EXPERIMENTAL EVALUATION OF LOW ROLLING RESISTANCE TYRES FOR HEAVY GOODS VEHICLES IN SOUTH AFRICA

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1. Introduction

Globally, transport is one of the major contributors to climate change, accounting for 23% of CO_2 emissions in the energy sector [1]. In South Africa, transport accounts for around 10% of the country's greenhouse gas emissions [2]. Of this, road transport is significantly overrepresented, accounting for around 90% of this figure, and of this road freight transport with heavy commercial vehicles comprises 21% [3]. The South African government has set a target of 5% greenhouse gas emissions reduction from transport by 2050 [4] – a challenging target in a developing economy. With an ever-increasing logistics demand, it is crucial that reducing emissions associated with heavy commercial vehicles must be tackled.

Of the various technological and logistics interventions which can reduce emissions in road freight transport, low rolling resistance or 'green' tyres present a relatively low-barrier-to-entry solution. Bradley and Delaval [5] reported that green tyres can improve fuel consumption, and hence reduce greenhouse gas emissions, by 4–6%. In road freight transport where fuel accounts for approximately 36% of operating costs [6], these savings can have a significant impact on an operator's bottom line, while reducing carbon emissions.

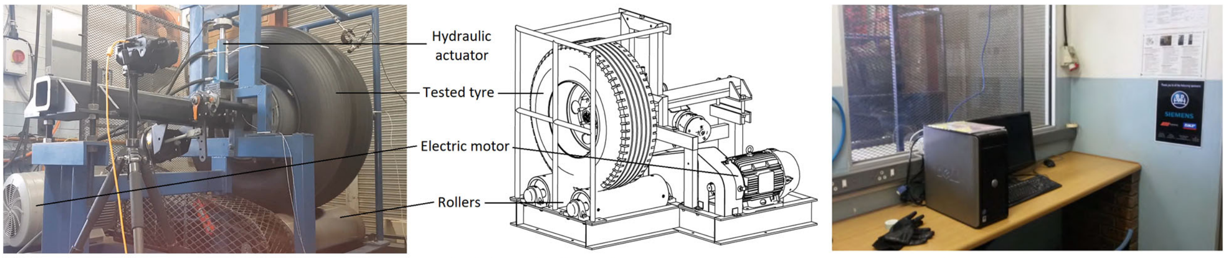
Despite these benefits, the uptake of green tyres by industry in South Africa has been limited. Possible reasons include: cynicism surrounding tyre manufacturers' claims of savings, overemphasis on the capital cost of tyres over the impact which tyres have on operating costs through fuel consumption, lack of visibility that tyre purchasing managers have that tyre choice affects fuel consumption, uneasiness over the limited applicability of green tyres to urban logistics and off-road operations, and concerns over the reduced tyre life of low rolling resistance tyres.

To address concerns surrounding tyre manufacturers' claims of the performance benefit of low rolling resistance tyres, we present two independent sets of experiments in which the performance of green tyres is compared to conventional 'black' tyres. First, the rolling resistance coefficients of green and black tyres were measured using a custom-built test rig. Then, full-scale vehicle tests were conducted measuring the fuel consumption on two 56-tonne interlink trucks using the green and black tyres under steady highway conditions. Analysis and comparison of the two sets of results and the development of an easy-to-use model of energy loss mechanisms, revealed local conditions, such as vehicle combination mass, steady-state operating speed of the vehicle, and air density significantly impact the expected fuel and CO_2 savings. Finally, we present an example comparison calculation of the green tyres versus the black tyres on the bottom line; including the fuel and tyre costs (addressing the valid concern that low rolling resistance tyres do have a reduced wear resistance). The calculation illustrates the importance of including the fuel consumption costs in deciding which tyres to purchase; the improved fuel consumption offsetting the increased tyre costs if the tyre wear is manageable.

2. Methodology

2.1. Laboratory testing of low rolling resistance tyres

A custom-built test rig was used to measure the rolling resistance of green and black truck tyres (See Figure 1). The rig was adapted from a previous experiment which was used to measure the temperature increase of the components surrounding the brakes due to the heat dissipation from the brakes and energy dissipation from the tyres and bearings [7]. The test rig was used to test a pair each of Michelin X Line Energy (the green tyres) and Michelin X Multi (the black tyres). The tyre size used in both cases was 315/80 R22.5. The tyres were fitted to dual rims in each case and tested in dual tyre configuration. (Note that Figure 1a and 1b show a single tyre case.) Both sets of tyres were driven for 20,000 km on vehicles before being tested in the laboratory.



a) Custom-built test rig b) Schematic of test rig c) Control room

Figure 1: Custom-built test rig used to measure rolling resistance

The rig consists of one half of a BPW Eco Plus 2 axle. The axle can be fitted with single or dual rims fitted with truck tyres. The tyres rest on two rollers which are driven by a 30 kW Siemens electric motor via a chain drive. A hydraulic piston between the axle and the rig frame controls the vertical load on the wheel. The wheel speed is controlled using a Siemens variable speed drive which outputs the required power required to drive the rollers which drive the tyres. A Siemens programmable logic controller (PLC) modulates the wheel speed and hydraulic axle load. The two smooth rollers do not perfectly reproduce driving conditions on a flat rough road surface. However, the tests are representative. The overall cyclical tyre deformation under the simulated axle load is comparable, and this deformation accounts for the majority of energy losses in a rolling tyre.

The power required to overcome the rolling resistance can be calculated by measuring the power required to drive the motor and subtracting other losses in the system. In this case, the dominant power loss not associated with rolling resistance comes from the four roller bearings. An estimated 200 W of power was lost in the bearings, estimated from empirical equations given in an SKF catalogue. Each set of dual tyres was tested at an angular speed of 21.3 rad/s equivalent to 40 km/h (11.1 m/s) for a period of 4 hours with a vertical load of 30 kN. The power measurements were averaged from the final 2 hours of testing once the tyres had approached steady-state temperature.

The 30 kN vertical load at the actuator produces a vertical load of $30\times882/1312 = 20.2$ kN at the centre of the dual tyres. The diagram of forces illustrating the lever arms is shown Figure 2. The 20.2 kN vertical load of the tyres equates to a vertical load on an axle of $2\times20.2/9.81 = 4.12$ tonne. A realistic axle load for an unladen vehicle. The motor was run at an angular speed of 21.3 rad/s. Estimating the rolling radius to be 0.522 m produces an equivalent speed of 11.1 m/s (40.0 km/h). More realistic speeds heavy vehicle speeds of 80–100 km/h could not be achieved due to the limitations of the test rig.

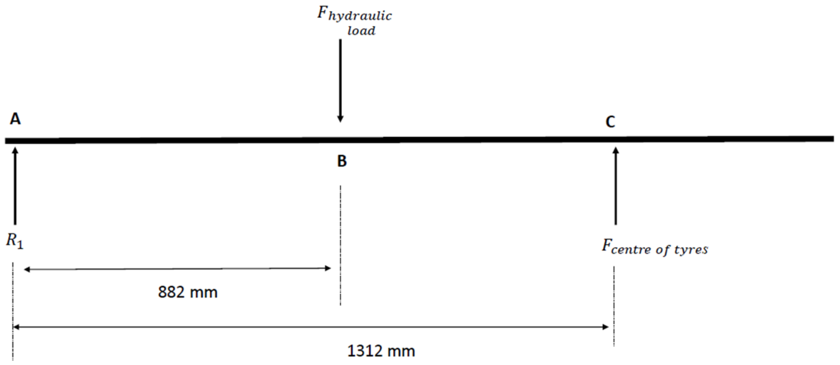


Figure 2: Relating the hydraulic load to the vertical load at the centre of the tyres

2.2. Track testing of low rolling resistance tyres

The same model tyres were tested on two full-scale vehicles on the high-speed oval track at Gerotek, west of Pretoria. Two identical 7-axle interlink (or ‘B-double’) tautliner vehicle combinations were used for the trials, comprising Iveco Stralis 6x4 truck-tractors and 2-axle Afrit leader and follower trailers. Dual-tyre configurations were used on all trailer axles, as is common for vehicles of this type in South Africa, resulting in a total of 26 tyres per vehicle. The ‘test’ vehicle was fitted with Michelin X Line Energy tyres, and the other ‘baseline’ vehicle was fitted with Michelin X Multi tyres. All tyres were size 315/80R22.5. Both vehicles were loaded with 2-tonne pallets of cement bags to almost the maximum permissible combination mass of 56 tonnes according to South African regulations. The vehicles and test track are shown in Figure 3 and Figure 4.

Figure 3: The two test vehicles at Gerotek

Figure 4: The oval high-speed test track at Gerotek

Each vehicle was instrumented with an 'SRF Logger' [8], developed at the University of Cambridge. The SRF Logger comprises a custom-developed app installed on an Android smartphone (Samsung S8 devices were used), and a Bluetooth dongle connected to the vehicle CAN bus which communicates vehicle CAN messages to the device. The app combines CAN bus data with data from the phone's internal GPS and accelerometer sensors, as well as internet-derived information on local weather, temperature, and wind speed. Additional instrumentation included infrared tyre temperature sensors directed on one drive axle tyre of each tractor, and a "sight-glass" fuel level indicator on each fuel tank. The latter was required to ensure that the fuel was filled to the same point when refilling. The fuel quantity filled was measured from the fuel bowser using a mechanical volumeter with a precision of 0.1 litre. The electronic instrumentation is shown in Figure 5.

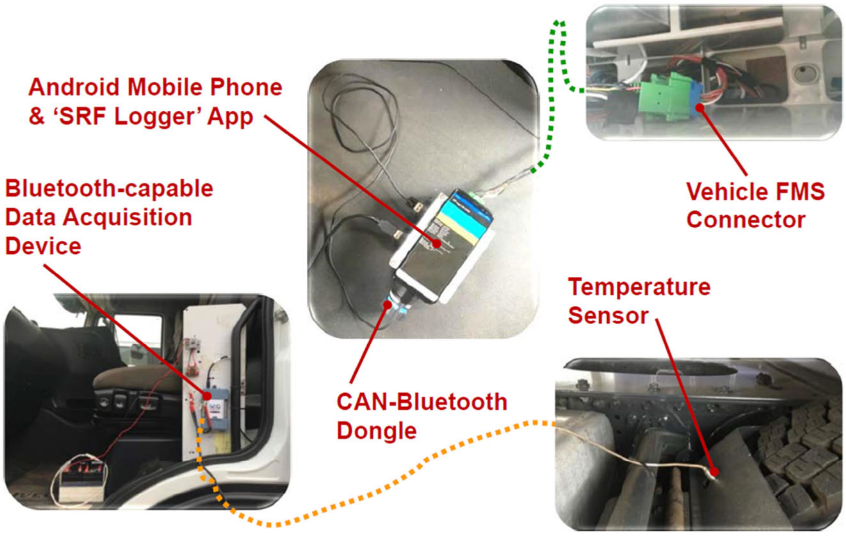


Figure 5: Vehicle instrumentation, including SRF Logger and tyre temperature sensor

The vehicles were driven by professional drivers on the track simultaneously at 80 km/h using cruise control, in four 2-hour intervals per day, over two days. After each 2-hour interval, the drivers swapped vehicles to normalise for any driver differences. At the end of the first day, all tyres were swapped between the two trucks, to normalise vehicle differences. The drivers were given a resting time between each testing interval as per best practice. This was determined to be 15 minutes after the first and third driving intervals and 30 minutes for lunch after the second driving interval. Fuel pump measurements of fuel usage were taken during the 30-minute lunch interval and after the final session when the fuel was refilled to the sight glass line. In the morning before the first session, the volumetric fuel level had dropped due to the cooler temperatures and the fuel had to be topped up 2–3 litres. These top-up amounts were small compared to the total fuel used for the day of almost 600 litres per vehicle.

3. Results and Discussion

3.1. Laboratory test results

The power required to overcome the rolling resistance of the X Multi duals at a vertical load of 20.2 kN and an angular speed of 21.3 rad/s was measured to be 1.59 kW, and 1.34 kW for the X Line Energy duals. The estimated 200 W to overcome the resistance in the bearings has been subtracted from both values. Assuming a simple rolling resistance model (where rolling resistance is a linear function of vertical load only, and where there are no secondary velocity-dependent effects), the coefficient of rolling resistance for the X Multi tyres was thus estimated to be:

$$(1.59 \text{ kW}) / (11.1 \text{ m/s}) / (20.2 \text{ kN}) = 0.0071$$

and for the X Line Energy tyres:

$$(1.34 \text{ kW}) / (11.1 \text{ m/s}) / (20.2 \text{ kN}) = 0.0060.$$

The coefficients of rolling resistance are within the range of 0.006–0.01 presented by Wong for truck tyres on concrete and asphalt [9] and appear realistic despite the noted limitations of the test rig. The results are summarised in Table 1.

Table 1: Test rig measurements of X Multi and X Line Energy rolling resistance

	X Multi (black tyres)	**X Line Energy (green tyres)**
Vertical load at actuator [kN]	30.0	
Vertical load at the tyre [kN]	20.2	
Angular speed [rad/s]	21.3	
Equivalent longitudinal speed [m/s]	11.1	
Power consumption [kW]	1.59	1.34
Rolling resistance coefficient [-]	0.0071	0.0060

Using a model of fixed proportions of the energy loss mechanisms (e.g., rolling resistance and aerodynamic drag), we can calculate the percentage improvement in fuel and CO2 savings due to an improvement factor y_k:

$$\text{Fuel and CO}_2\text{ saving improvement} = 1 - \left(\frac{x_k}{y_k} + \sum_{\substack{i=1 \\ i \neq k}}^{n} x_i \right) \tag{1}$$

Here x_k is the proportion of energy required to overcome loss mechanism k for which an improvement y_k is implemented, and x_i is the proportion of energy required to overcome the other loss mechanisms.

For the green tyres, the improvement factor in rolling resistance $\boldsymbol{y_{k=1}}$ is 0.0071/0.006 = 1.18. Using the modelled proportions for a 5-axle tractor semitrailer at a combination mass of 36.3 tonne on level road operating at 105 km/h detailed by Woodroofe **[10]**, $\boldsymbol{x_{k=1}}$ = 0.32 (rolling resistance), $\boldsymbol{x_{i=2}}$ = 0.53 (aerodynamic drag), and $\boldsymbol{x_{i=3}}$ = 0.15 (auxiliary and drivetrain losses). The calculated fuel and CO2 saving improvement using equation (1) is thus:

1 − (0.32/1.18+0.53+0.15) = 4.9%

which is in line with the quoted values of Bradley and Delaval [5].

3.2. Track test results

The calculated fuel saving benefit of the green tyres over the black tyres is summarised in Table 2. Results derived from both CAN bus data and fuel pump measurements are included. Savings of 8–10% were recorded and the average saving of the CAN data measurements is 8.8%. In the afternoon session on the first day of testing, the fuel pump measurement was incorrectly noted. This was due to the sight glass (an external PVC pipe connected to the fuel tank with a line marked on it) shifting due the duct tape glue holding the PVC tube in place melting in the extreme heat of above 30 °C. The manual fuel pump measurements from the other three readings are in good agreement with the CAN data measurements.

Table 2: Calculated fuel savings of the XLine Energy tyres relative to the X Multi tyres

	Test Day 1: 24 Oct				Test Day 2: 25 Oct			
	Session 1	Session 2	Session 3	Session 4	Session 1	Session 2	Session 3	Session 4
CAN data measurement	**8.0%**	**9.0%**	**9.8%**	**8.1%**	**8.0%**	**9.3%**	**9.3%**	**9.2%**
Fuel pump measurement	**8.7%**		**Sight glass error**		**10.1%**		**8.6%**	

The results of Bradley and Delaval [5] for similar tyres suggest a saving of 4–6%, and based on the measurements of rolling resistance and using a model from the literature a saving of 4.9% was calculated in Section 3.1. The higher-than-expected savings of 8–10% (average 8.8%) measured from the full-scale vehicle tests are potentially due to a combination of the 56-tonne combination mass which is relatively high compared to global norms, the 15% lower air density in Pretoria (altitude of 1340 m above sea level) as compared to sea level, and the high ambient temperatures during testing (>30 °C, during which the better heat dissipation characteristics of the green tyres is more pronounced). The speed of 80 km/h used for testing was also relatively low compared to the 105 km/h used by Woodrooffe [10], who observed a saving of 5%.

Equation (1) can be improved by including adjustment factors to align the base model of energy loss mechanisms with those of the tested vehicle:

$$\text{Fuel and CO}_2\text{ saving improvement} = \frac{\sum_{i=1}^{n} x_i \prod_{j=1}^{m} \Delta_{i,j} - \left(\frac{x_k \Delta_{k,j}}{y_k} + \sum_{\substack{i=1\\ i\neq k}}^{n} x_i \prod_{j=1}^{m} \Delta_{i,j}\right)}{\sum_{i=1}^{n} x_i \prod_{j=1}^{m} \Delta_{i,j}} \tag{2}$$

Where $\Delta_{k,j}$ is an adjustment factor for the loss mechanism k for which an improvement y_k is implemented, and $\Delta_{i,j}$ is the adjustment factor for the other loss mechanisms.

The adjustment factor for the rolling resistance due to the higher combination mass, $\Delta_{k=1,j=1}$ is 56/36.3 = 1.54 (as rolling resistance is linearly proportional to the vertical load on the tyres). The adjustment factor for the aerodynamic drag in terms of the 15% reduction in density, $\Delta_{i=2,j=1}$ is 0.85 (as aerodynamic drag is linearly proportional to air density). Accounting for the difference in speed, $\Delta_{i=2,j=2}$ is 80^2 / 105^2 = 0.58 (as rolling resistance is linearly proportional to the square of the speed). Substituting these adjustment factors into equation (2), the fuel and CO_2 emissions reduction in using green tyres is:

$$\text{Fuel and CO}_2\text{ saving improvement} = \tag{2}$$

$$\frac{(0.32 \cdot 1.54 + 0.53 \cdot 0.85 \cdot 0.58 + 0.15) - \left(0.32 \cdot \frac{1.54}{1.18} + 0.53 \cdot 0.85 \cdot 0.58 + 0.15\right)}{(0.32 \cdot 1.54 + 0.53 \cdot 0.85 \cdot 0.58 + 0.15)}$$

$$= 8.3\%$$

Accounting for just the combination mass adjustment would predict a saving of 6.4% (an absolute increase of 1.5% on the saving of 4.9%), for just the density 5.3% (an absolute increase of 0.4% on the saving of 4.9%), and for just the speed 6.2% (an absolute increase of 1.3% on the saving of 4.9%). The fuel and CO_2 saving improvement adjustment increase due to the increased combination mass of 1.5% on the 4.9% suggests that the use of low-rolling resistance tyres holds substantial benefit for high-capacity vehicles with a high combination mass, including those approved using performance-based standards (PBS). An Australian Level 2 PBS vehicle may have a combination mass of up to 85 tonnes [11]. In South Africa, Level 2 PBS vehicles of up to 84 tonnes are operational [12].

The fuel and CO_2 saving improvement adjustment increase due to the decreased speed of the vehicles of 1.3% on the 4.9%, demonstrates that low rolling resistance tyres have increased benefit when operated at low speeds. This suggests that low rolling resistance tyres are suitable for urban deliveries where vehicle speeds are lower as compared to long haul transport. However, this benefit should be carefully balanced against the increased tyre scrubbing which may occur on urban deliveries and the poorer tyre wear resistance of low rolling resistance tyres. The benefit of fuel savings using the green tyres may be negated by the increase cost of tyre replacement.

A portion of the unaccounted for 0.5% (8.8% - 8.3%) could possibly be due to the >30 °C ambient temperatures. It is recognized that the measurement uncertainty makes the calculated 0.5% value speculative; nevertheless, temperature measurements show that temperature plays a significant role. Table 3 shows the recorded increase in tyre temperature relative to the ambient temperature for the two tyre ranges. The green tyres consistently operated at around 5–12 °C cooler (on average 7.4 °C) than the conventional tyres; confirming the lower energy dissipation in the green tyres.

Table 3: Increase in tyre temperature above ambient temperature

	Test Day 1: 24 Oct				Test Day 2: 25 Oct			
	Session 1	Session 2	Session 3	Session 4	Session 1	Session 2	Session 3	Session 4
Ambient	**30.0 °C**	**30.4 °C**	**30.6 °C**	**30.7 °C**	**30.0 °C**	**30.0 °C**	**30.0 °C**	**30.1 °C**
Green Tyre	**13.8 °C**	**20.9 °C**	**22.1 °C**	**20.3 °C**	**17.0 °C**	**17.7 °C**	**17.3 °C**	**15.8 °C**
Black Tyre	**25.4 °C**	**29.9 °C**	**31.3 °C**	**29.1 °C**	**22.2 °C**	**23.4 °C**	**22.3 °C**	**20.8 °C**

3.3. Converting the fuel savings into bottom line savings

The X Line Energy or green tyres have been shown to reduce the fuel costs over the X Multi tyres or black tyres by 8–10% (8.8% average); the fuel costs are reduced by a factor of 0.912. The green tyres have an increased cost associated with their use due to their poorer wear; estimated to be 33%, based on information supplied by Michelin South Africa. The tyre costs are increased by a factor of 1.33. Estimating the fuel costs to be 36% of the overall cost of operation and the tyre costs to be 3% [6], the overall cost reduction or bottom line improvement (ignoring externalities) is:

$$\text{Cost reduction} = \frac{(36+3)-(36\times 0.912+3\times 1.33)}{36+3} = 5.6\% \qquad (3)$$

For a typical profit margin of 4% in South Africa [13], the above calculation suggests that using low rolling resistance or green tyres can more than double the profit.

4. Conclusions

1. Both controlled laboratory tests and full-scale vehicle tests were conducted to compare the rolling resistance performance of Michelin X Multi ('black tyres') and Michelin X Line Energy (low rolling resistance 'green tyres').
2. The laboratory measurements of coefficient of rolling resistance of the black tyres and green tyres were 0.0071 and 0.0060 respectively.
3. In the full-scale tests, two fully laden B-double combinations operated at steady highway speeds of 80 km/h demonstrated a fuel consumption saving of 8–10% (8.8% average) for the green tyres compared to the conventional black tyres.
4. Based on the laboratory measurements of rolling resistance and using a model of fixed proportions of the energy loss mechanisms from the literature, the fuel and CO_2 savings benefit of the green tyres was estimated to be 4.9%. Adjustment factors were applied to the energy loss mechanism model which accounted for the test vehicle having an increased mass, operating in lower density air, and at lower speeds. The calculated improvement of using the green tyres when including these adjustment factors was 8.3%. This agrees well with the measured values from the full-scale tests of 8–10% (8.8% average).
5. The adjustment factor due to the increased combination mass indicates that significantly higher savings of fuel and CO_2 emissions can be expected when using low rolling resistance tyres on high-capacity vehicles with a higher combination mass as compared to conventional vehicles. Further factors which increase the benefit of using low rolling resistance tyres are lower vehicle speeds, higher altitudes with lower density air, and environments with a high ambient temperature. The influence of these factors illustrates the importance of understanding the local operating conditions when evaluating the performance benefit of low rolling resistance tyres or other intervention to reduce fuel consumption and CO_2 emissions.
6. The green tyres were found to operate on average 7.4 °C cooler than the conventional tyres during the testing, indicating less energy dissipation.
7. Finally, an example comparison calculation of the green tyres versus the black tyres on the bottom line; including the fuel and tyre costs, shows that green tyres can more than

double the profit for a suitable long haul freight task in which the tyre wear is manageable and does not increase the tyre costs beyond 33%.

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