How agricultural tires contribute to the energy efficiency of the tractor

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Abstract

For several years, a joint work between Michelin and INRAE has been launched to define a protocol for evaluating traction efficiency using a specific test bench allowing the tire to be tested in real usage conditions while controlling and measuring all the influential external parameters.

Considering the variety of uses and types of soil encountered by an agricultural tractor, it is important to be able to differentiate the different sources of energy loss in the interaction of the tire with the ground to assess the influence on vehicle consumption. To achieve this, a hybrid method with experimental measurements and modeling has been developed to evaluate tire rolling resistance, ground compaction and slipping losses, relatively to use conditions (soil, nature of the work, load, pressure….).

In this work, the first results on soft soil, using ENTAM protocol, show a great importance of energy loss due to soil compaction and tire rolling resistance specially at low tractive effort. At higher traction, slipping losses became preponderant. Thus, the tire design and pressure management could be adapted to the usage to improve energy efficiency. This approach allows to feed a life cycle analysis tool for different types of usage and vehicles; this work shows that a major part of the environmental impact of the tire is due to the use phase of the tire on vehicle.

Keywords: Agriculture traction, agricultural tire, propulsion efficiency, energy efficiency, modeling and testing

1. Introduction

In the agricultural domain, Michelin has been innovating for more than 20 years to improve its tires for better energy efficiency of agricultural machinery. Numerous innovations have made it possible to reduce soil compaction by vehicles and improve their traction efficiency: the transition from diagonal structure tires to radial tires, then to wide tires and Ultraflex technology for use at low inflation pressure. This led to the standardization of so-called IF or VF tires, which have become widely used among tire manufacturers and on the market. More recently Michelin has participated in the development of centralized inflation systems (CTIS) by designing the Michelin EvoBib tire for polyvalent usage, optimized for use both on the road and in the field.

To promote these innovations and continue to improve its tires, Michelin has been working for many years on tools and methods for performance evaluation through digital simulation tools, laboratory, and vehicle tests. These first evaluations made it possible to determine the energy dissipation mechanisms in the tire. However, current simulation and laboratory test tools do not fully consider the interaction between the tire and the agricultural soil in all its complexity, and measurements on vehicles in the field are expensive and difficult to perform considering the numerous influential external parameters (soil, weather, vehicle, implement…). The dispersions associated with each of these parameters add an additional degree of complexity.

For several years, joint work between Michelin and INRAe has been launched to define a protocol for evaluating traction efficiency using a specific test bench allowing the tire to be tested in real usage conditions while controlling and measuring all the influential external parameters. The implementation of this hybrid method [experimental measurements / modeling] also makes it possible to feed a life cycle analysis (LCA) tool for tires for different types of usage and vehicles.

2. Context

How agricultural tires contribute to the energy efficiency of the tractor:

It is commonly accepted that for an agricultural tractor, energy losses due to the tire represent between 20% and 30% of the power provided by the engine. The main types of soil and uses impacting fuel consumption can be divided into several categories:

1. By type of soil :
   - Road: speeds reached can be high, from 40 to 65 km/h, the ground is considered non-deformable.
   - Field: speeds are often limited from 3 to 15 km/h, the soil is deformable with a variety depending on the current crop operation, location and weather.
2. By type of use according to the agricultural cycle during the year:

   example of typical use of a medium power tractor, 100kW
   - 30% Tillage, in the field with a high level of traction.
   - 20% Seeding and Spreading, in the field with a low level of traction.
   - 20% transportation, on road or hard surfaces.
   - 15% grassland & feeding , in the field with a low level of traction.
   - 15% Loader, hard soil (farmyard, sheds …).

Due to the variety of uses and types of soil encountered by the tractor, it is important to be able to differentiate the different sources of energy loss existing in the interaction of the tire with the ground to assess the influence on vehicle consumption.

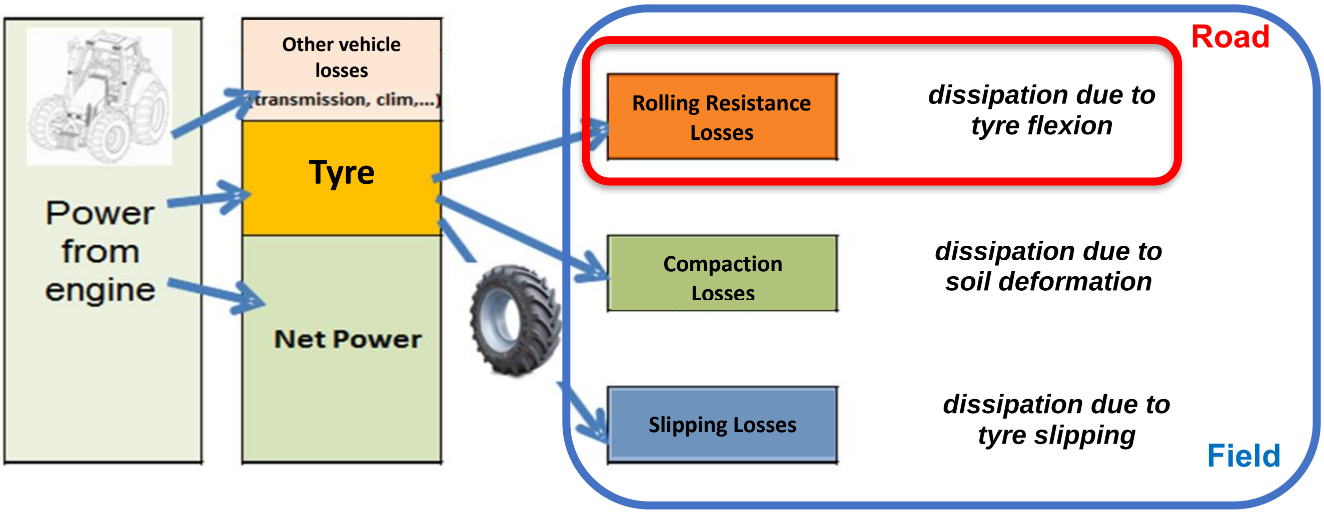
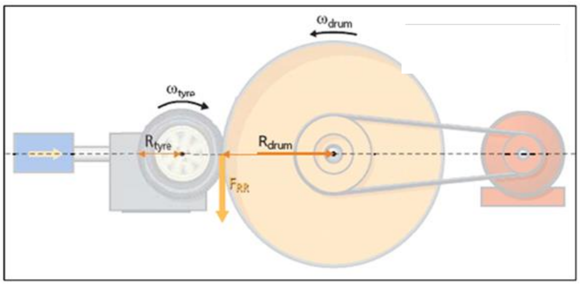


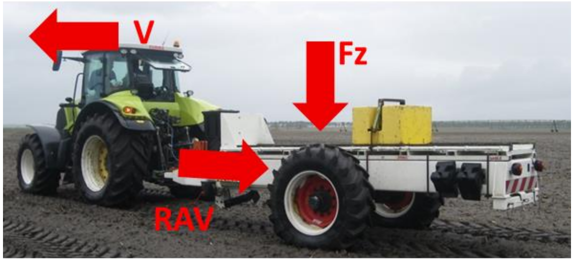
Fig. 1 : Nature of energy loss in the interaction of the tire with the ground

This decomposition by nature of loss makes it possible to act on the right levers to improve energy consumption depending on the type of use and soil, in fact the tire performance compromise is often antagonistic, this approach makes it possible to make the right choice of tire design and conditions of use (pressure, load, etc.). For example: lowering the pressure improves compaction and slippage but degrades rolling resistance (depending on the nature of the soil).

Current Materials and Methods:



Rolling Resistance (RR) is measured on a drum in a similar way than car or truck tires. This laboratory test method by deceleration makes it possible to measure and control all the factors influencing the rolling resistance performance (load, pressure, temperature ...).



The soil resistance (Rsoil) due to compaction is more complex to measure and cannot be determined directly. The moving resistance (Rav) is measured by a trailer and a tractor instrumented, integrating the Rolling Resistance and the soil resistance of the tested tires on the trailer (without tractive force). The soil resistance is then obtained by the formula:

Rsoil = Rav - RR.

The traction performance of the tire in the field is measured with two agricultural tractors (one driving and one braking), by measuring the tractive effort and the associated slip rate: Net Traction (NT) = function (Slip ratio). This requires measuring the rolling circumference to calculate the slip ratio (in function of vehicle speed V and wheel rotation w).

The use of these three test methods makes it possible to determine the different natures of energy losses in the interaction of the tire with the ground but the heterogeneity of the measurement materials (on drum, trailer and tractor) and methods makes it difficult to determine the distribution of losses with a good precision. Taking also into account the necessary control of the environmental conditions for field tests (vehicle effect, lead ratio, soil conditions, load transfer…).

Existence of a recognized “European” method:

Between 2010 and 2016, the ENTAM (European Network for Testing Agricultural Machinery, bringing together the expertise of different European institutes) establish a common method for evaluating the performance of agricultural tires. A working group “New experimental method for measuring the energy efficiency of tires in real condition on tractors” defined the soil conditions (mainly: texture, level of compaction and humidity) as well as the experimental methods to use to obtain results that can be recognized between countries. The efficiency indicators defined by the method (PLI – Pull Loss Index, and CLI – Carry Loss Index) are global indicators, giving access to the overall loss of energy between the input and the output of the vehicle, without possible access to the decomposition of losses between the tire and the ground. The values obtained are associated with different operating points of the tire (most commonly traction coefficients in the range [0 – 0.4]).

The existence of a described and recognized European method – which defines the means of testing, the field, the metrics and the methods for calculating them, is the starting point of the present work. The objective, around the INRAE single wheel test bench, is to valorize the information obtained for a tire in different functioning point, to make modifications of indicator calculation methods, to conclude on tire energy efficiency and energy loss decomposition.

3. Materials and Methods

INRAE, on its AgroTechnoPôle site at Montoldre, has a sophisticated test bench making possible to isolate the tire contribution to the system and measure its efficiency. Integrated into the ENTAM method, this device is used to provide measurements with several levels of traction coefficients applied to the tire and provide overall efficiency information at these functional points. The objective of the work is to fully exploit the recorded information to extract measurement points distributed over the full explorable traction range, then to adjust recognized model curves to (1) make the conclusions more robust, (2) aggregate data over identical ranges of traction coefficients, and (3) access the quantities explaining the different losses, i.e. rolling resistance, slipping, etc.

3.1 Single Wheel test bench

The INRAE Single wheel system is attached to the tractor at three points, making it possible to test a single tire, providing to it with input power (torque and speed), and measuring the output powers. This test bench (see Photo) presents several specificities:

- It allows to test the tire in real conditions (soil, humidity, speed, etc.) in an analytical way, the tire being tested alone.
- The load at the pneumatic and ground interface is perfectly constant by constructing the system chassis around the parallelogram principle: the application of a motor torque to the wheel drive hub does not generate any load transfer, thus the load is fixed by additional masses to the own weight of the chassis for each new test.
- The tractor provides the needed power source to drive the wheel and is also the brake of the system allowing the generation of a traction force between the wheel and the tractor. Thus, the gear engaged and the engine speed set the order of magnitude of the vehicle speed during the test;
- The application of a torque to the test wheel is obtained by a hydraulic motor which is electronically regulated to obtain, on demand, either a constant torque or a constant traction force; the change in target value of torque or tractive force can be modified instantly using the electronic interface;
- The system is instrumented to measure in real time the various physical parameters:
    - Torque applied to the wheel
    - Wheel angular speed
    - Tractive force generated by the test wheel (horizontal force)
    - Linear speed of the wheel, through dGPS with centimeter precision

The acquisition frequency is around 100Hz, making it possible to obtain a new set of data every centimeter of progress at a test speed of 1m/s.

The test conditions such as inflation pressure, load at the interface, etc. can be adjusted between each test. Unlike the ENTAM method which test the tire on the two way of the trajectory with identical conditions, the method developed mixes the levels of Traction Coefficient (or Traction Ratio TR = Traction Force / Vertical Load) in both travelling directions of the Single wheel in the field test, by providing randomly distributed TR levels, with the aim of exploring the inevitable dispersions of soil conditions, possible field obstacle, etc. The Single wheel test bench can measure on hard ground tire rolling resistance, or on targeted agricultural soil moving resistance on soft soil and slip rate. Thus, by using the same tool and methods, the sources of errors are minimized and the decomposition into nature of losses more robust.

3.2 Data processing and model fitting

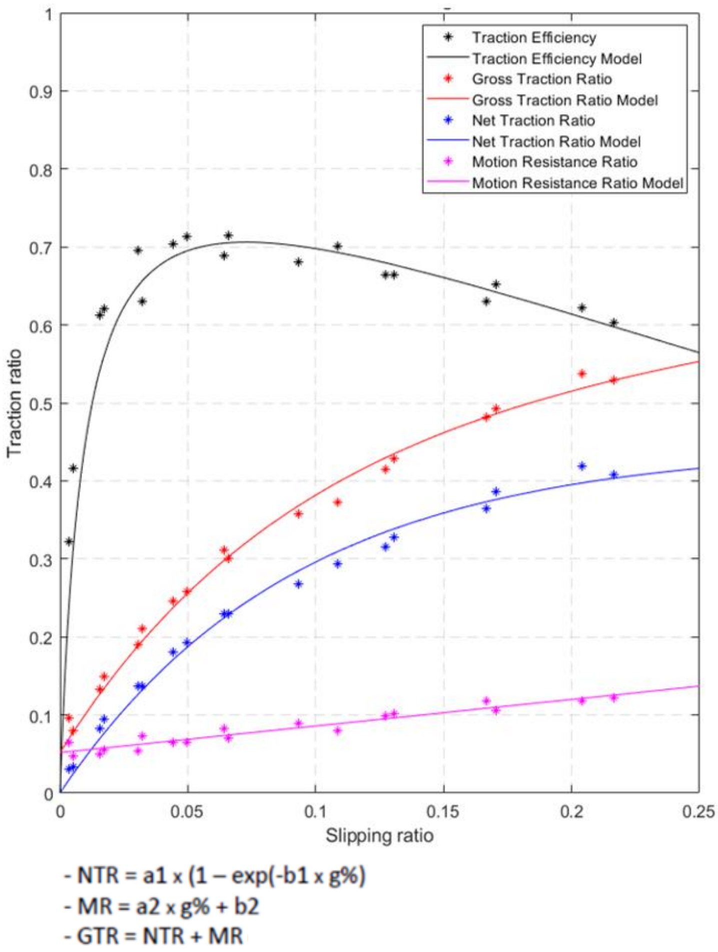
The data from the Single Wheel sensors recordings were also processed using a method that diverged slightly from that of the ENTAM method:

1. <u>Raw data processing:</u>
   - Each half turn of the wheel is processed to provide a set of average data.
   - The possible slope of the field on this half-turn of the wheel is extracted and used to correct the impacted quantities, in particular the tractive force; the average values for each level of traction are calculated (Gross Traction Ratio GTR, Net Traction Ratio NTR on the wheel, Motion Resistance Ratio MR of the tire and Traction Efficiency = NTR / GTR).
   - A recording under the same pressure and load conditions is made on hard ground (macadam) to provide rolling resistance on hard ground.
   - A test at zero traction force on the wheel with the motor torque just necessary to compensate the moving resistance of the tire is also recorded to access the rolling circumference.

   This method of processing raw data makes it possible to increase the exploration range of Traction Ratio explored during the test. It has the disadvantage of generating an experimental dispersion in the measured points, but the adjustment to the model then largely nuances this point.

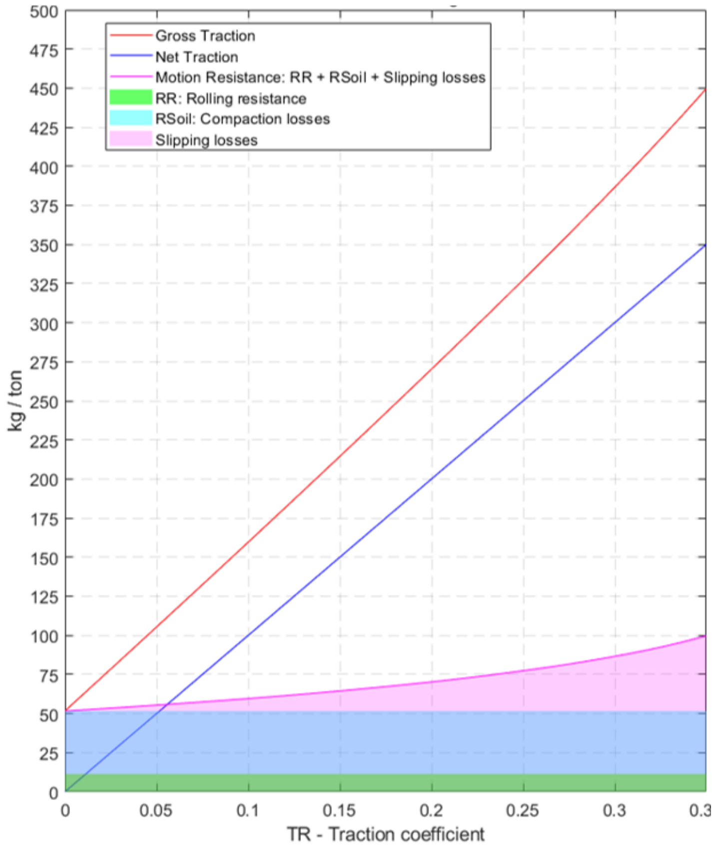
- <u>Adjustment of experimental data around a model:</u>

  The values obtained experimentally disperse in their position on the Traction Ratio values. Thus, the model developed by Mr. ZOZ (Ref. 1) is implemented for data adjustment. This model has the advantage of dissociating the energy loss quantities during the adjustment and using "black box" recordings to ultimately isolate the sources of power losses, even when they are difficult to discern from the noise of the experimental measurement. Of course, some assumptions must be accepted such as the independence of the rolling circumference from the slipping level for a given experimental configuration of inflation pressure, load, humidity, soil resistance...



3.3 Extraction of energy efficiency and nature of losses

The availability of models for each configuration allows to evaluate, all over the traction range studied the power supplied (Gross Traction), the power delivered by the wheel (Net Traction), the rolling resistance, the compaction losses and the slippage losses (see Graph). The expression of these quantities can then be produced according to the Traction Ratio (TR) level, or according to the slip level, allowing an objective comparison of tires under each of their conditions of use (pressure, etc.). It also becomes possible to calculate an overall efficiency index, over a given range, representative of a given agricultural use (rather "traction" or "load-carrying" tires).



3.4 Life Cycle Assessment methodology (LCA)

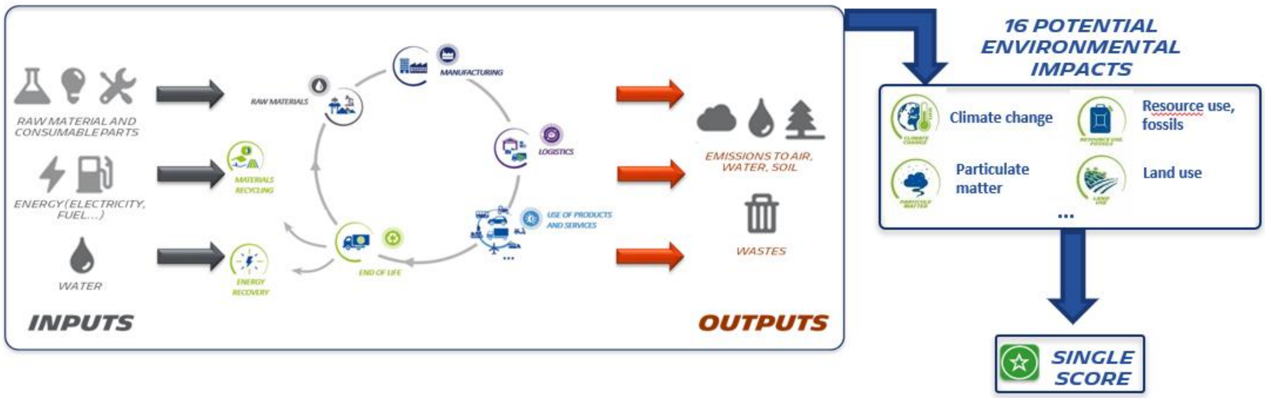
<u>LCA Goal:</u>

- "LCA quantifies the environmental impacts of a product, a process, a good or a service, from the extraction of raw materials to its elimination at the end of its life, through the phases of distribution and use, or from 'cradle to gate'."
- Present an overall vision of the potential impacts ("hot spots").
- Avoid "good" environmental ideas that transfer the pollution elsewhere.
- Compare the potential impacts of different scenarios, for example, two different tire designs.

<u>Methodology:</u>

The Michelin LCA tool called "MILCA" has been approved by the company "RDC Environment" in compliance with ISO 14040 and 14044 standards. It is a holistic assessment of the potential environmental impact of a service provided, it is composed of:

- Functional Unit definition: what is the service provided, for example the tire will perform 50.000km or 5.000 hours.
- Inventory of the inputs and outputs of the analysis.
- Potential environmental impacts Assessment with European unique score definition (PEF).



What we need to perform an LCA:

- Inventory of the raw materials and Manufacturing Stage (extraction, transport, energy …).
- Use Stage with the energy consumed by a tire in its use phase (and wear particle emission):
  - Measurements of tire energy efficiency and different energy losses at many different usage points (linked with the work done on single wheel with INRAE).
  - Relation between the energy dissipated by the tire and the vehicle fuel consumption.
  - Usage description and duty cycles (speed, traction, time distribution, soil …).
- End of life inventory, after shredding in Europe 60% of material recovery and 40% of energy recovery

A working group is in progress with INRAE to define a common methodology to harmonize LCA at different scale: tire, vehicle and farm (Project STAIRS - GRAND DÉFI ROBOTIQUE AGRICOLE).

4. Results and Discussion

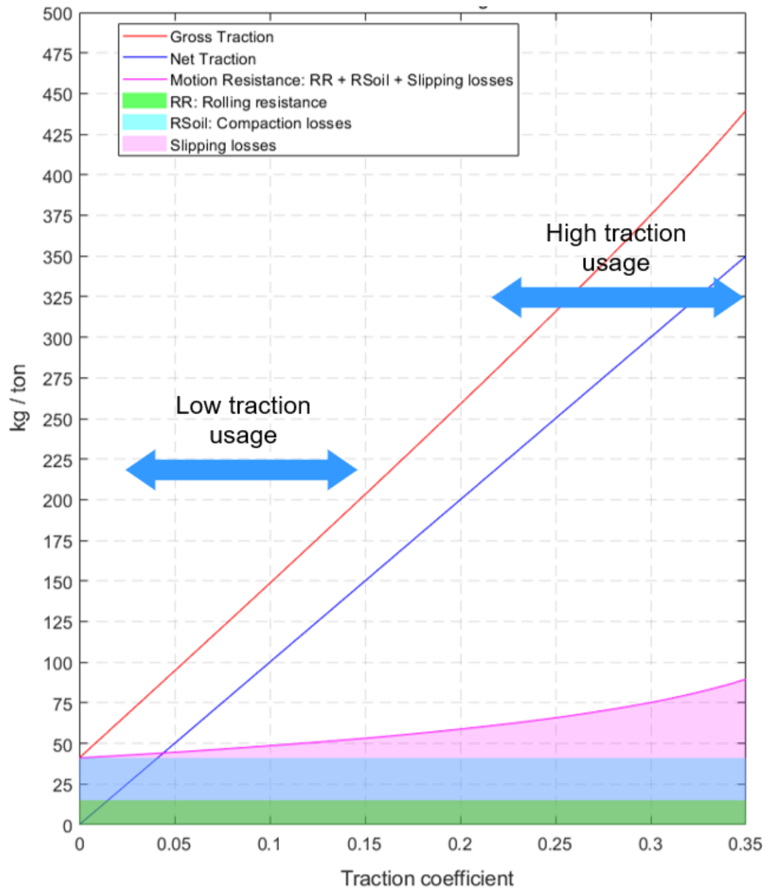
4.1 Results obtained on energy efficiency:

Distribution of losses sources:

The tests carried out in 2023 on ENTAM soil with 650/65 R42 Michelin MultiBib tire under field operating conditions of pressure and load are used for this example.

For low traction forces in transport, seeding and spreading operations (Traction Ratio around 0.1), the loss of energy by soil compaction (Rsoil) is a major part of the Motion Resistance with 60% of contribution, followed by rolling resistance (RR) with 30%, slipping losses represents only 10%. It is necessary to reach high traction forces on tillage type of work (TR~0.3) to obtain a significant part of losses due to slippage with 40% of contribution, at the same level of soil compaction.

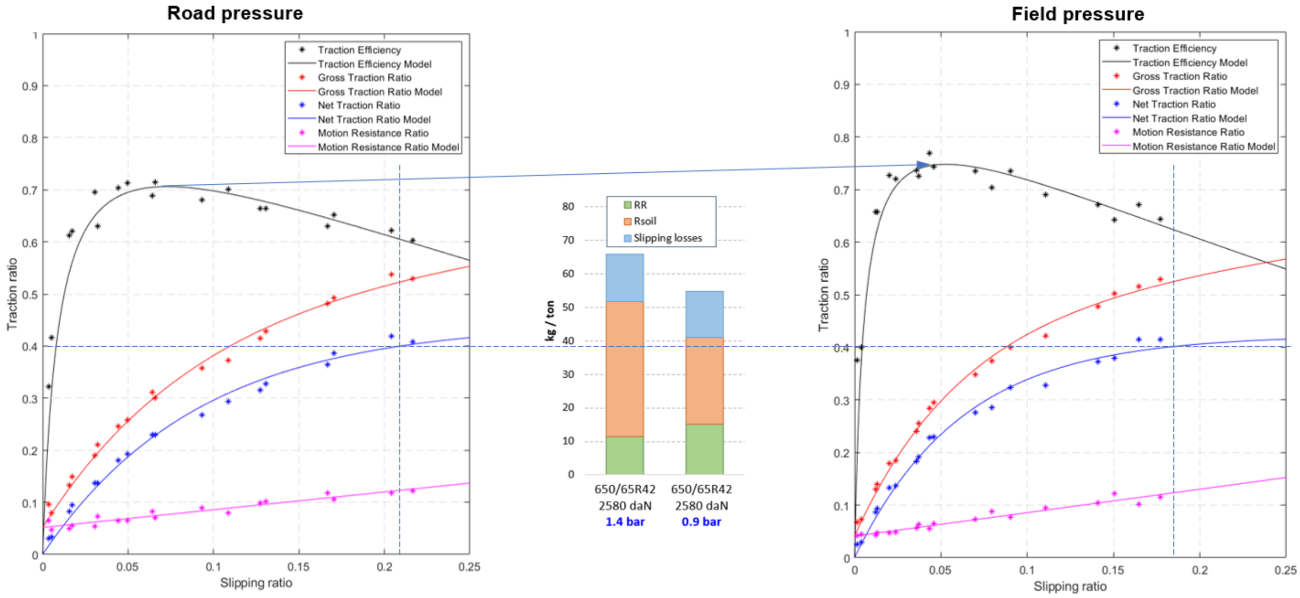
Warning: on very soft and wet soils the distribution of losses should be significantly different, the contribution of Rsoil and slippage will be greater relative to the Rolling Resistance.



The development in Montoldre, on the AgroTechnoPôle, of "large-sized soil boxes", with homogeneous and progressive textural natures in clay content, and controlled conditions of test concerning slope (horizontal), soil compaction and "manageable" humidity, will allow in the very near future to study these impacts very precisely.

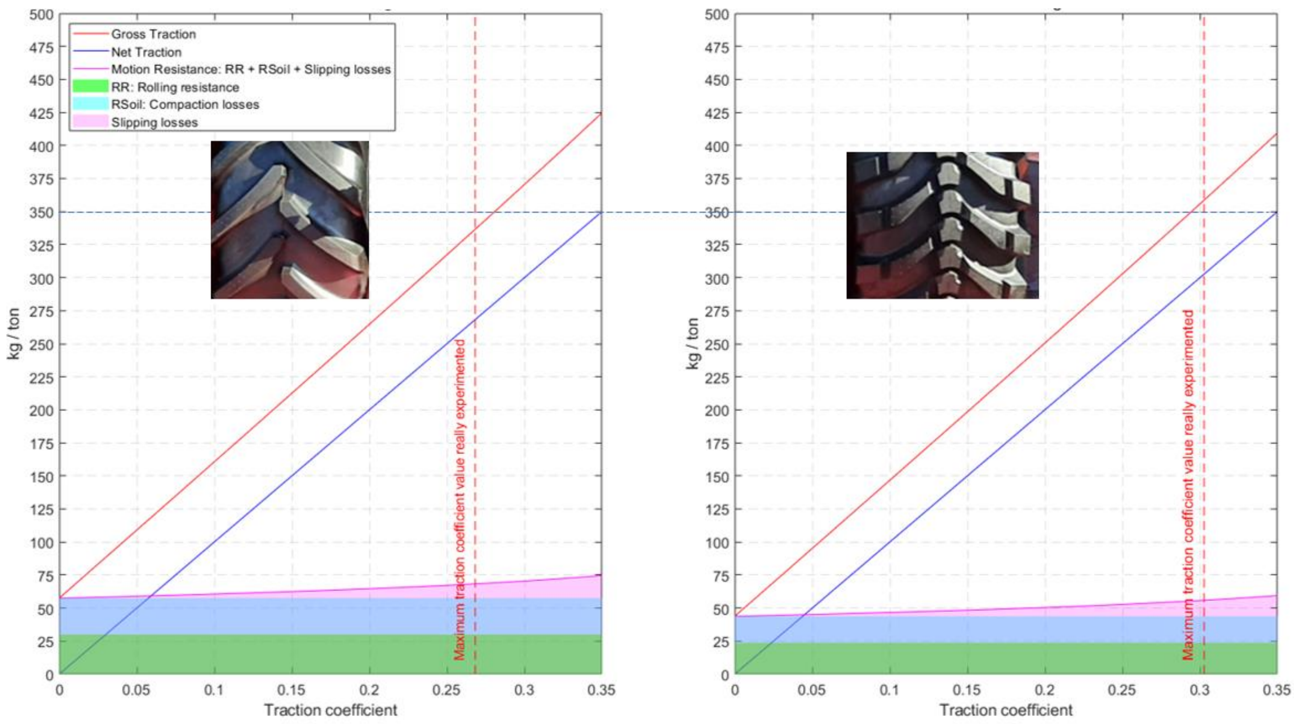
Effects of tire inflation pressure:

On the same test plan, a comparison with a higher road-type inflation pressure is presented. Low inflation pressure improves the traction efficiency of the tire, losses through slippage are thus reduced (on the curves presented below: 18% slippage instead of 21% for a Net Traction Ratio of 0.4). The soil compaction is also reduced (see Rsoil on histogram in the center), on the other hand the Rolling Resistance (RR) of the tire is penalized. For field use, it will be preferable to select a low inflation pressure, but this choice could be different for use on harder ground with a low level of traction, increase in Rolling Resistance could be too much penalizing.



Effects of tire range:

On high-power tractors equipped with 710/70 R42 tires, choosing the right tire range allows, depending on use, to significantly reduce energy consumption, as shown on the graphs below in the comparison of tires Michelin AxioBib 2 (on the left) and Michelin EvoBib (on the right).



On this type of ENTAM soil, the EvoBib tire has a level of traction equivalent to the high traction AxioBib 2 tire (at a TR level of 0.35) and makes it possible to reduce moving resistance by 25% (RR + Rsoil) over the entire range of use thanks to its innovative design. The development of such EvoBib pneumatic technologies is associated with Centralized Inflation System (CTIS) which allows adaptation of the operating point of the tire according to the use in real time (load, pressure, speed, ground, etc).

4.2 Results on Life Cycle Assessment:

The different energy losses due to the rolling resistance of the tire, soil compaction and slippage can then be integrated into the Life Cycle Assessment tool on the usage phase of the tire in addition to the extraction of raw materials, manufacturing, transport and end-of-life management.

Example of Low HorsePower (LHP) tractor and Michelin Multibib tire LCA:

Functional Unit: « Set of front and rear tires that allow a LHP tractor to work on a medium-sized European farm (42ha) » with the methodology presented in the previous chapter (3.4).

The usage phase of the tire is a major part of the environmental impact of an agricultural tire. It counts for 90% of the unique score (PEF method), far away from the raw materials at 8%.

Hence the importance for Michelin in its “all-sustainable” approach to take the use phase into account in its life cycle assessment and to characterize as finely as possible the different typologies of use and corresponding energy losses (high traction during plowing, hard soil during transport, soft soil during spraying and spreading …).

5. Conclusions

The test bench called "Single Wheel", developed by INRAe, is managed by the AgroTechnoPôle of Montoldre in Allier, on homogeneous agricultural surfaces prepared in a standardized manner according to the ENTAM protocol (European Network for Testing of Agricultural Machines).

The use of this test bench for different pneumatic solutions and usage configurations (pressure, load, relative tractive effort) makes it possible to experimentally explore a large part of the tire's operating range. The physical quantities thus measured feed recognized functional models and thus consolidate the performance evaluation, making it possible to isolate the different sources of energy loss (deformation of the tire when rolling, deformation of the ground by compaction and slippage during traction).

The results confirm the historical design choices and allow us to work on the right technological levers for future tire designs and will permit to develop new tire and soil models for energy efficiency evaluation in real usage for vehicle consumption optimization.

The implementation of this hybrid method [experimental measurements / modeling] also makes it possible to feed a life cycle analysis (LCA) tool for tires for different types of usage and vehicles.

The availability in a very near future, in 2025, of 4 large soil boxes, with homogeneous textures and increasing clay content, perfectly horizontal and flat, will be another step towards the method implementation by varying only the soil conditions. The experiments can be done the same day, under the same conditions.

Acknowledgements

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