
Development of a vehicle-road interaction analysis framework for truck tyres

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The current state of global warming requires immediate measures to reduce greenhouse gases and resource efficient vehicles act as a part of the solution. Rolling resistance of truck tyres is one of the main contributors to the environmental impact of road freight transport. To achieve adequate range for future battery electric trucks, parameters influencing rolling resistance and other tyre properties need to be researched carefully. Tyre manufacturers are able to affect rolling resistance by optimising tyre design, rubber compounds, and by balancing between conflicting properties such as rolling resistance, wear, particulate emissions and grip. Vehicle manufacturers on the other hand can focus on enhancing the optimal usage of the tyre with simulations and testing. The aim of the present work is to develop an FE truck tyre and road modelling framework to be able to quantify and optimise the energy consumption due to rolling resistance and its potential trade-offs with e.g. damaging vehicle forces and road damage. To build an accurate FE truck tyre model, different measurements has been performed to characterise material properties and the tyre structure. Furthermore, a suitable constitutive model is chosen which takes into account amplitude and frequency dependent stiffness and dissipation characteristics. To model the tyre rubber, a parallel rheological framework is used to simulate amplitude and frequency dependency of storage and loss modulus. Currently, there are no simple parametrisation methods and the usage of more advanced constitutive models have a trade-off between tuneable parameters and accuracy. Therefore a simple and robust parametrisation technique for filled rubber with clear and understandable tuneable parameters that can be used in FE tyre simulations is under development. The objective of the tyre model is to enable trade-off evaluations between different properties such as energy consumption and wear of truck components. The ultimate goal is to assess the society-benefit of innovative vehicle chassis and tyre technologies with the developed vehicle-road interaction framework.

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1. Introduction

Rolling resistance (RR) of truck tyres consumes a very large part of the driving torque. This directly affects greenhouse gases and the profitability of truck operation. In 2019, the European Union (EU) set new targets for heavy duty vehicles to reduce average certified truck CO₂ emissions by 15% by 2025 and with 30% by 2030 in the EU [1]. All of the manufacturers must comply with these targets or otherwise they are given financial penalties per manufactured vehicle for excess emissions, 4250 €/gCO₂/tkm by 2025 and 6800 €/gCO₂/tkm by 2030. These targets require at least partial electrification of the heavy duty segment. Although the electrical motor losses are low, the batteries are much larger and heavier than the fuel tanks. This makes reduction of the aerodynamic drag and rolling resistance even more important to be able to build electrified trucks with sufficient range.

Even though rolling resistance is a well-known and researched phenomenon, it is still one of the most cumbersome tyre properties to measure and simulate. For measurements this is partly due to vertical loading forces being multiple orders of magnitude higher than measured longitudinal resisting forces and all the parameters affecting the RR. Great difficulty to characterise filled rubber behaviour arises from its highly nonlinear mechanical behaviour. Filled rubber properties are frequency, amplitude and temperature dependent [2]. Rubber even changes its mechanical properties depending on the previously applied maximum load (Mullins effect) [3], and the properties change over time when tyre experiences ageing. The mechanical behaviour of filled rubber is hysteretic, and 80-95% of rolling resistance is generated by the hysteretic behaviour of the rubber. Due to this hysteretic behaviour, a rolling tyre has a centre of contact pressure in front of the rotation axis [4] which results in a braking moment (Figure 1). Therefore accurate modelling of the tyre rubber properties is crucial for rolling resistance simulations.

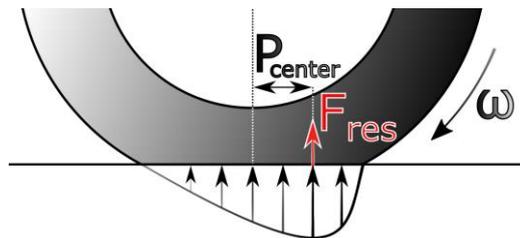


Figure 1: Contact pressure due to hysteretic behaviour of rubber in rolling motion.

The remaining part of the rolling resistance is due to frictional effects (adhesion, stick and slip) at the contact patch. These are highly dependent on the surface roughness and the rigidity of the road. All these properties together with a composite steel-rubber-fabric structure make RR highly nonlinear and difficult to model and measure. FE simulations of tyres often include nonlinear elasticity and viscoelasticity, near incompressibility, damage, large strains and rotations, follower forces, frictional effects, and possibly temperature effects.

EUs tyre labelling system ranks truck tyre rolling resistance from grade A to F and provides an easy way to compare different tyres. A is the lowest value (< 4 kg/ton) for rolling resistance and F is the most energy-inefficient tyre (≥ 8.1 kg/ton). The tyre is warmed up by rolling it against a drum with 85% of the maximum tyre load, constant speed and temperature ($+25$ °C) until the tyre reaches a stable temperature distribution and rolling resistance, according to ISO 28580:2009 [5]. The warmup takes three hours and then a single RR value is measured. This way to evaluate RR is a major simplification and lots of information is lost by having only one measurement point. Examples of lost information are tyre pressure, different loading conditions, velocity and temperature dependency, tyre cooling and the effect of different surfaces. Rolling resistance is usually at its highest value when the tyre is cold [6]. This is interesting to note since for example distribution vehicles often drive only 10-20 minutes and then stop to unload or load the vehicle. In this case the vehicle would almost always have cold tyres and from this perspective EU labelling of rolling resistance is an insufficient indicator for these type of vehicles. Furthermore in Europe, truck drivers are not allowed to drive continuously more than four and half hours, which means that the labelled value is correct at its best only 50% of

the time during highway driving. Therefore, there is a need to develop more detailed testing and simulation methods to assess rolling resistance more accurately.

Reducing rolling resistance usually has undesirable effects on braking and handling properties and usually influences negatively the wear properties and product cost. Tyre wear generates PM1.0-PM10 size particles which can end up in alveoli and cause harmful diseases. Currently, there are no standard procedures to assess tyre particle emissions and it is difficult to know where all the particle emissions end up [7]. In certain operating conditions the benefits in lower rolling resistance might be less important than actually having a better wear resistant tyre that dissipates more energy. Better tyre recommendations based on the specific usage conditions could yield more resource efficient vehicles. It is important to be able to simulate tyres in a more accurate way to understand and balance different tyre aspects. To achieve this, the objective is to develop a vehicle-road analysis framework (Figure 2).

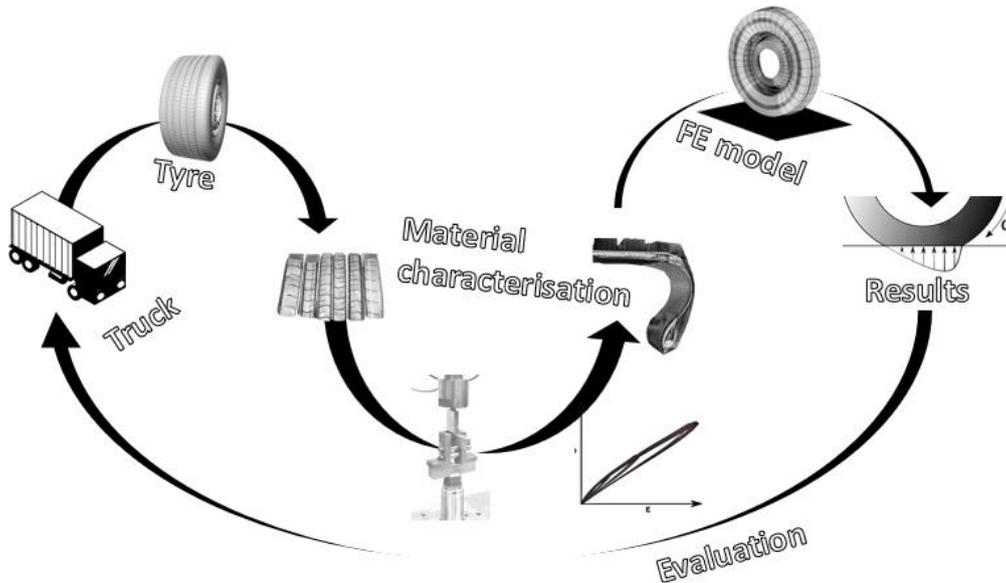


Figure 2: Framework for vehicle-road analysis.

2. Vehicle-road interaction

Rolling resistance can be defined as a longitudinal force resisting the motion of the vehicle. The coefficient of rolling resistance (C_{rr}) is unitless and described as the ratio between longitudinal resisting force (F_x) and vertical force (F_z), $C_{rr} = \frac{F_x}{F_z}$. The measurements done according to the ISO 28580:2009 testing standard are correlated to a drum that has an outer diameter of 2 m with a correction equation because the contact area is smaller than driving on a flat road [5]. The usual drum values result in slightly erroneous measurement values, since a smaller diameter alters the contact pressure of the tyre and results in a too high tyre temperature. The measurements can be improved with a load cell that can be used in real road traffic.

Tyre manufacturers can reduce the rolling resistance by rubber compounding but this causes a compromise with other critical properties, e.g. comfort, grip and abrasion resistance. Rubber compounding is always balancing between conflicting goals. Vehicle manufacturers on the other hand can focus on enhancing the optimal usage of the tyre with FE simulations in an early stage of vehicle design rather than reducing rolling resistance by compounding. Parameters that contribute to rolling resistance, wear and load carrying capacity are for example number of axles, axle loads, wheel alignment, steering and suspension solutions, tyre pressure, tyre and ambient temperature. Directing cooling airflow away from the tyres could be an effective way to increase tyre temperature and reduce rolling resistance [8]. An example of the complexity of the RR and the need to understand tyre-road interaction is the effect of tyre pressure on rolling resistance. On hard surfaces, increasing tyre

pressure has a decreasing effect on rolling resistance, whereas on soft surfaces a higher tyre pressure can have an inverted effect. This is due to the larger penetration of the surface [9].

For constitutive modelling purposes it is important to take into account the amplitude dependency of the storage and loss modulus, which is called the Fletcher-Gent effect or the Payne effect [10]. Storage and loss modulus are measures of stiffness and dissipation, respectively. The Fletcher-Gent effect can be explained as a rapid decrease of storage modulus after a certain strain amplitude.

By far the most popular way to simulate hysteretic effects of tyre rubber is using Prony series in combination with a hyperelastic model [11]. The problem with linear viscoelastic models such as Prony series is that the viscoelastic properties are not dependent on the strain amplitude as they are for the rubber used in tyres. Therefore different parts of the tyre require a new set of parameters to accurately simulate the tyre rubber even if the used material would be identical. Nonlinear viscoelastic material models on the other hand are able to simulate the Fletcher-Gent effect but the parameters are not intuitive and require stress-strain data as an input for the parameter optimisation. Especially when multiple nonlinear viscoelastic models are organised in parallel the parameters lose their meaning and tuning of the parameters after optimisation becomes cumbersome. More accurate models usually have a trade-off between number of parameters and accuracy.

In this research, a viscoplastic parallel rheological modelling technique is chosen to simulate tyre rubber and it is able to capture the Fletcher-Gent effect. A parametrisation method that reduces the tuneable parameters of the constitutive model is being developed where the amount of tuneable parameters is not dependent on the number of different viscoelastic or plastic networks. Figure 3 shows the combined effects of viscoelastic, plastic and total response of all parallel models in different amplitudes and frequencies. The Prony series gives the model the rate dependency (frequency stiffening) whereas the plastic elements give the amplitude dependency for the model (Fletcher-Gent effect) and additional width of the hysteresis loops.

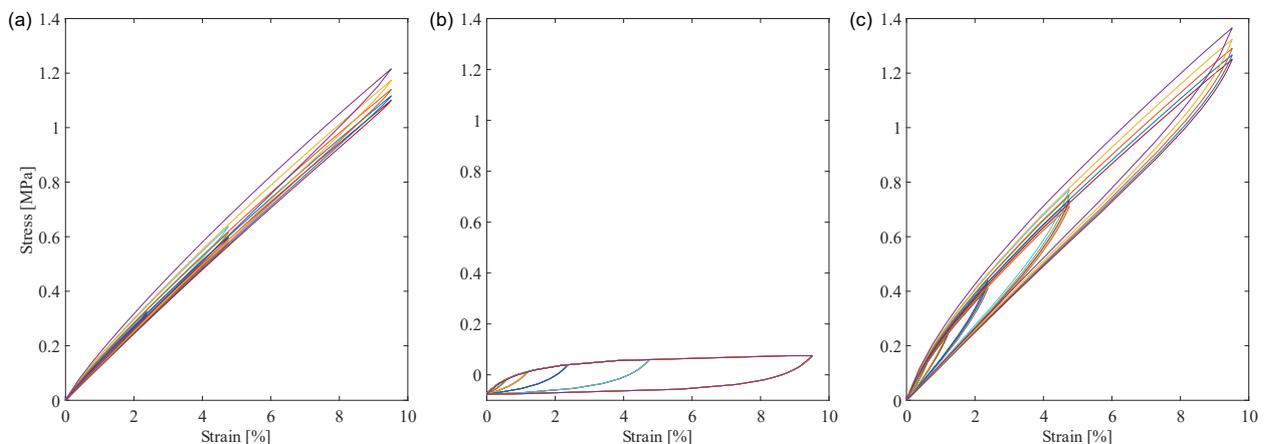


Figure 3: Example results of parametrised material model. Hysteresis loops from Prony series (a), hysteresis loops from plastic networks (b) and the total response (c).

Figure 4 illustrates the calculated storage and loss modulus values over a large range of frequencies and amplitudes. Increased rubber temperature above glass transition temperature increases the molecular movement of the rubber which reduces hysteretic effects. Thus, the rolling resistance reduces with increasing tyre temperature. The simulations can be done by parametrising the rubber in its working temperature or by making the parameters temperature dependent.

An FE truck tyre model is currently being developed with the help of reverse engineering techniques. To be able to model the tyre 3D-scanning is used for the outer geometry of the tyre. X-ray (Figure 5) and CT-scanning are used for reconstructing the belt structure. Dynamic mechanical analysis (DMA) is used to test the tyre rubber properties and is used for parametrisation. To measure different parameters a measurement fixture has been built to tests the stress-strain response in shear and tension. To be able to choose sufficient amount of rubber specimens to DMA tests,

thermogravimetric analysis, laser spectrometry and IRHD hardness tests have been conducted to samples from different positions from the tyre section.

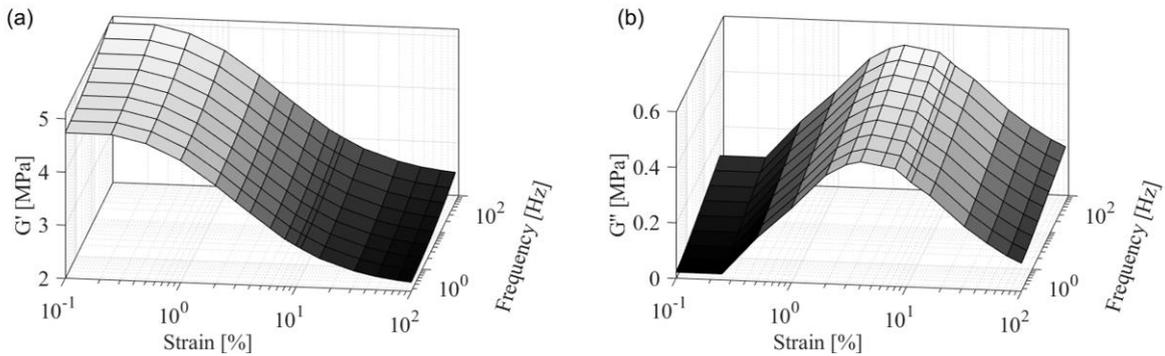


Figure 4: Amplitude and frequency dependency for the parametrised material model. (a) Storage modulus G' and (b) loss modulus G'' .

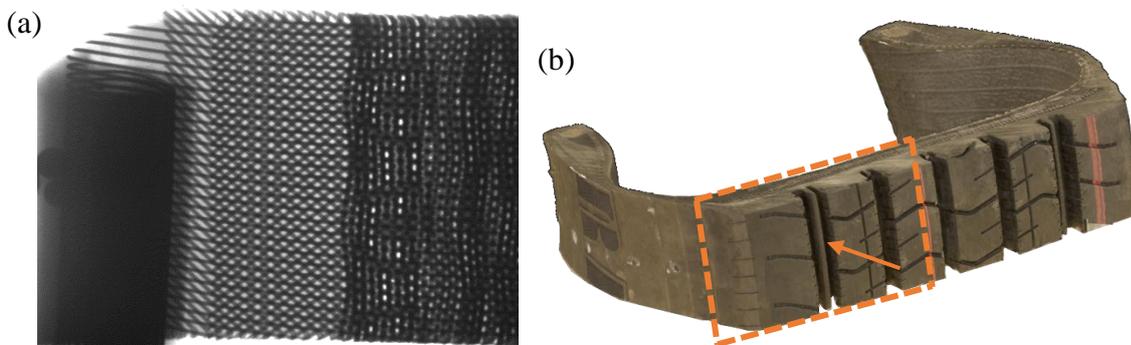


Figure 5: (a) X-ray image from the belt structure and (b) photoscanned 3D-model of a tyre section and the position of the X-ray image.

3. Discussion and conclusions

Understanding tyre behaviour and being able to simulate tyres accurately is essential to reach the strict green-house gas emission goals. For the tyre rubber, a suitable modelling technique has been chosen and a parametrisation technique to effectively capture the Fletcher-Gent effect is being developed. Parametrisation methods are as important as the constitutive models employed. A simple and robust parametrisation technique enables quick parameter studies and removes the need to have a set of rubber test data to conduct sensitivity studies. Moreover, the same parametrisation technique could be used with other rubber simulations such as bushing and vibration isolator simulations.

Further on, the developed FE truck tyre model is intended to be used in balancing between conflicting requirements, such as rolling resistance, wear, handling and damaging forces to the vehicle and road. With the help of an accurate physical model of a tyre within the vehicle-road simulation framework, an assessment of society-benefit of future vehicle technologies is more feasible.

In the near future, whole tyre measurements will be conducted in a climate wind tunnel using different ambient temperatures to quantify the temperature effects on transient and stabilised rolling resistance. Not only is the goal to create a vehicle-road interaction simulation framework but also to develop a convenient method to test tyre rolling resistance in real road operation. Therefore a load cell that can be used in real road rolling resistance measurements instead of usual drum and flat belt measurements is planned to be developed.

Acknowledgements

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