MOTION RESISTANCE MEASUREMENTS ON LARGE LUG TYRES

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Motion resistance of tyres directly contribute to the operational costs of all vehicles. Advances in the design and simulation of large off-road vehicles (construction, mining, agriculture etc.) have increased the need for accurate models of large off-road tyres. Vehicle OEMs use coast down and drawbar pull tests to determine the motion resistance of tyres used. Drum test rigs and motion resistance test trailers can also be used to determine motion resistance. Most research on motion resistance to date have been conducted on passenger car tyres with on-road truck tyres coming into focus. Motion resistance studies on agricultural tyres traversing over deformable terrain have been conducted in the past. However as more off-road vehicle are being used on-road OEMs of off-road vehicle are infesting in motion resistance measurements on non-deformable terrain. This paper compares different methods used to measure the motion resistance of a large lug tyre, as used in agricultural applications, on non-deformable terrain. Some basic considerations that need to be taken into account are the very low longitudinal forces that need to be measured compared to the large vertical load carried by the tyre and tyre operating conditions.

Keywords: motion resistance, drum test, drawbar pull, coast down test, motion resistance measurement trailer, agricultural tyres, large lug tyres

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Notation

A	Vehicle frontal area	[m^2]
a	Acceleration	[m/s^2]
C_d	Drag coefficient	[]
C_r	Motion resistance coefficient	[]
C_{rDB}	Motion resistance coefficient drawbar pull	[]

C_{vr}	Vehicle motion resistance coefficient	[]
F_{pl}	Parasitic losses	[N]
F_r	Motion resistance force	[N]
F_{r01}	Motion resistance force measurement on drum one	[N]
F_{r02}	Motion resistance force measurement on drum two	[N]
F_{r25}	Motion resistance force at 25 degrees Celsius	[N]
F_x	Longitudinal Force	[N]
F_{xDB}	Longitudinal Force measured during drawbar pull	[N]
F_z	Vertical Load	[N]
I_{fw}	Inertia of front wheel	[kg.m^2]
I_{rw}	Inertia of rear wheel	[kg.m^2]
K_r	Drum diameter correction factor	[]
K_t	Temperature constant	[]
L_m	Load on tyre normal to drum	[N]
M	Vehicle mass	[kg]
r	Test drum radius	[m]
r_{rr}	Tyre rolling radius	[m]
r_1	Radius drum 1	[m]
r_2	Radius drum 2	[m]
r_T	One half of the nominal tyre diameter	[m]
R_{RL}	Road Load	[N]
R_{RL_cd}	Road Load from coast down	[N]
$R_{RL\text{-}comp}$	Road Load with inertial compensation	[N]

t_{amb}	Temperature ambient	[°C]
T_{pl}	Torque on drum from parasitic losses	[N.m]
T_t	Torque on drum	[N.m]
V	Vehicle velocity	[km/h]
W	Vehicle weight	[N]

Greek letters

θ	Track Gradient	[°]
ρ	Air density	[kg/m^3]

1. Introduction

Over the last decade considerable advances have been made in the levels of detail design and simulation of large off-road vehicles. This includes vehicles for the construction, mining and agricultural industries amongst others. These advances in simulation have been driven as many of these large vehicles, which still fits within the legal road limits, are being used on public roads thus they need to comply with strict national road traffic and Carbon Dioxide (CO_2) emissions regulations all over the world. Even with the larger vehicles the Original Equipment Manufacturers (OEMs) have to compete with increased production requirements on the one hand, which means operating at higher velocities and on the other hand stricter industrial regulations, CO_2 emissions regulations as well as Occupational Health and Safety (OHS) regulations. This has forced OEMs to invest in more detailed simulation orientated design processes to increase efficiency of the vehicles. The increase in production operating conditions typically drives improved handling characteristics and lower operating costs as the vehicles need to travel safely at higher velocities over longer distances. OHS regulations together with CO_2 emission regulations and end-user requirements drives operator comfort, lower CO_2 emissions, lower operating costs and payload isolation.

On large off-road vehicles, as with passenger cars, the tyres play a very important role in the dynamic behavior of the vehicle as all of the tractive forces (lateral and longitudinal directions) acting on the vehicle goes through the tyre to the terrain. The motion resistance of the tyres contributes continuously to the operating costs of the vehicle together with the efficiency of the vehicle drivetrain. These vehicles also operate at different vertical loads (between un-laden and laden conditions) and large variants of tyre pressures for different terrains and loads. All of this adds to the complexity of the vehicles behavior and changes the contribution of the motion resistance in the operating cost and efficiency of the vehicle. The vehicle OEMs can drive the design for improved drivetrain efficiency and the tyre manufacturer drives improved tyre design for lower motion resistance and improve traction in tyres. Vehicle OEMs frequently use drawbar pull and coast down tests to determine the motion resistance of tyres which enables them to decide on which tyre to use on their vehicles to run at the highest efficiency on deformable and non-deformable terrain. Tyre manufacturers mostly use drum test rigs to determine the motion resistance of their tyres in indoor laboratories. This paper describes and compares different methods used to measure the motion resistance of a large lug/ high lug profile tyre, as used on agricultural vehicles, on non-deformable terrain. Research and test procedures are well established for passenger car tyres, but very limited for large tyres, especially with off-road construction and large lugs/high lug profile or large tread blocks. With the limitation of test equipment capable to test large tyres, OEM’s of agricultural, construction and mining vehicles have internal test procedures/specifications to measure motion resistance, which does not always result in the same results obtained during independent third party vehicle evaluation testing. As a result OEM's are asking the question of which method should be used to measure motion resistance?

2. Motion Resistance Measurements

Several methods exist to determine the motion resistance of tyres on passenger cars, commercial, heavy duty, agricultural and construction vehicles. These methods include coast down tests, drawbar pull tests, motion resistance test trailers and drum test rigs. However no comparison could be found in literature where all these methods are compared on the same tyre as each method has its own complicating factors and limitations. Motion resistance is a very difficult measurement as the longitudinal force on a free rolling tyre, is very small compared to the applied vertical load on the tyre, especially on non-deformable terrain. The motion resistance on concrete is typically less than 2% of the vertical load and very dependent on the tyre construction, rubber compound, inflation pressure, travel velocity, temperature and terrain, as described by Gillespie, 1992. On passenger vehicles traveling non-deformable terrain and at high inflation pressures the motion resistance can be as low as 0.5% which places a lot of emphasis on the accuracy of the measurement systems used during these tests. Due to the very low longitudinal load compared to the large vertical load measured on the axle when driving on non-deformable terrain, wheel force transducers in general are not the ideal measuring equipment to use for this specific application. In the passenger car and commercial semi-truck industries a large variety of tyre parameterization test rigs are available. Many test laboratories are spread worldwide and most have the capability to parameterize these relatively small tyres. MTS is a large supplier of these test rigs. Only a few examples of test equipment is referenced in this paper. Typical indoor laboratory test rigs are drum test rigs or flat track rigs. Some test rigs can only be used for traction characterization, where other test rigs can only conduct side force vs slip angle tests or motion resistance measurements.

The MIRIAM project, an acronym for "Models for motion resistance In Road Infrastructure Asset Management systems" is a project with twelve partners from Europe and USA. This project focused on reducing the energy consumption due to the tyre/road interaction, by selection of pavement with lower motion resistance. Sandberg (2011) did a comprehensive study of all possible methods for measuring motion resistance from inner and outer drums, with different surface textures, to a motion resistance trailer and coast down tests on passenger and commercial semi-trucks. However this study was unable to directly compare different techniques on the same tyre.

The University of Hohenheim, has multiple large tyre test rigs in the form of a flatbelt test stand, single wheel test trailer and an instrumented test tractor, as described by Witzel (2018). Due to the very low force ratio of motion resistance to vertical load it is no always possible to measure motion resistance with equipment designed to measure traction or braking tests. Other single wheel test trailers have been built for agricultural tyres, used and upgraded from early 1960's to present. These trailers can be used on any terrain. Billington (1973) introduced the NIAE MkII single wheel tester in 1973. Ambruster and Kutzbach (1989), developed a single wheel tester which parameterized a driven wheel at pre-set slip angles. Shmuleviuch et al. (1996) presented a new field single wheel tester. It is unknown if these single wheel testers are still in service and how accurately they would measure motion resistance. Test rigs used by fka research institute in Aachen, Germany, to measure motion resistance include the Mobile Tyre Test Trailer and the Truck Tyre Test Rig which is a 2.5m drum test rig.

Coast down tests are typically conducted with the use of the ISO 28580-2009 and SAE J2263-1996 standards. Any vehicle can be used during a coast down test as these tests can be conducted with only the use of a Global Positioning System (GPS). Ambient conditions needs to be noted and sometimes measured, dependent on which standard is used for the motion resistance calculations. These tests are dependent on the gradient of the test surface and the texture of the test surface. Tests are conducted in opposite directions to eliminate wind direction and gradient effect. The inertia of the test vehicle's drivetrain can have an effect on the test results, however if the same vehicle is used to compare different tyres, this can be neglected to an extent depending in which context the rolling resistance is used. Laboratories conducting motion resistance testing according to ISO 28580-2009 calibrates/aligns their test equipment relative to a master laboratory and reference tyre. This allows one to be able to compare results between different tests laboratories. This indicates the possible variance in motion resistance coefficients, C_r, that one can obtain even between testing laboratories.

The laboratory alignment procedure in ISO 28580, which, for passenger tyres uses two alignment tyres to calibrate a test laboratory to a master laboratory, states that it will compensate for differences induced from tests conducted using different options under the test standard. These options include the use of one of four measurement methods (force, torque, power, or deceleration), textured or smooth drum surface, correction of data to a 25°C reference temperature, and correction of data from tests conducted on a test drum of less than 2.0-m in diameter to a 2.0-m test drum. The ISO test standard strives to be functional with the various technical capabilities. In ISO 28580, Section 10.2.2: "The reference machine laboratory control tyre monitoring must occur at a maximum interval of one month. Monitoring must include a minimum of 3 separate measurements sometime during this one month period. The average of the 3 measurements made during a one month interval shall be evaluated for drift from one monthly evaluation to another." Per ISO 28580, Section 10.5.5: "The alignment process must be repeated at least every second year and always after any significant machine change or any drift in candidate machine control tyre monitoring data."

In summary the literature has indicated that measuring the motion resistance coefficient of a tyre has many contributing factors from ambient temperature, tyre operating temperature, test vehicle efficiency, tyre rubber compounds, tyre tread patterns, terrain surface texture, and terrain unevenness to terrain stiffness. Different methods used to determine the motion resistance includes tests such as drum tests rigs, coast down tests, drawbar pull tests and trailer test.

The equipment used in this study was not aligned to a master laboratory but the same measuring equipment was used as far as possible during all of the tests conducted during this study, with the aim of comparing measurements from different test methods on the same tyre. Testing was conducted over a period of six weeks.

3. Motion Resistance Test Setups and Theory

The intent of this paper is to compare motion resistance values calculated from different test methods, in the form of drum, coast down, drawbar pull and trailer tests, on the same tyre. The tyre of interest for this study is a Trelleborg TM700 280/70R16 agricultural large lug tyre with a load index of 109 and velocity rating of 40km/h. This specific tyre was chosen as it has large lug/ high lug profile tyre which causes vibration which can be seen in the measurements, it is a typical agricultural tyre that is also used on-road between farms, the tyre has a soft rubber compound and fits on all the test equipment used in this study. A test velocity of 18 km/h was selected as this is the normal operating velocity of the vehicle that these tyres would be used on. The same non-deformable, concrete test section was used for the coast down, drawbar pull and motion resistance trailer measurements, thus eliminating the effect of the terrain from these measurements. All tests were conducted at unregulated tyre pressures, which allowed the tyre pressure to increase and stabilize during the tests. The tyre pressures were verified at cold/start conditions and not adjusted during tests only monitored with the use of a pressure transducer mounted in the rim during some of the tests. The inflation pressure of 200 kPa and 80 kPa was chosen to due to the specified Trelleborg load limitation of 640kg per wheel at 80 kPa. The wheel load of the test vehicle was at 80% of the specified load at 80kPa as indicated in Figure 1.

TM700

Size	Load-Index/ Speed Symbol	psi bar	9 0,6	12 0,8	17 1,2	23 1,6	29 2,0	35 2,4	43 3,0
		Km/h				Kg/Tyre			
240/70R16 TL	104A8 (104B)	**40 S** 10 HT S	425 455	490 525	630 675	775 830	850 910	**900** 965	1530 H (#)
260/70R16 TL	109A8 (109B)	**40 S** 10 HT S	530 570	590 630	700 750	810 870	920 980	**1030** 1100	1750 H (#)
280/70R16 TL	112A8 (112B)	**40 S** 10 HT S	580 620	640 680	760 810	880 940	1000 1070	**1120** 1200	1900 H (#)
280/70R18 TL	114A8 (114B)	**40 S** 10 HT S	600 640	660 710	790 850	920 980	1050 1120	**1180** 1260	2010 H (#)
280/70R20 TL	116A8 (116B)	**40 S** 10 HT S	590 630	675 725	875 940	1075 1155	1175 1260	**1250** 1340	2125 H (#)

H (#) = Maximum speed 10 Km/h. - Harvesting machines in cyclic loading service and field to farm transit.

Figure 1: *Trelleborg TM700 technical data.*

The same test vehicle was used during the drawbar pull and coast down methods thus having the same parasitic losses during these tests.

The following section describes the test setup and the theory behind the methods.

3.1 Drum Test Rig

The drum tests were conducted with the tyre mounted on a steel rim and running on a smooth aluminum surface drum with a radius, *R*, of 0.8m. The ambient temperature, t_{amb}, during the tests were kept at 25 °C in an air-conditioned laboratory. The applied vertical load, L_m, was measured with the use of a ULP load cell with a maximum rating of 10kN. The input torque on the drum, T_t, was also measured. The drum test setup is shown in Figure . Tests were conducted at a vertical load, L_m, of 2452N at multiple velocities, v, including 18km/h and cold inflation pressures of 80 and 200kPa respectively. Tyre carcass temperature and pressure were monitored with the use of a FLIR thermal imaging camera and pressure transducer mounted in the rim. All coordinate systems are defined as per ISO 8855-2013.

The torque method described in ISO 28580-2009 was used to measure the motion resistance coefficient, C_r, of the tyre on the drum test rig. During these tests the input torque, T_t, on the drum was measured. L_m was limited to 2452N due to the narrow test drum. At higher loads the tyre would deform around the edge of the drum and would thus not be a representative measurement. The parasitic losses, F_{pl}, are calculated using eq. 1.

$$F_{pl} = \frac{T_{no\_load}}{r} \tag{1}$$

The measured torque, T_{no_load}, is the torque required to keep the drum rotating with no applied load on the drum from the tyre. The motion resistance force, F_r, expressed in Newton is calculated using eq. 2

$$F_r = \frac{T_t}{r} - F_{pl} \tag{2}$$

The C_r is then calculated using eq. 3

$$C_r = \frac{F_r}{L_m} \tag{3}$$

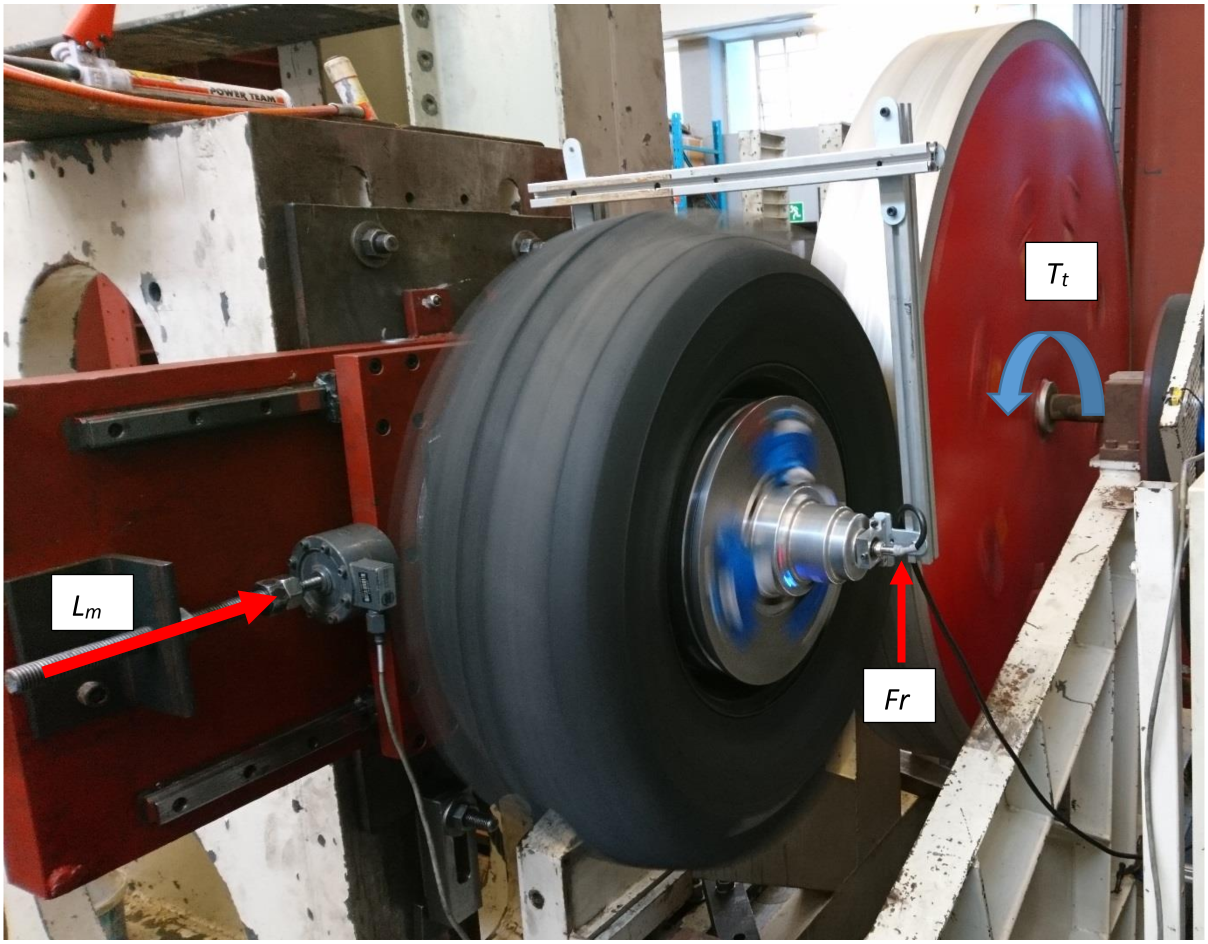

Figure 2: *Drum test rig****.***

Temperature correction for tests, conducted at a different ambient temperature, are altered using eq. 4.

$$F_{r25} = F_r[1 + K_t(t_{amb} - 25)] \qquad (4)$$

Where K_t is a constant with a value of 0.010, as described in ISO 28580-2009.

Drum diameter correction is completed using eq. 5.

$$F_{r02} \cong K_r F_{r01} \qquad (5)$$

Where eq. 6 describes K_r:

$$K_r = \sqrt{\frac{\left({r_1}/{r_2}\right)(r_2+r_T)}{r+r_T}} \tag{6}$$

With

r_1 = 0.8m (for the 1.6m diameter drum used in the current study)

r_2 = 1m (for the standard drum as described in ISO 28580-2009)

r_T is one half of the nominal tyre diameter, 0.4m (for the test tyre used in current study)

$F_{01} = F_{r25}$

The results from the drum tests are discussed in section 4. It should be noted that the radial run out of these large lug agricultural tyres are more than the allowed 0.5mm, as specified in ISO 28580-2009, however the ISO specification was used as a baseline/reference for the tests conducted.

3.2 Motion Resistance Test Trailer

Field testing was conducted at the Gerotek Testing Facilities in the west of Pretoria, South Africa. The test track used was a 400m smooth section of the suspension track, with a 0.068% or 0.038° gradient from East to West. Test runs were performed in both East and West directions over the same test section. The ambient test conditions ranged from 25 to 30 °C with wind still conditions. The test setup of the motion resistance trailer is shown in Figure 3. Tests were conducted at a constant velocity of 18km/h with a vertical load, F_z, of 5690N on each of the tyres at inflation pressures of 80 and 200kPa respectively. This vertical load was selected to facilitate a direct comparison of motion resistance measurements, from the trailer measurements, to the motion resistance measurements from the drawbar pull and coast down tests conducted on a test vehicle. The inflation pressures were set at the beginning of the test and not adjusted during the tests. A six component load cell was used to measure the longitudinal force, F_x, at the tow hitch. The orientation of the six component load cell had one S-Type in the longitudinal direction, two S-Types in the lateral direction and three S-Types in the vertical direction. The S-Type load cells used in the six component load cell each has a 1kN rating. Data was sampled at 1 kHz with 16-bit resolution. A VBOX III differential GPS was used to measure the tow vehicle's velocity and ensure that the test was conducted at a velocity as constant as possible. The motion resistance was calculated using eq. 7 and 8

$$F_r = \frac{mean(F_x)}{2} \tag{7}$$

With

$$C_r = \frac{F_r}{F_z} \tag{8}$$

The drum tests indicated that the measured motion resistance is inversely proportional to the tyre inflation pressure which is directly proportional to the tyre carcass temperature. As the tyre pressure and operating temperature increase and stabilize, the motion resistance also decreases and stabilize when the tyre reach operating temperature. The typical stabilization time for the tyres used during these field tests were in the order of 90 minutes of running at a constant velocity of 18km/h. This is due to the tyre being an undriven tyre with also no braking torque applied to the tyre during the tests.

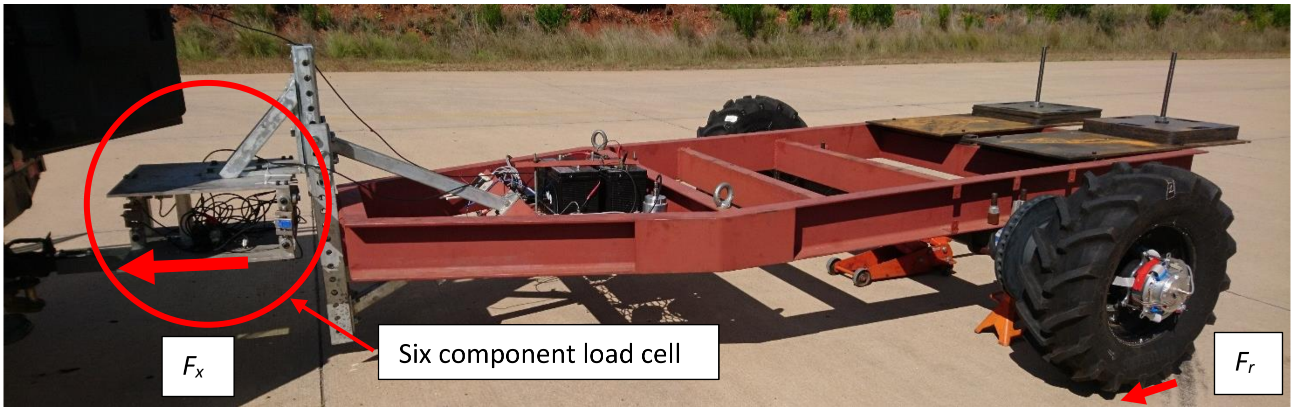

***Figure 3**: Motion resistance test trailer setup.*

The results from the motion resistance trailer tests are discussed in section 4.

3.3 Drawbar Pull Test

The drawbar pull tests were conducted on the same 400m test section used for the motion resistance trailer tests, with the use of a Land Rover Defender 110 vehicle fitted with the Trelleborg TM700 280/70R16 tyres, as shown in Figure 4. The test vehicle was towed by another vehicle at a constant velocity of 18km/h. The vertical load on the tyres due to the weight of the vehicle, W, on each tyre was on average 5788N due to the 50:50 weight distribution of the vehicle. Tests were conducted in both directions on the same test section with tyre inflation pressures of 80 and 200kPa respectively. Ambient test conditions were 25 to 30 °C with an 11km/h easterly wind. This is noticed during the analysis of the results. The drawbar pull tests were conducted from ambient conditions to see the effect that the tyres and drivetrain warming up to operating conditions have on the C_r. The test vehicle's velocity was measured with the use of a VBOX III differential GPS. The longitudinal towing force, F_{xDB}, was measured with the use of a S-Type load cell with a maximum rating of 5kN. The tow rope was in-line with both vehicles in a horizontal position to ensure that a pure longitudinal force was measured.

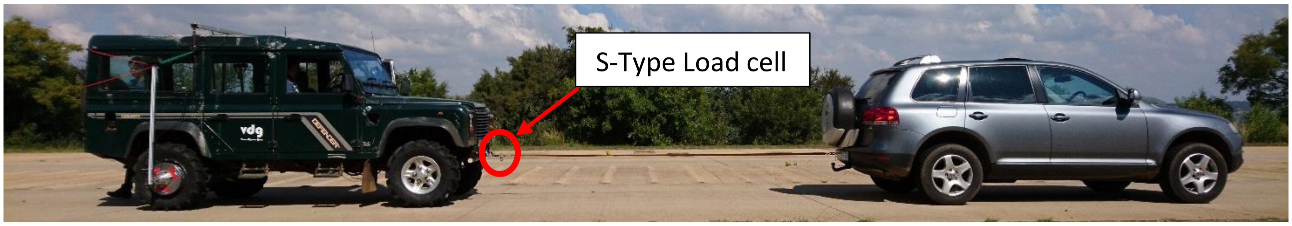

Figure 4*: Drawbar pull test setup.*

F_{xDB} in the tow rope during a drawbar pull test, measures the total road load, R_{RL}, as described by Gillespie, 1992. The total road load is given in eq. 9 as:

$$R_{RL} = C_{vr}W + {}^{1}\!/_{2}\,\rho V^{2} C_{d} A + W sin\theta \quad (9)$$

Tests were conducted at a constant velocity of 18km/h, thus the aerodynamic drag of the vehicle was low and in the order of 30N with the effect of the test track gradient on the measurements at only 4N per wheel.

The C_{rDB} was thus calculated using eq. 10

$$C_{rDB} = \frac{F_{xDB}}{W} \quad (10)$$

The results from the drawbar pull tests are discussed in section 4.

3.4 Coast Down Test

The coast down tests were conducted with the same Land Rover Defender 110 vehicle as used in the drawbar pull tests and on the same 400m test section, as shown in Figure 5.

Figure 5: Vehicle setup used for coast down testing.

Tests were conducted at tyre inflation pressures of 80 and 200kPa respectively. Test runs were done in both East and West directions over the same test section. The ambient test conditions ranged from 25 to 30 °C with wind still conditions. Two drivetrain configurations were used during the tests. The first setup was a standard drive train setup where the test vehicle was driven up to a velocity just above 40km/h after which the transmission was placed in Neutral and the vehicle was allowed to coast to a standstill. SAE J2263-1996 specifies in section 12.6 that data analysis on coast down test should be restricted to velocities from 115 to 15km/h, however the maximum velocity of 40km/h was a restriction set by the tyre velocity rating. In the second drivetrain configuration, the drive shafts of the vehicle were disconnected from the hubs. This was done by replacing the splined spiders that connect the drive shafts to the hubs, with splineless spiders as shown in Figure 6.

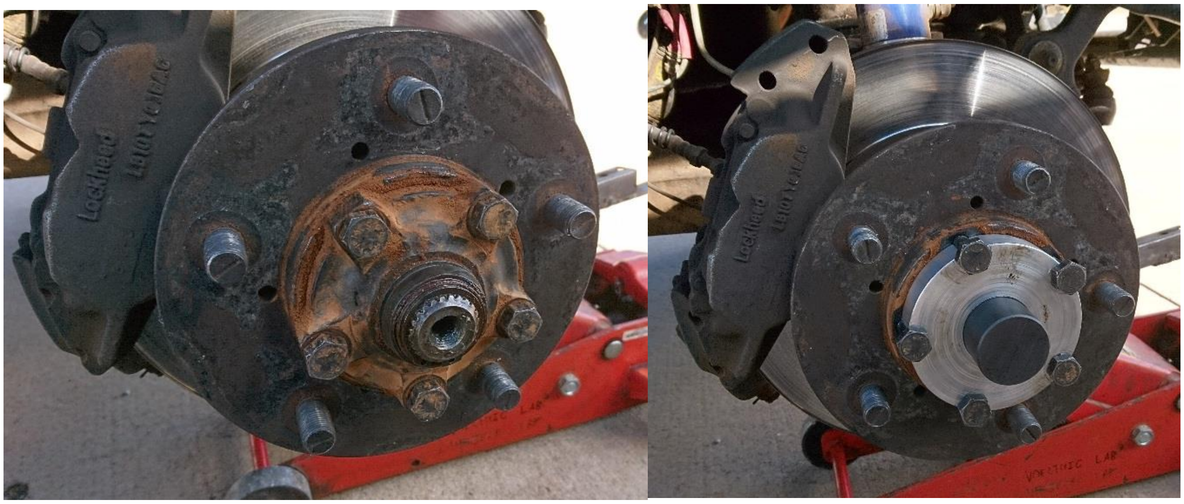

Figure 6: Standard splined spiders (left) and custom splineless spiders (right) on wheel hubs.

For the second drivetrain configuration, the test vehicle was pushed with another vehicle up to a velocity above 40km/h and allowed to coast down to a standstill. These two configurations were used to investigate the inertial effects of the connected and disconnected drivetrain on the measured motion resistance during coast down tests.

The inertial effects from the wheels were taken into consideration when calculating the road load from the coast down, R_{RL_cd}, with the use of the measured acceleration, a, as described in SAE J2263, 1996 as shown in eq. 11:

$$R_{RL\_cd} = Ma \qquad (11)$$

With the acceleration, a, calculated form the V vs. time measurements as recorded from the GPS during the coast down.

The inertia of the front and rear wheels were measured and calculated with the use of the Bifilar pendulum method as described in section B.3.2 of ISO 28580:2009. Compensated road load, R_{RL_Comp} is described in eq. 12:

$$R_{RL\_comp} = \left(M + 2\left(\frac{I_{rw}}{(r_{rr})^2}\right) + 2\left(\frac{I_{fw}}{(r_{rr})^2}\right)\right) * a \tag{12}$$

The wheel inertias effectively increase the apparent mass of the vehicle which increases the R_{RL}. The higher road load will result in a higher C_r because the equation to calculate C_r remains the same by using eq. 13:

$$C_r = \frac{R_{RL\_comp}}{M * g} \tag{13}$$

The results from the coast down tests are discussed in section 4.

4. Results

The results for the tests conducted on the drum test rig, revealed the relationship between motion resistance coefficient, inflation temperature and tyre carcass temperature as they are all directly related. Tests were conducted at a constant velocity of 18km/h, from an ambient temperature of 25 °C and initial inflation pressure of 200kPa, for 10 hours on day 1 and for 5 hours on day 2. Data sets were recorded at 1000Hz, on a 16 bit resolution data acquisition system, for one minute out of every 10 minutes rolling. Figure 7 shows how the pressure and temperature are directly proportional to each other, compared to the C_r which decreases as the pressure inside the tyre and tyre carcass temperature increase and stabilize as seen in Figure 8 and Figure 9.

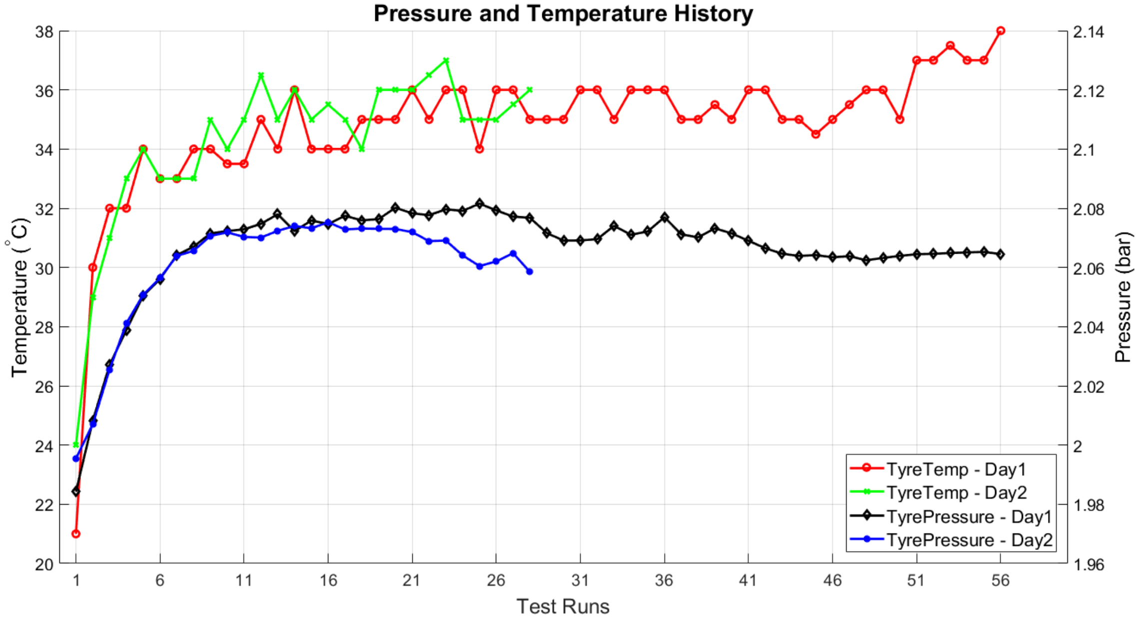

Figure 7*: Pressure and temperature during drum test with a test run every 10 minutes.*

The boxplots in Figure 8 and Figure 9 show the mean (in red) and variance in the measured data on this large lug tyre. The variance is due to a combination of factors in the form of the imbalance, radial run out of large lug tyres and rolled steel rims being not concentric when compared to a machined Aluminium rim. The natural frequencies and mode shapes of the tyre can also contribute as they occur at very low frequencies and sometimes fall within the operating frequencies of large lug tyres (Becker and Els, 2011). This however was outside the scope of this study.

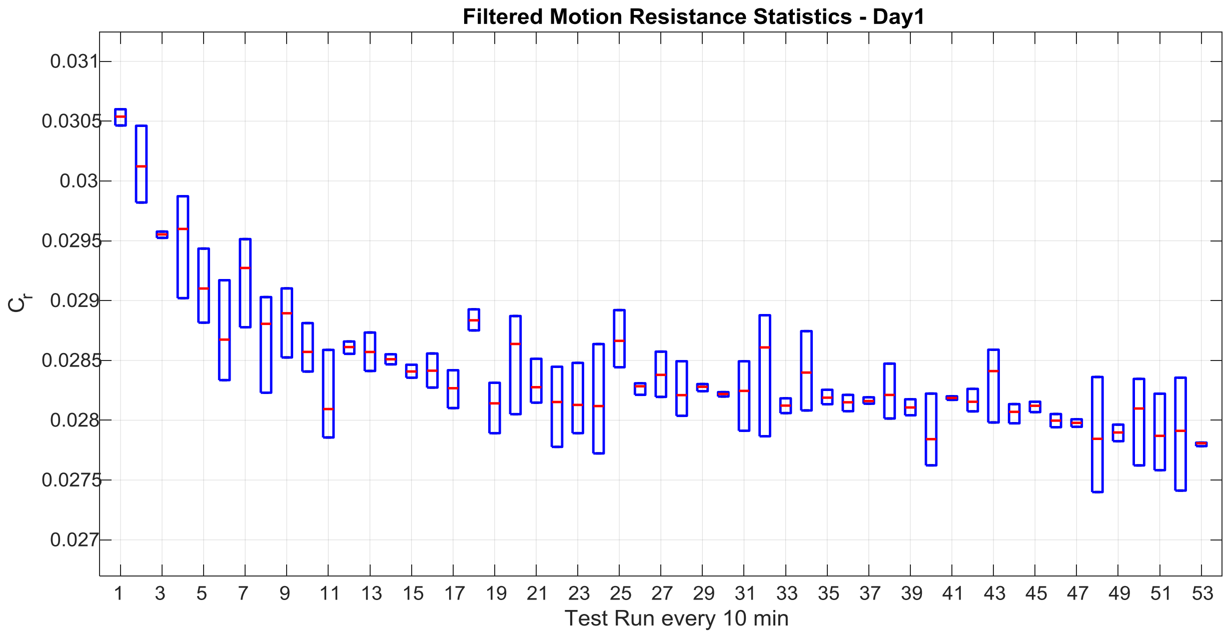

Figure 8*: Drum Test results day 1, with a test run every 10 minutes.*

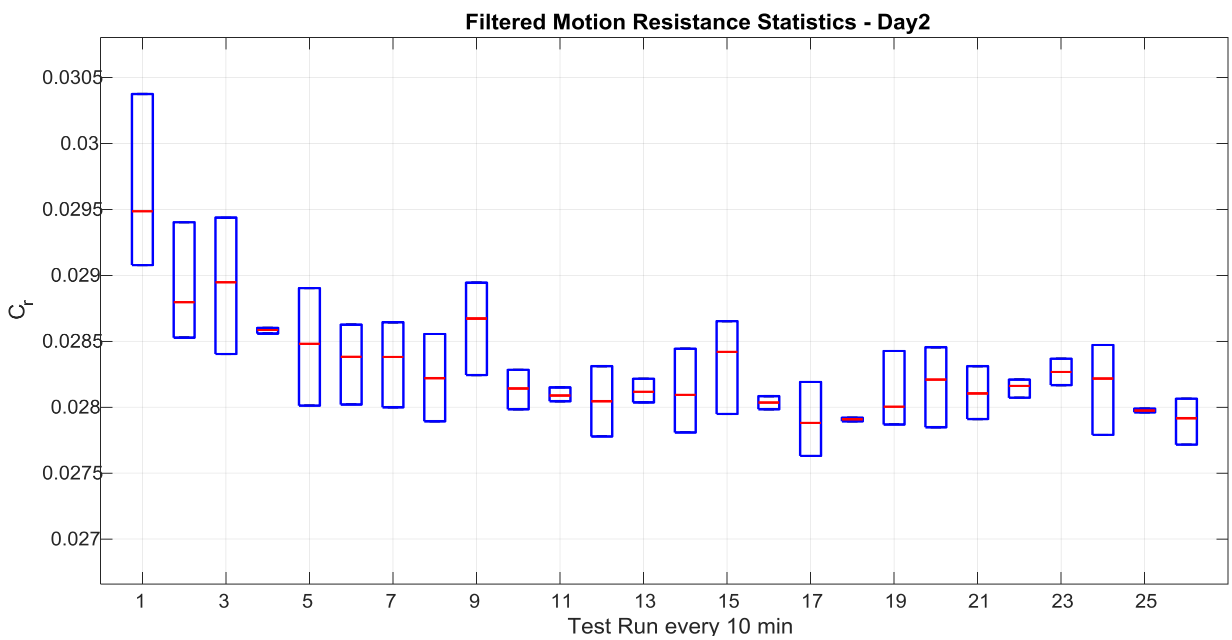

Figure 9*: Drum test results day 2, with a test run every 10 minutes.*

It is known that the C_r decreases as the tyre pressure is increased. The same trends are seen for both test days as the tyre pressure increases and temperature stabilizes when it reaches operating conditions.The mean C_r from the drum test results are shown in Figure 10. The C_r stabilizes during both test days around 0.028, which indicates a stable and repeatable test setup.

Figure 10*: Mean motion resistance drum test.*

The results for the motion resistance trailer tests are shown in Figure 11. Tests were conducted from an ambient temperature of 25 °C and one can see how the C_r decreases as the tyre reach operating temperature and pressure. From this graph one can note the effect of the 0.068% gradient of the test track has on the results, in the difference between the measurements taken in the East vs West directions, however the mean C_r value of these tests correspond to the drum test rig measurements of 0.028.

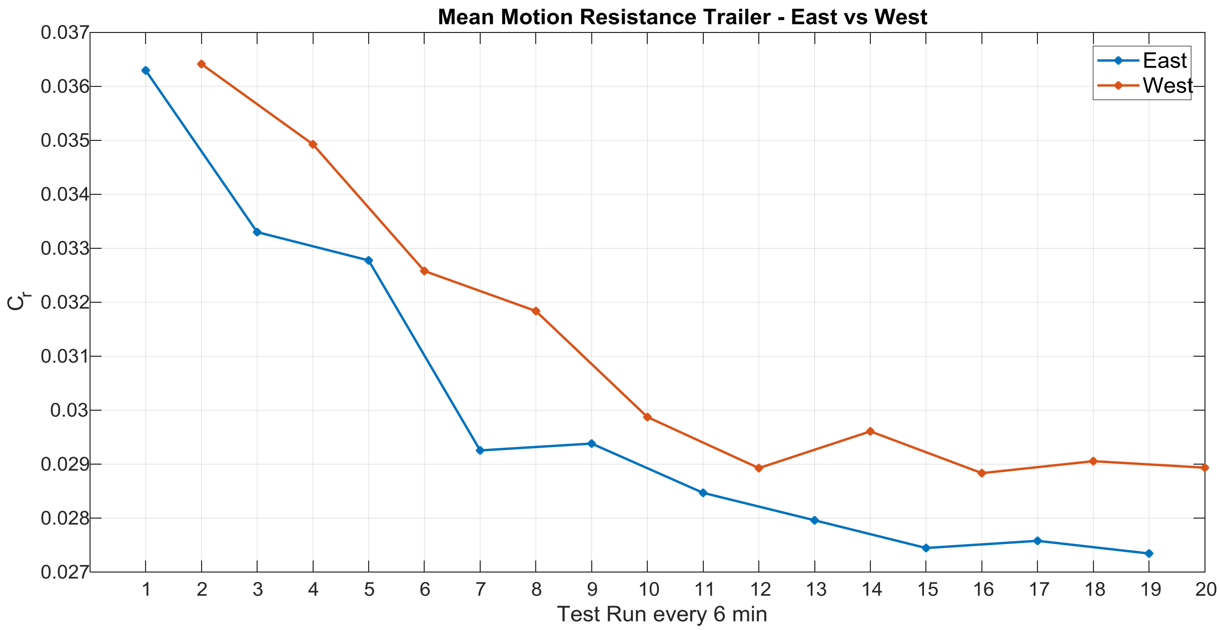

Figure 11: *Motion resistance trailer test results.*

The C_r calculated from the drawbar pull tests are shown in Figure 12. Data sets were recorded over the same 400m section as per the motion resistance trailer tests and in both directions. Test were conducted at an ambient temperature of 28 °C. The same trends are noted as in the previous tests except that measurements stabilized faster due to a higher ambient temperature on the day of testing. The box plot again shows the variants in the measurement values and it is concluded that the stretch in the tow rope may also have been a contributing factor to the larger variants.

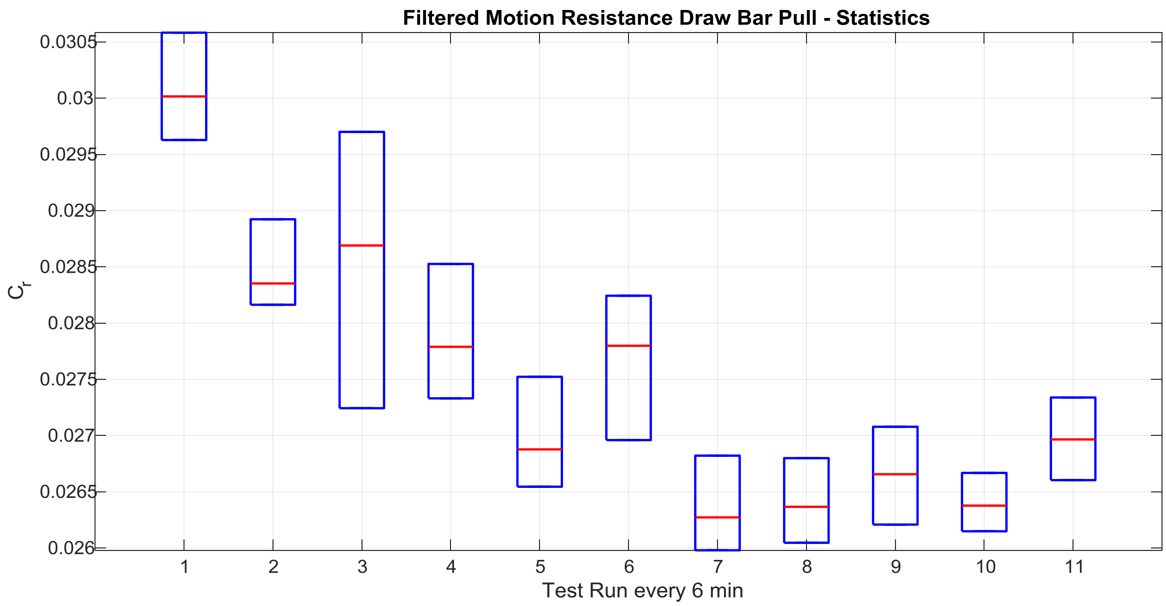

Figure 12*: Drawbar pull test results.*

The mean C_r for both directions during the drawbar pull tests are shown in Figure 13.

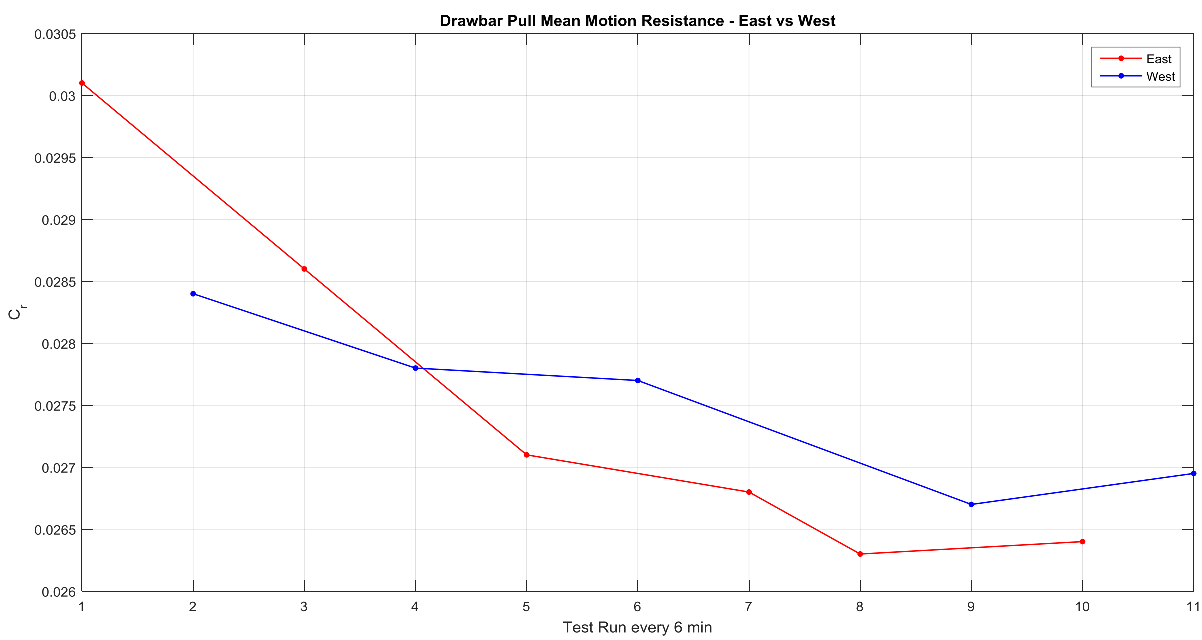

Figure 13*: Drawbar pull tests East and West results.*

Figure 14 shows the coast down measured velocities vs. time results. The cost down tests were very repeatable in both the East and West directions.

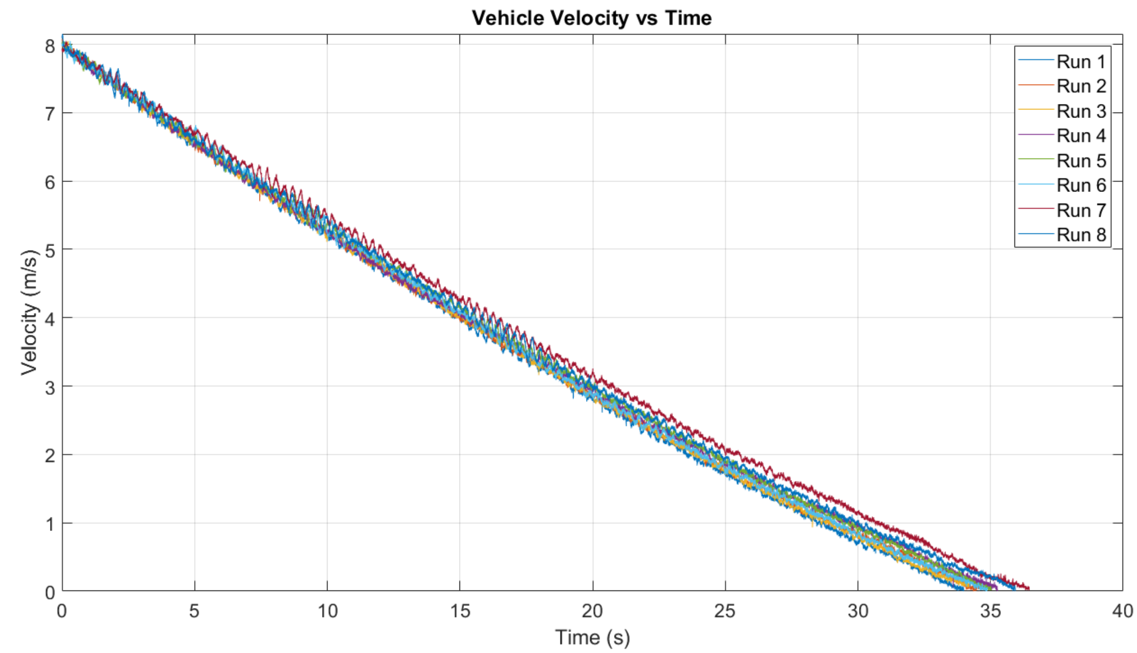

Figure 14: *Coast down tests East and West velocity vs. time results.*

The calculated C_r results for the coast down tests are shown in Figure 15 and Figure 16 for inflation pressures of 200 and 80kPa respectively. In these graphs the inertial effects as well as the disconnected drivetrain effects are shown. The aerodynamic drag contribution to the motion resistance or road load varies from 146N down to zero during the coast down from 40-0km/h. All of the different combinations of inertial effects and drivetrain disconnected can result in a 16% difference in C_r measurements.

Additional tests were conducted on the drum test rig at velocities from 3 to 24km/h in 3km/h increments at inflation pressures of 200 and 80kPa respectively. This was done to facilitate the comparison of the drum tests at different velocities to the coast down tests. These results are also shown in Figure 15 and Figure 16 respectively together with the coast down methods. From these results one can see that the C_r is directly proportional to the velocity and inflation pressure. It is noted that the C_r as calculated with the use of the coast down methods diverge considerably when compared to the drum tests at different velocities.

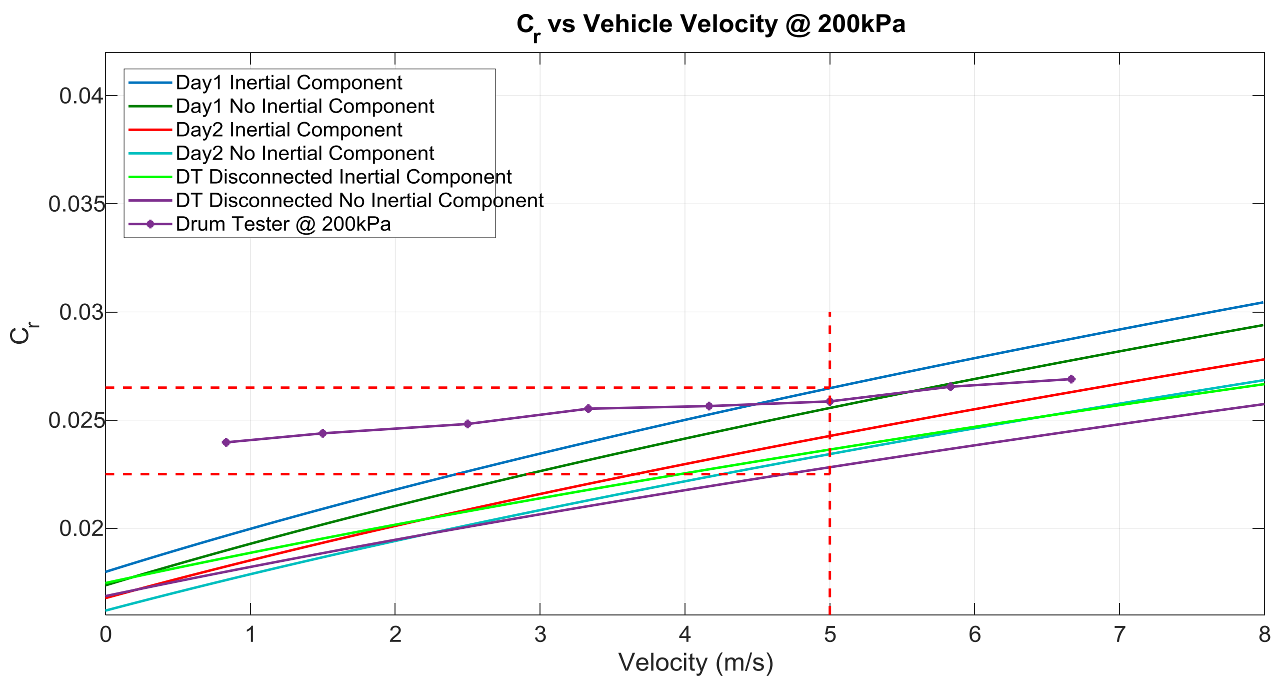

Figure 15*: Coast down with and without inertial effects and drivetrain disconnected at 200kPa.*

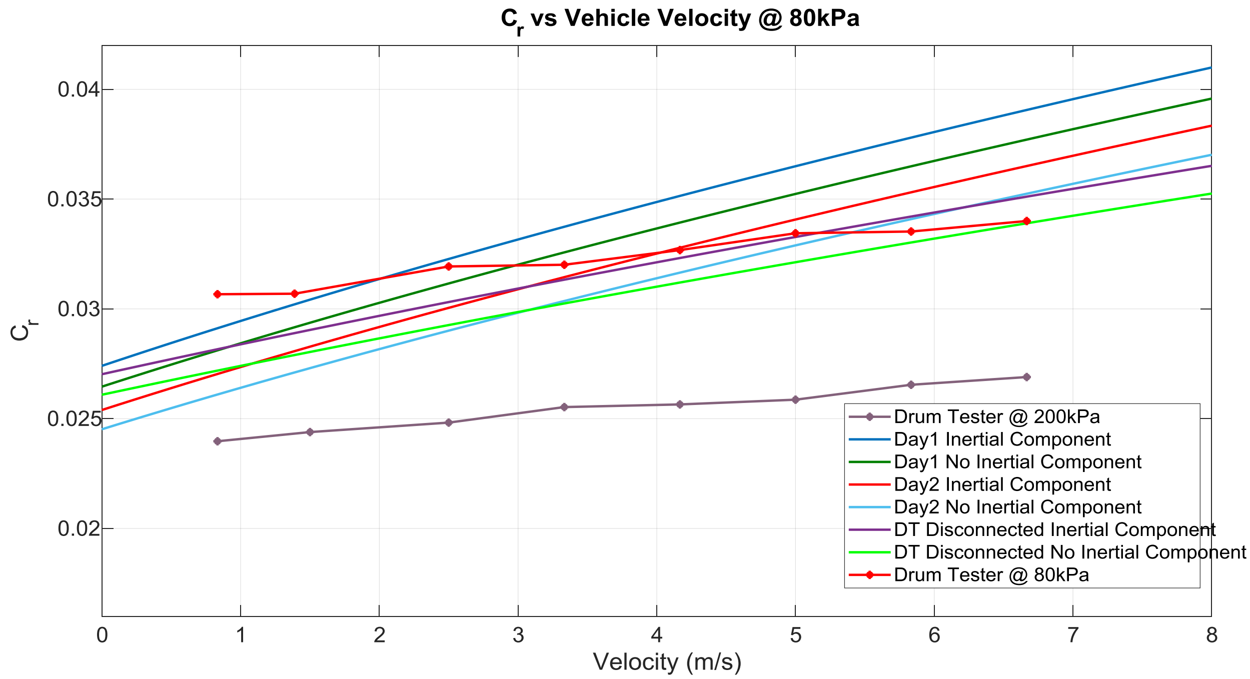

***Figure 16**: Coast down with and without inertial effects and drivetrain disconnected at 80kPa.*

An interesting phenomena noted in Figure 15 and Figure 16 is that the C_r as measured with the drum test and motion resistance test trailer resulted in a higher value compared to the coast down test at very low velocities. It is expected that the C_r values calculated from the coast down test would result in a higher C_r due to the aerodynamic drag, inertia of the wheels and drive train of the vehicle, which appears not to be the case. On the specific tyre used in this paper an increase of 26-30% in C_r was measured with the decrease of inflation pressure from 200 to 80kPa, as shown in Figure 16. This highlights the importance of running tyres at the correct inflation pressure for the specific vertical load that the tyre is operating at, as this has a direct impact on fuel efficiency and tyre wear. This effect is especially applicable when driving on non-deformable terrain.

5. Conclusions

The four methods used to measure the C_r in this paper has produced very interesting results. Very consistent C_r were obtained with the use of the drum test rig, motion resistance test trailer method as well as with the drawbar pull test method. The coast down C_r measurement illustrates the effect the inertial effect, drive train inertia and aerodynamic drag has on the measurements. The fact that a lower C_r is calculated below 5m/s, with the coast down method compared to the other three methods, does raise concerns with regards to the accuracy of the coast down method at velocities lower than 5m/s. It is expected that the coast down method will always produce a higher C_r compared to the other three test methods due to the inclusion of the complete vehicle and all of losses. The drum, drawbar pull and trailer tests results in very similar results. The trailer test is the preferred test method as it is independent of the inertial effects of the vehicles drivetrain. Various tyre sizes, inflation pressures and vertical loads can be tested with the use of a single tow-vehicle-trailer combination.

It is thus noted that the coast down test method should be used with caution. Especially when determining the C_r on agricultural or construction vehicles which operates most of the time below 5m/s. SAE J2263-1996 specifies in section 12.6 that data analysis on coast down test should be restricted to velocities from 115 to 15km/h. The 15km/h or 4.1m/s lower limit correlates to the data shown in Figure 15 and Figure 16. With this in mind it is suggested that coast down tests conducted on agricultural or construction vehicles are conducted from the maximum self-propelled velocity that the vehicle can run at, as it may even be lower than 15km/h. It is suspected that for these slow moving vehicles a more linear velocity vs time graph will be measured during the coast down tests. This was also seen for the tests conducted in this paper as the initial vehicle velocity was only at 40km/h, when compared to tests conducted from 115km/h.

This study also shows the importance of running tyres at the correct inflation pressure for the specific vertical load that the tyre is operating at as this has a direct impact on fuel efficiency and tyre wear. This can be used to justify the additional capital cost of running a vehicle with Central Tyre Inflation (CTI), especially if the vehicle is operated on deformable terrain at low inflation pressures and non-deformable terrain at high inflation pressures.

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