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COMPARISON OF TYRE ROLLING RESISTANCE FOR DIFFERENT MOUNTAIN BIKE TYRE DIAMETERS AND SURFACE CONDITIONS

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ABSTRACT
Tyre-road rolling resistance is a major factor in the performance of a vehicle. By investigating the rolling resistance, a better understanding of the efficiency of different wheel diameters will develop. A major issue in the mountain biking world is the relative merits of using 26in. versus 29in. wheels and the resultant effect on cyclist performance. As rolling resistance is indicative of the behaviour of a vehicle over specific terrain, it can be viewed as an objective parameter to compare the relative performance of these two wheel sizes. The aim of this study was to evaluate the rolling resistance of four mountain bikes as affected by wheel diameter and terrain type, cyclist mass, tyre inflation pressure and suspension type using coast-down tests. The following major conclusions were drawn: average rolling resistance of the 26in. diameter wheel was higher than that of the 29in. diameter wheel; a sand surfacing had the highest rolling resistance coefficient; terrain surface showed the largest effect on rolling resistance coefficients measured, followed by the cyclist mass, wheel diameter and tyre inflation pressure; and the best combination for maintaining momentum after traversing over an obstacle was high tyre inflation pressure, low cyclist mass and full suspension 29in. wheel diameter option.

Key words: Rolling resistance; Mountain bike; Tyres; Road surface.

INTRODUCTION

The invention of the wheel is one of the most significant advances in history. As the need for more efficient transportation increased through history, the wheel evolved to allow faster transport between origin and destination. Cycling has been a mode of transportation since the first bicycle was invented in 1790. In 1868, cycling became an organised sport. There are four important components of a bicycle that affect a bicycle's performance when racing: frame mass; brakes; suspension; and wheels. As the bicycle evolved, the wheel evolved with it to the modern 26in. diameter wheels. A larger diameter wheel was developed in the mid-1990s for mountain bikes, having a diameter of 29in. This wheel diameter was professed to be unbeneficial until it was reintroduced in 2001, raising debate about the difference in speed and performance between the 26in. and 29in. wheels (Herlihy, 2004). It is customary to express the wheel diameter of mountain bikes in inches, and a specific mountain bike is often referred to in terms of its wheel diameter (26er or 29er). In this article, the same custom is adopted.

Rolling resistance between the wheel and road surface is a major factor in the performance of any vehicle. By investigating the physics between the wheel-terrain surface interactions, a better understanding of the performance efficiency of different wheel diameters will develop.

The terrain surface has a major impact on the rolling speed of a wheel and the overall performance of the vehicle (Jackson *et al*., 2011). Grappe *et al*. (1999) found increased rolling resistance for bikes with added mass and decreased rolling resistance for conditions of increased tyre inflation pressures.

PURPOSE OF RESEARCH

The debate around the relative effects of using a 26in. compared to a 29in. wheel diameter in mountain biking contains many personal and subjective arguments. One potential objective parameter that should differentiate between the relative performances of the two options is the rolling resistance of mountain bikes with the two wheel diameters. The aim of this article is to evaluate the rolling resistance of four mountain bikes as affected by:

- 26in. and 29in. wheel diameters for each terrain surface;
- Four different terrain surfaces;
- Three different tyre inflation pressures;
- Three different cyclists with different masses; and
- Two different suspensions for each wheel diameter.

The conservation of momentum for two wheel diameters was investigated to determine the diameter which provides the best all-round performance. Coast-down tests were conducted to determine the rolling resistance, while the investigation of momentum preservation was conducted by introducing an obstacle on the bituminous surface and repeating the coast-down test.

BACKGROUND

Since the first bicycle was invented in 1790, the bicycle's evolution progressed in terms of comfort, speed and safety. The cycling world advanced into eight different types of races namely road races, track cycling, cyclo-cross, mountain bike racing, BMX, bike trials, cycle speedway and motor-paced racing (Herlihy, 2004). One of the main focus areas of the advancements of the bicycle, aside from safety against component failure, is performance. The structural components of a bicycle have been the foundation of experimentation since the 1890s when the first metallurgical innovation was used to improve the safety against component failure and, in so doing, the overall performance of the bicycle. The invention of pneumatic tyres increased the rider safety and comfort of the bicycle even more in 1890 (Herlihy, 2004). The geometry of a bicycle is generally the same although the different uses of the bicycle affects the quality, mass, size and shape of the different components. The general components of a mountain bike are shown in Figure 1. The following subsections discuss the four major components and related mechanisms of the bicycle, and their relative importance and potential influence in rolling resistance.

Frame

Minimising the mass of a bicycle is essential to reduce the energy required to propel the bicycle. The bicycle frame and geometry determines how the bicycle handles due to the position that the cyclist assumes on the specific frame. Mountain bikes are designed for manoeuvrability and stability (Ballantine & Grant, 1998).

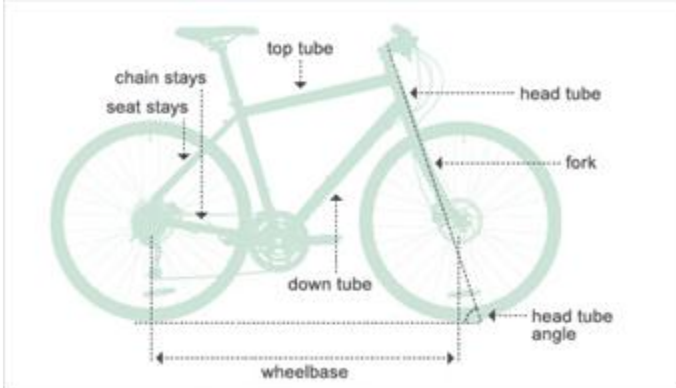

***FIGURE 1*: COMPONENTS FOUND ON A TYPICAL MOUNTAIN BIKE** (Brown, 2012)

Wheel

As the bicycle evolved, the wheel evolved with it to allow for comfort, speed and safety (Herlihy, 2004). The basic components of a bicycle's wheel are the hub, spokes and rim. The hub forms the rotational axle in the centre of the wheel. It comprises of an axle, hub shell and bearings. The axle of the hub allows for the wheel to be easily removed or attached to the frame. The bearings allow for the wheel to easily and smoothly rotate around the axle. The rim forms the outermost hoop of the wheel where the tyre connects to the wheel. The spokes are the connectors between the hub and the rim (Downs, 2005; Grant, 2010).

The tyre consists of four major components that influence the performance of the entire bicycle, namely the tyre width, tread pattern, tread count and tyre inflation pressure. The quality of any of the components of the wheel affects the performance and durability of the wheel.

For many years, 26in. wheels were the most general size of wheels that mountain bikes were sold in (Herlihy, 2004). Cyclists have been arguing for years that the smaller diameter wheels are more efficient and provide a faster performance on any terrain surface. The key to reducing rolling resistance is to minimise the tyre casing deformation and, in so doing, minimising the loss of energy. Comparing the difference between deformation of the 26in. and 29in. wheels with the same tyre inflation pressure, it is evident that the larger wheel diameter suffers less deformation. This means that the 29in. wheel should provide a better performance than the 26in. wheel. The conservation of rotational momentum by the longer effective leverage provided by the 29in. wheel, results in less energy required to overcome any tyre bulge that exists at the contact patch between the tyre and the road surface. The effective contact patch area of a 29in. wheel is longer and narrower than that of a 26in. wheel under optimal conditions, leading to similar total contact patch areas (Huang, 2011).

Tyre inflation pressure affects the contact surface between the tyre and the ground. When the tyre is under inflated, the rolling resistance increases (Grappe *et al*., 1999). When the tyre is over inflated, there is poor grip due to the minimal contact surface, which will result in slippage. The slippage will render the brakes ineffective, especially during wet conditions. Optimal tyre inflation pressures are shown in Table 1 (Khan, 2003).

***TABLE 1*: OPTIMUM MOUNTAIN BIKE TYRE INFLATION PRESSURE**

Cyclist mass (kg)	Mountain bike tyre inflation pressure [kPa]
50	241 to 262
60	248 to 269
70	262 to 283
80	276 to 296
90	290 to 310
100	303 to 324

Suspension

The rolling resistance of a bicycle is affected by the vertical load compliance of the bicycle frame and components. The purpose of the suspension is to dampen the impact (caused by moving over rough terrain) that is transmitted to the rest of the frame and the cyclist. The suspension effectively reduces the amount of fluctuations on the tyres, which reduces the rolling resistance. Mountain bike suspensions can be divided into three types - Rigid, Hardtail and Full suspension. Rigid bikes have no suspension and are not very common in mountain biking. A *Hardtail* only has suspension at the front fork that absorbs shock from impact through coil or air compressed shocks. A Full suspension bike has suspension on the front fork and at the rear stays. The implementation of the rear shock improves comfort and riding quality when going downhill or passing over rocky sections due to the rear shock absorbing most of the impact. Front suspension is implemented through the use of shock absorbers in the front fork. The suspension fork design has become more sophisticated allowing for more travel, adjustable travel and a lockout mechanism. The addition of the shock absorber may add mass but greatly increases comfort, performance and control. The suspension also increases traction, resulting in much quicker cornering, as well as better climbing (Sutherland, 1995; Ballantine & Grant, 1998).

Cyclist

The mass of the cyclist affects the rolling resistance of the bicycle tyre. The technique of the cyclist also contributes to the rolling resistance of the tyres by the way that he/she distributes his/her mass whilst riding. The two tyres may not support the same mass and hence offer the same contact surface which will affect the rolling resistance of each. The bicycle suspension will determine whether the vertical load on the tyre will fluctuate or not. The combined rolling resistance of both tyres will, in effect, change depending on the technique of the cyclist (Ballantine & Grant, 1998).

Rolling resistance

Rolling resistance is the reaction force acting on the bicycle due to the interaction between the mountain bike tyre and the terrain surface it is travelling on. The interaction between the tyre and the terrain surface causes a loss of energy. The main cause of this loss of energy is the deformation of the tyre (depending on tyre properties), the deformation of the terrain surface (depending on terrain material properties) and the movement below the surface. A distinction is made between basic rolling resistance, which occurs on a frictionless horizontal surface, and additional resistances which arise due to uneven and macro textured surfaces (Karlsson *et al*., 2011). The following components directly affect the rolling resistance of a mountain bike (SCHWALBE, 2011):

- Combined mass of the cyclist and bicycle components - causes deformation of tyres, increasing contact surface area between tyre and terrain surface;
- Wheel components:
  Tyre width - wider tyre increases contact surface area between tyre and terrain surface;
  Tyre inflation pressure - lower tyre inflation pressure create larger contact surface area between tyre and terrain surface;
  Tread type - larger tread type creates larger contact surface area between tyre and terrain surface; and
  Wheel diameter - Smaller diameter at the same tyre inflation pressure and mass cause greater tyre deformation;
- Suspension causes less vertical mass fluctuation transferred to tyres, decreasing tyre deformation.

The terrain surface has a major contribution to the rolling resistance of the bicycle:

- Terrain texture - rolling resistance of soft terrain is larger than firmer terrain due to decrease of terrain surface deformation and increase in roughness increases tyre / terrain friction;
- Terrain compaction - combination of rocks and compacted sand cause smaller rolling resistance than rocks and soft sand; and
- Presence of obstacle on terrain surface.

The resistant forces on the bicycle include rolling, gradient and air resistance. The speed of the bicycle has a great effect on the total resistance on the bicycle with speeds above 10km/h causing air resistance to become a resistance factor. The effect of gradient resistance can be minimised by using a test section of horizontal terrain and performing the test in both directions. Air resistance can be minimised by performing rolling resistance tests on a wind-still day (Rutman, 2007).

Various studies have been conducted measuring and evaluating the effect of rolling resistance on cyclists and their performance (Grappe *et al*., 1999; Titlestad *et al*., 2006; Takken *et al*., 2009; Bertucci & Rogier, 2012). These studies confirmed the relative importance of terrain conditions and cyclist properties on the rolling resistance and related performance properties, however, none of these studies compared the relative effect of the use of 26in. versus 29in. wheel diameters on the cyclist performance.

The rolling resistance force experienced by a wheel subjected to a wheel load W, is defined by Equation 1 (Rutman, 2007):

$$F_r = C_r W \qquad (1)$$

Where: F_r- rolling resistance (N); W-load on wheel (N)

(load is assumed to be constant for the experiment as the cyclist does not change position during the experiment)

$$C_r = {}^{c_l}/_{r}$$

rolling resistance coefficient (dimensionless)

c_l- rolling resistance coefficient or coefficient of rolling friction with dimension length (m)
r - wheel radius (m)

The air resistance force is defined by Equation 2 (Rutman, 2007):

$$F_d = \frac{1}{2}\rho C_d A V^2 \qquad (2)$$

Where:
F_d - air resistance (N)
ρ - air density at location of tests=1.07 kg/m^3
(assumed to remain constant for the experiment as it is conducted at the same altitude and location)
C_d - coefficient of drag= 0.76 (dimensionless)
(calculated using Bertucci *et al*. (2013), assumed constant for specific bicycle / cyclist combination used in experiments)
A - frontal projected area of bicycle and cyclist= 0.509 m^2
(measured and assumed constant for specific bicycle / cyclist combination used in experiments)
V - velocity relative to air (m/s)

The gradient resistance force is defined by Equation 3 (Swain, 1998):

$$F_g = WG \qquad (3)$$

Where:
F_g - gradient resistance force (N)
W - load on wheel (N)
$G = \frac{h}{l}$- grade inclination (m/m)

The total resistance experienced by the bicycle is, therefore, defined by Equation 4 (Rutman, 2007):

$$F_T = F_r + F_d + F_g \qquad (4)$$

The power required to overcome the moving force at a certain speed can be calculated using Equation 5:

$$P = F_T V \qquad (5)$$

Where:
P - power (Watt)
F_T - total resistance force (N)

Coast-down test

The coast-down test is a standard way of determining the rolling resistance of a vehicle. The following steps are followed when conducting a coast-down test:

- Accelerate to a predetermined velocity (V) (based on calibrated speedometer);
- Free-ride the vehicle in a straight line until it comes to a stop;
- Measure the distance (s) and time (t) taken for the vehicle to come to a stop; and
- Determine the rolling resistance coefficient using Equation 6 (Delanne, 1994; Rutman, 2007):

$$Cr.g = \frac{\Delta v}{\Delta t} \qquad (6)$$

Where:
Δv - difference between initial (v_0) and final (0) velocity (m/s)
Δt - time taken to stop (s)
Note: $F_g = 0$ for a gradient of 0, while $F_g \approx 0$ for relatively slow initial speed

The coast-down test has to be performed in both directions of a specified section of terrain. The average of the results is taken. This removes the effect of any small gradient differences.

METHODOLOGY

Data analysis

The experimental work and results consist of 5 parts:

1. The difference in the effect on rolling resistance of 2 wheel diameters was tested. The test was conducted on 4 different terrain surfaces namely a single bituminous sealed road, sand with gravel, grass and soft sand. Gravel, for this study's purposes, refers to an unconsolidated variety of small rocks and pebbles (less than 25mm diameter);
2. The difference in the effect on rolling resistance of 3 different cyclists' masses was tested. The test was conducted on the same 4 terrain surfaces and the same 2 wheel diameters;
3. The difference in the effect on rolling resistance of different tyre inflation pressures was tested. The test was conducted on the same 4 terrain surfaces, the same 2 wheel diameters and the different cyclists' masses;
4. The difference in the effect on rolling resistance of 2 different suspensions was tested. The test was conducted on the same 4 terrain surfaces, the same 2 wheel diameters, the different tyre inflation pressures and the same 3 different cyclists' masses; and
5. The difference in the effect on rolling resistance of the 2 wheel diameters with an obstruction on the terrain surface was tested. The test was conducted on the gravel surface with the same 2 wheel diameters at 2 different tyre inflation pressures and the same 3 different cyclists' masses. The difference between the rolling resistances measured when rolling over an obstruction and the rolling resistances of the corresponding terrain surfaces and wheel diameters previously measured were calculated. These differences are the preservation of momentum of each wheel diameter in terms of rolling resistance force.

Procedures

The test was conducted at the Rhino Park Airfield in Pretoria. Four horizontal sections with different terrain surfaces were selected where the coast-down test was conducted. The 4 surfaces were selected to realistically represent the surfaces encountered on mountain bike trail routes (Figure 2). The obstacle used was a rock with a height of 100 mm selected to provide adequate obstruction while not harming the tyres. The method to determine the loss of momentum due to an obstacle has been devised to enable the effect of a relatively large anomaly (much larger than normal unevenness or obstacles such as smaller rocks), within the riding path to be quantified (to enable comparison between situations), in a manner that has practical relevance to the cyclist.

Two calibrated Global Positioning System (GPS) devices (velocity accuracy of ± 0.5km/h) were used to measure and collect the speed and location of the mountain bikes during the coast-down tests. Typical speed / time data are shown in Figure 3. Data analysis excluded the last number of points (less than 2km/h speed) as the cyclist was losing balance at this low speed and came to a virtual standstill. Exclusion of this data did not affect the outcome of the analysis significantly.

***FIGURE 2*:** **FOUR SURFACE TYPES USED IN EXPERIMENT**

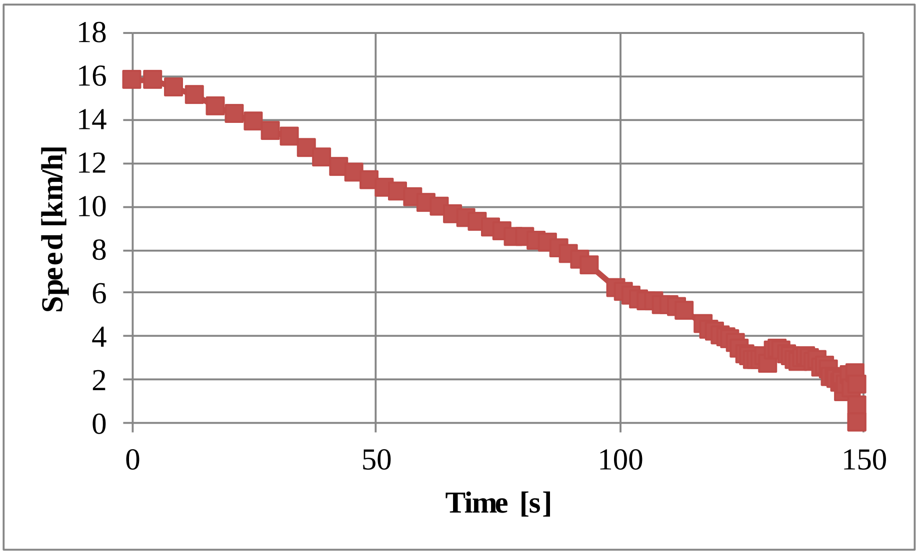

FIGURE 3: EXAMPLE OF SPEED/TIME DATA OBTAINED FROM GPS ON BIKE

FIGURE 4: EXAMPLES OF FOUR MOUNTAIN BIKES USED IN EXPERIMENT

Cyclists and bikes

Three cyclists were used in the experiment. Their masses were adjusted using weights to represent masses of 70, 80 and 90 kg respectively. The cyclists accelerated to 15km/h to incorporate some air resistance in the measurements and calculations. The 3 cyclists had similar frontal projected areas as required in Equation 2. Four mountain bikes were used in the experiment, consisting of a Hardtail 26in. (HT26), Full suspension 26in. (FS26), Hardtail 29in. (HT29) and Full suspension 29in. (FS29) (Figure 4). Data collected from the GPS devices for each of the tests were analysed using Equations 1 to 7 to generate the rolling resistance coefficients for each of the collected data sets. In this article the rolling resistance coefficients were used in the discussions and analyses.

FINDINGS

All Data

All the calculated rolling resistance coefficients are shown in Figure 5 to indicate the general trends observed for all conditions. The data were analysed for each of the different parameters separately, based on the average rolling resistance coefficients calculated for each of the various parameters. A summary of the mean, standard deviation (SD) and Coefficient of Variation (CoV) of the rolling resistance coefficients calculated for the 5 main parameters investigated in the paper are provided in Table 2. These values were used in the analysis, with small SD and CoV values indicating relatively small differences between the parameters in the analysis. The horizontal axis legend (Figure 5) indicates the frame type (FS - or HT - Hardtail), wheel diameter (26 or 29in), cyclist mass (70, 80 or 90kg), tyre inflation pressure (180, 250 or 500kPa) and surface type (bituminous, grass, gravel or sand).

Wheel diameter

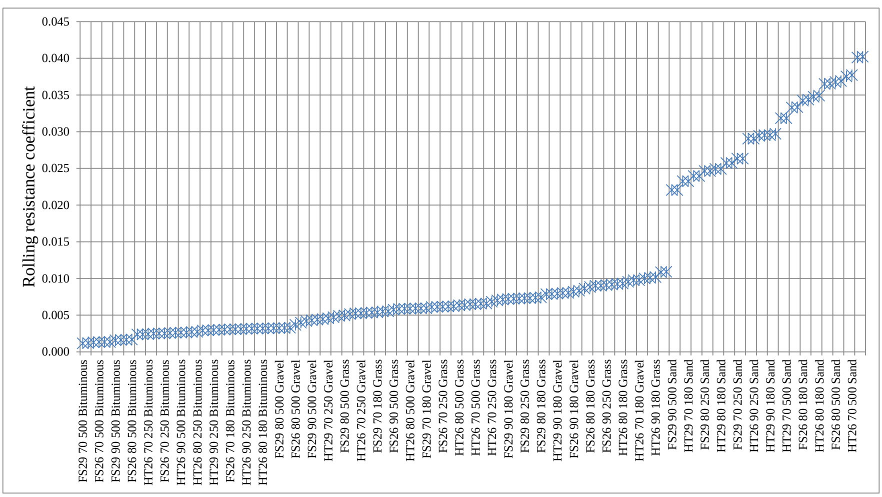

***FIGURE* 5: ROLLING RESISTANCE COEFFICIENTS (four types of cycles, cyclist's masses, wheel diameters analyses inflation pressures and surfaces analyses)**

The average rolling resistance of the 26in. diameter wheel was higher than that of the 29in. diameter wheel. As one of the main objectives of this article was to evaluate the effect of the wheel diameter on the rolling resistance, the rolling resistance coefficient data for the 2 wheel diameters and suspension types are shown in Figure 6 for the different surface types. The data indicated that the 26in. wheel diameter (both suspension types) had higher rolling resistance for the sand, grass and gravel surfaces. For the bituminous surface the differences were negligible. The data thus indicate that the 29in. wheel diameter should provide a benefit when riding off-road surfaces, but on paved surfaces the benefit will be negligible.

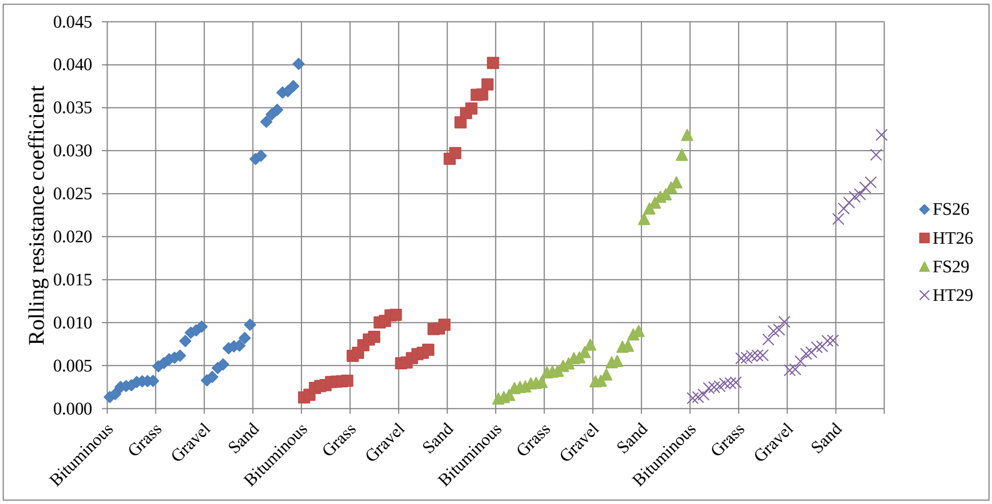

***FIGURE 6*: MEASURED ROLLING RESISTANCE FOR FOUR MOUNTAIN BIKES (indicating effects of wheel diameter and suspension type)**

Terrain surfaces

Analysis of the data in Table 2 and Figure 5 indicates that the bituminous surface had the lowest average rolling resistance coefficients, followed by the grass and gravel surfaces with similar values, and the sand surfacing with the highest average rolling resistance coefficient, being a factor of between 4.5 and 15 times higher than the other 3 surfaces.

Tyre inflation pressure

The data in Table 2 and Figure 5 indicate that higher tyre inflation pressure caused lower rolling resistance. This is in line with published data (Grappe, *et al*., 1999). Data in Table 2 are based on 3 repeats of each measurement.

***TABLE 2*: MEAN AND STANDARD DEVIATION OF ROLLING RESISTANCE COEFFICIENTS FOR ALL PARAMETERS**

Parameters	Mean rolling resistance coefficient	SD rolling resistance coefficient	Coefficient of Variation [%]
Surfacing			
Bituminous	0.002	0.001	29%
Grass	0.007	0.002	23%
Gravel	0.006	0.002	33%
Sand	0.030	0.006	18%
Tyre inflation pressure			
180kPa	0.012	0.011	91%
250kPa	0.012	0.011	94%
500kPa	0.011	0.012	114%
Cyclist mass			
70kg	0.011	0.012	107%
80kg	0.012	0.011	98%
90kg	0.012	0.011	93%
Wheel diameter			
26in.	0.013	0.013	100%
29in.	0.010	0.009	93%
Suspension type			
Hardtail	0.011	0.012	103%
Full suspension	0.012	0.011	95%

Cyclist mass

The average rolling resistance coefficient was not affected to the same degree by cyclist mass, as it was by the tyre inflation pressure and surface type. Although a general increasing rolling resistance coefficient trend was visible as the cyclist mass increased, it does not constitute a major increase. Therefore, cyclist mass appears to be a second order effect on rolling resistance.

Suspension type

Data from Figure 6 indicate that, in terms of rolling resistance and the 4 surfaces evaluated, there was not a measurable advantage in using a full suspension as opposed to a Hardtail suspension.

All parameters

When evaluating the average rolling resistance ranges for all 5 parameters examined, the terrain surface showed the largest effect on the rolling resistance, followed by the wheel diameter and tyre inflation pressure. Both the cyclist mass and the suspension type showed only second order effects on the rolling resistance. This may be partly attributed to the relatively small difference in the mass of the cyclists in the experiment.

As a final evaluation of the parameters, the correlation coefficients for the parameters evaluated were calculated against the rolling resistance, and the coefficients are shown in Table 3. The data confirmed that the surface was dominant in determining the rolling resistance, with the cyclist mass and wheel diameter showing relatively equal, but secondary importance.

***TABLE 3*: CORRELATION COEFFICIENTS BETWEEN ROLLING RESISTANCE AND SELECTED PARAMETERS**

Parameter	**Correlation coefficient**
Tyre inflation pressure	-0.052
Wheel diameter	0.027
Cyclist mass	0.028
Surfacing	0.814

Obstacle

The last test evaluated the effect of a 100mm high obstacle (rock) that the mountain bike had to negotiate during a typical coast-down test on the distance before the mountain bike came to a standstill. The objective was to determine to what extent a typical obstacle will affect the momentum of the cyclist. The percentage shorter distance that each of the mountain bikes travelled after traversing the obstacle is shown in Table 4. Higher values indicate that the mountain bike came to a standstill in a shorter distance after the obstacle (greater loss of momentum) than for lower values, with a 100% value indicating that the mountain bike stopped at the obstacle. The obstacle test was only conducted on the bituminous surface.

***TABLE 4*: PERCENTAGE SHORTER DISTANCE TRAVELLED AFTER INTRODUCING OBSTACLE**

Tyre inflation pressure [kPa]	**500**			**250**		
	Cyclist mass [kg]			**Cyclist mass [kg]**		
	70	**80**	**90**	**70**	**80**	**90**
HT26	10%	12%	16%	19%	23%	28%
FS26	6%	8%	14%	14%	16%	20%
HT29	5%	5%	6%	7%	11%	16%
FS29	2%	3%	5%	6%	8%	10%

HT= High tyre inflation pressure FS= Full suspension

Analysis of the data in Table 4 indicates that the best combination for maintaining momentum after traversing over an obstacle was the high tyre inflation pressure, low cyclist mass and the full suspension 29in. wheel diameter option. The 29in. wheel diameter had an advantage over the 26in. wheel diameter, with even the low tyre inflation pressure of the Hardtail 29in. mountain bike being on par with the high tyre inflation pressure full suspension 26in. mountain bike.

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions are drawn:

- The 26in. wheel diameter (both suspension types) has a higher rolling resistance than the 29in. wheel diameter for the sand, grass and gravel surfaces, with the bituminous surface showing negligible differences;
- The sand surface had a rolling resistance coefficient factor of between 4.5 and 15 times higher than the gravel, grass and bituminous surfaces;
- No measurable advantage could be identified in using a full suspension as opposed to a Hardtail suspension in terms of rolling resistance on the four surfaces evaluated;
- Terrain surface showed the largest effect on the rolling resistance coefficients of the mountain bikes, surfaces and conditions evaluated, followed by the cyclist mass and wheel diameter, and finally the tyre inflation pressure; and
- The best combination for maintaining momentum after traversing over an obstacle is the high tyre inflation pressure, low cyclist mass and full suspension 29in. wheel diameter option.

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