almost proportional to the load Z applied on the tire, it can be characterized using a rolling resistance coefficient C_{RR} , without units or expressed in kg/t:

$$C_{RR} = \frac{F_{RR}}{Z} \quad (1)$$

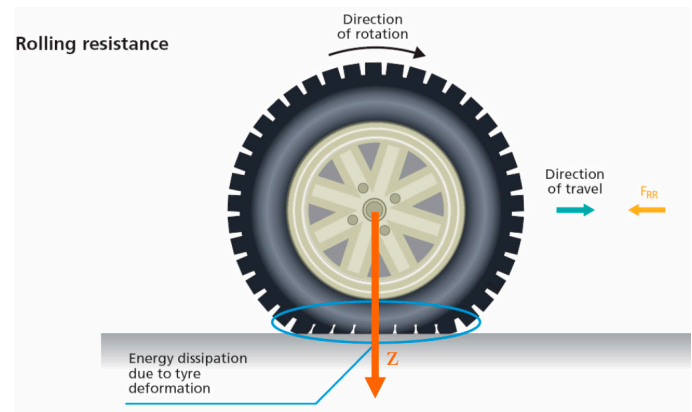


Figure 1: definition of tire's rolling resistance [2]

In the Michelin Performance and Responsibility report [3], the main environmental impact of the tire life cycle has been assessed to be, by far, linked to the rolling resistance of the tire while in use, compared to the production, design and manufacturing process. Indeed, rolling resistance accounts for up to 20% of fuel consumption from cars and 30 to 40% from trucks, while comparing it to the other resistive forces that have to be overcome by the vehicle. Furthermore, a study conducted by the U.S. National Research Council with funding from NHTSA showed that a 10% reduction in rolling resistance coefficient will yield a 1% to 2% increase in passenger vehicle fuel economy [4]. On the other hand, in support of their SmartWay® Transport program, the U.S. Environmental Protection Agency provided further evidence that reducing parasitic losses, such as rolling resistance, in heavy-duty highway

vehicles won't only reduce fuel consumption and greenhouse gas emissions, but will also provide NO_x reductions [5,6].

PURPOSE AND SCOPE

The work described in this paper was done to provide facts about energy efficient tires as they do not only help to reduce fuel consumption on passenger cars and commercial vehicles, but also contribute to limit environmental consequences of road transport, in particular the discharge of CO₂, CO and NO_x emissions. This paper has two distinct parts: the first part aims to specify a more appropriate rolling resistance vs. fuel consumption prediction law expressed in terms of kg/t and l/100km respectively, which has been established using simulation for vehicles having either a manual or an automatic transmission. Additionally the reliability of this approach is demonstrated in the second part of this paper, which is focused on validation tests and which also shows a reduction of CO emissions on a gasoline car and NO_x emissions on a Diesel car and a heavy duty vehicle, while reducing the power required to the engine. Finally the ultimate value of the tire is discussed in an economical and tangible way.

ROLLING RESISTANCE AND FUEL CONSUMPTION SIMULATIONS

ROLLING RESISTANCE MODELLING

Several methods for measuring rolling resistance exist since a tire's energy efficiency depends on many factors such as load, pressure, speed, ambient temperature, road surface roughness and rolling time, etc. However if the target is to describe the generic behaviour of tire's rolling resistance, it appears reasonable to use only a single and unique value of C_{RR} per tire which could be, for example, measured using the forthcoming ISO 28580 test method [7].

For usual driving conditions, the influence of speed on rolling resistance can be neglected, whereas the load carried by the vehicle increases rolling resistance force in a nearly linear way. Likewise, transient effects are also not taken into account in this model since it can be assumed that for passenger cars and long-haul heavy vehicles, the tire reaches its steady state operating temperature for major journeys relatively quickly. However, for short haul heavy vehicles, on/off road and urban bus tires this hypothesis does not hold true. Indeed, these tires never have enough time to reach thermal equilibrium as the vehicles continuously experience stop and go phases, while noting that it may take more than two hours for truck tires to reach thermal equilibrium.

Yet, in the case that the tires are not inflated to their correct pressure or appear to be worn, some corrections have to be performed to calculate an effective C_{RR} . Indeed, under inflated tires have a higher deflection

which leads to an increase in rolling resistance. For the example of a passenger car, a 6% increase in C_{RR} is expected when the tires are 30kPa below recommended pressure and 30% for 100kPa below [8]. Furthermore, when tires wear, the tread loses volume of hysteretic rubber and rolling resistance is lowered, when tires are totally worn, by approximately 20% for passenger car tires and 40% for truck tires, depending on tire design, wear profile and ageing.

Moreover, rolling resistance is usually measured on a test drum which imposes a curvature to tires which then leads to a higher deformation in the contact patch and thus to a larger rolling resistance than on a flat track. It has been shown that the curvature of the test drum can be adjusted to any curvature, including a flat surface, via Clark's Formula [9]:

$$C_{RR}(drum) = C_{RR}(flat) \cdot \sqrt{1 + \frac{R_{tire}}{R_{drum}}} \quad (2)$$

where R_{tire} and R_{drum} represent the radius of respectively the tire and the drum.

For a 2m diameter drum, which is stated as the reference in the ISO 28580, if we consider a passenger car tire having a 0.3m design radius and a truck tire having a 0.5m design radius, the rolling resistance on a flat ground should be 15 to 20% lower than the test measurement. On the other hand, the drum surface may also be either smooth steel or 80-grit 3Mite coated paper which does not really match the macroroughness of roads and tends to underestimate the actual rolling resistance on the vehicle. A macrorough surface can thus induce a larger rolling resistance of up to 40% [10]. Taking an average 15-20% correction factor for normal roads, these two opposite phenomena could more or less cancel each other. In other words, the rolling resistance coefficient C_{RR} measured on a test drum would be approximately equal to the one seen on the vehicle while driving on the road. Nevertheless, as it will be clarified further in this paper, the knowledge of the absolute value of rolling resistance isn't critical in predicting fuel savings. The difference in C_{RR} in kg/t between tire solutions is, in fact, much more important and will be assumed to remain the same on test drum and on vehicle.

Finally, the rolling resistance acting on the vehicle at a given velocity V can be expressed using the C_{RR} as previously estimated along with the vehicle's actual weight M and the gravitational acceleration g as:

$$F_{RR} = C_{RR} \cdot M \cdot g \quad (3)$$

Furthermore, if the vehicle is fitted with different tires, as it is often the case on trucks, an average rolling resistance coefficient must be computed by a weighted average of the individual tires $C_{RR,i}$ with the individual load applied on each Z_i :

$$C_{RR} = \frac{\sum_i C_{RR,i} \cdot Z_i}{\sum_i Z_i} \quad (4)$$

TIRE CONTRIBUTION TO FUEL CONSUMPTION

Naturally, rolling resistance is not the only force that the vehicle has to overcome to move forward. The effective power P_e which is required by the engine includes also several parts: aerodynamic drag, friction in the power train, a gravitational part each time the vehicle has to climb a slope, an inertial part each time the driver pushes the throttle to accelerate and auxiliaries. In addition, a thermal engine, including both gasoline and Diesel, dissipates a significant amount of energy in form of waste heat for every litre of fuel consumed and thus the concept of instantaneous efficiency η , which is function of engine torque and speed, needs to be introduced.

The power consumed by the combustion P_c is in fact 2.5 to 10 times greater than the engine-out power P_e , since the efficiency η varies generally between 10 and 35-40% depending on engine characteristics and operating point. Engine efficiency is defined as:

$$\eta = \frac{P_e}{P_c} \quad (5)$$

Figure 2 shows an example of a 1.5l-100HP Diesel engine map for a passenger car. The principle remains the same for a gasoline engine or for a Diesel engine designed for heavy trucks, whereas the torque, speed and engine efficiency values will change. The power required at the wheels is translated to the engine through the drive train into an engine torque proportional to the resistance to movement which includes the contribution of tire's rolling resistance, and to the engine speed, which is a function of the vehicle's velocity for a given gearbox ratio.

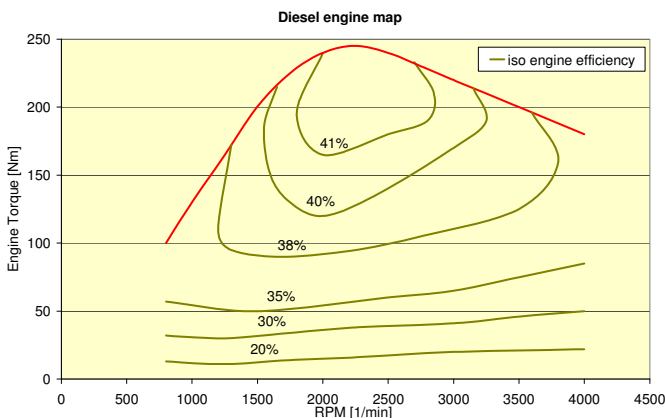


Figure 2: example of a 1.5l Diesel engine map

To calculate the fuel consumed by a vehicle over a given path, the instantaneous fuel consumption needs to be integrated over the total time of the journey for the following two cases:

1. When the driver is pushing the throttle, the instantaneous fuel consumption C can be expressed as a function of the required power P_e , the engine efficiency η , the fuel density ρ and the heat capacity H :

$$C = \frac{P_e}{\eta \cdot \rho \cdot H} \quad (6)$$

2. When the driver is not pushing the throttle, either the engine is turning at idle with an instantaneous fuel consumption depending on residual friction and auxiliaries, or the engine is "motored" and is applying a braking torque while the fuel is often shut off from the injectors. This is often done by drivers on more recent engines as a means to decelerate the vehicle.

Thus, to estimate the tire contribution to fuel consumption, the rate between rolling resistance power P_{RR} and required power P_e needs to be computed each time the engine is loaded in order to deduce the instantaneous fuel consumed due to rolling resistance component, C_{tire} :

$$C_{tire} = \frac{P_{RR}}{P_e} \cdot C = \frac{C_{RR} \cdot M \cdot g \cdot V}{\eta \cdot \rho \cdot H} \quad (7)$$

If δ is introduced as a binary function equal to 1 when the throttle is pushed and to 0 otherwise, the rolling resistance contribution to fuel consumption %RR can be expressed using the following expression:

$$\%RR = \frac{\int_0^t \frac{C_{RR} \cdot M \cdot g \cdot V}{\eta \cdot \rho \cdot H} \cdot \delta \cdot dt}{\int_0^t C \cdot dt} \quad (8)$$

Fuel economy simulations were completed with AVL Cruise® software [11] for various gasoline and Diesel cars and heavy trucks as shown in Table 1 over different usages which includes standardized cycles such as the EPA FTP-75 or the NEDC, as well as real journeys which were recorded using a GPS recording device.

Vehicle Segment	Engine	Transmission
European Small Car	gasoline 1.3l-75HP	manual
European Small Car	Diesel 1.5l-100HP	manual
European Uppermedium-sized Car	gasoline 1.8l-115HP	manual
European Uppermedium-sized Car	Diesel 2.0l-110HP	manual
European Medium Van	Diesel 2.5l-150HP	manual
American Uppermedium-sized Car	gasoline 3.0l-205HP	automatic
American Full-sized Pick Up	gasoline 5.4l-295HP	automatic
Asian Small Car	gasoline 1.3l-75HP	automatic
Asian Medium-sized Car	gasoline 1.8l-115HP	automatic
Asian Uppermedium-sized Car	gasoline 3.0l-205HP	automatic
European Medium Duty Truck	Diesel 11.0l-320HP	manual
European Heavy Duty Truck	Diesel 12.0l-480HP	manual
American Medium Duty Truck	Diesel 6.4l-350HP	manual
American Heavy Duty Truck	Diesel 12.7l-500HP	manual

Table 1: vehicle models used for Cruise® simulations