South African Journal for Research in Sport, Physical Education and Recreation, 2014, 36(1): 211-227.
Suid-Afrikaanse Tydskrif vir Navorsing in Sport, Liggaamlike Opvoedkunde en Ontspanning, 2014, 36(1): 211-227.
ISBN: 0379-9069

CLASSIFICATION OF MOUNTAIN BIKE TRAILS USING VEHICLE-PAVEMENT INTERACTION PRINCIPLES

Wynand J.vdM. STEYN, Handre VAN NIEKERK & Wietsche M.G. JACOBS
Department of Civil Engineering, University of Pretoria, Hatfield, Pretoria, Republic of South Africa

ABSTRACT

Various mountain bike trails exist in South Africa, but their difficulty ratings are generally unknown. By classifying the trails, risk of injury and uncertainty can be limited as information are provided on the difficulty of the trail. In creating a Trail Classification System (TCS) the principles of Vehicle-Pavement Interaction (V-PI) can be applied to develop an objective evaluation of trail difficulty. The objective of this paper was to describe the different aspects that contribute to the degree of difficulty of a mountain bike trail and adopt an existing trail rating system through application of V-PI data. Based on the information in this paper, it is concluded that trail roughness affects the measured riding quality value of a section and trail gradient is the main contributor to difficulty of a mountain bike trail in terms of physical exertion. It is recommended that the proposed TCS be implemented on mountain bike trails.

Key words: Mountain bike; Trail classification; Vehicle-pavement interaction.

INTRODUCTION

Mountain biking is a sport or recreational activity that consists of a person riding over a rough terrain, using a specially adapted mountain bike. Mountain bikes are designed to enhance durability and performance on rough terrain. Mountain biking consists of multiple categories such as: cross country, trail riding, all mountain, downhill, free ride, dirt jumping and trails, with the majority of riders involved in cross country and trail riding (Clarke, 2002). Most of the trails in South Africa are natural jeep tracks, hiking trails or single track footpaths, and are found going through private land owners' farms which leave the cyclists at risk not knowing the trail ahead of them. By classifying the trails on a more rational basis, the risk of injury and uncertainty can be limited for cyclists because they receive enough information on the difficulty of the trail.

The interaction of vehicle and pavement is an important aspect in transportation. In creating the Trail Classification System (TCS) the principles of Vehicle-Pavement Interaction (V-PI) can be applied to develop an objective evaluation of trail difficulty. Due to the popularity of mountain biking, trails are ridden everyday by newcomers to the sport of mountain biking. This increases the risk of injury due to cyclists trying to ride trails that they are not capable of, or trails unknown to them. The availability of a TCS for all types of mountain bike trails provides the cyclist with the necessary information, such as the surface type, maximum gradient and level of technical obstructions expected on the trail (Cessford, 1995; Pickering *et al*., 2010).

OBJECTIVE AND BACKGROUND

The objective of this study was to describe the different aspects that contribute to the degree of difficulty on a mountain bike trail and adopt an existing trail rating system through application of V-PI principles.

Mountain biking

The first mountain bike was a cruiser bicycle that was modified to enable cyclists to freewheel down mountain bike trails. The sport became popular in the 1970s in Marin County, California, USA. However, it was not until the late 1970s and early 1980s that road bicycle companies started to manufacture mountain bikes using lightweight materials. Throughout the 1990s and 2000s, mountain biking moved from a lesser-known sport to a mainstream activity complete with an international racing circuit and a world championship (Mountain Bike Hall of Fame, 2012).

A bicycle frame is the main part of a bicycle, onto which the wheels and all other components are attached (Figure 1). The geometry of a mountain bike varies based on the angle of the seat post and the head tube measured from the horizontal. Mountain bike frames are manufactured using materials such as carbon steel, steel alloys, aluminium alloys, titanium and carbon fibre (Sparks, 2007; Brown, 2012).

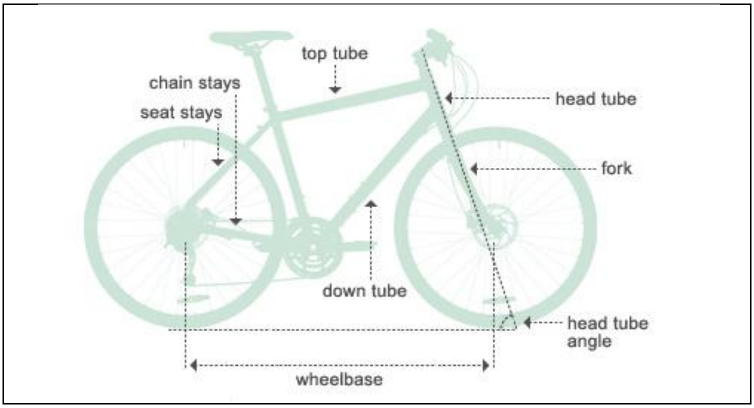

***FIGURE 1*: TYPICAL MOUNTAIN BIKE FRAME** (Brown, 2012:online)

Two major wheel sizes are used for mountain bikes. These are the traditional 26 inche wheel and the more recent 29 inche wheel. The 26 inche wheel has a rim diameter of 559mm while the 29 inche wheel rim size has a diameter of 622mm. 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 paper, the same custom is followed. The motivation for the 29inche wheel size is mainly that it provides increased rotational inertia, providing more stability on the bicycle and making it easier to keep angular momentum when riding over small climbs and rough sections. It further decreases the approach angle of impact with larger obstacles (Ninerbikes, 2012).

Rolling resistance is affected by wheel diameter, width, pressure and tyre tread. When riding off-road mountain bike trails, these factors affect the cyclist's comfort and riding quality. Lower tyre inflation pressures and wider tyres are more suitable for mountain biking, but it increases rolling resistance due to the fact that small bumps and gravel bits are absorbed by the tyre, and subsequently increase cyclist comfort. Higher tyre inflation pressure decreases the rolling resistance, riding comfort and control of the cyclist (Nilges, 2005). Typical tyre inflation pressures for mountain bikes range between 200 and 325kPa (Khan, 2003).

Mountain bike suspensions can be divided into three categories: 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 mountain bike has a shock 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 (Wilson, 2004) (Figure 2).

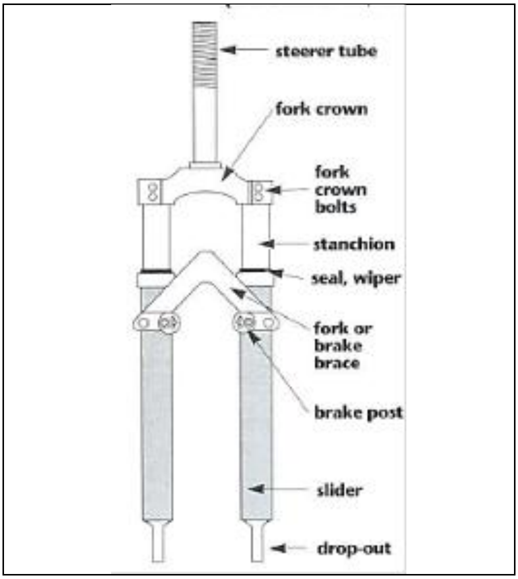

***FIGURE 2*:** **TYPICAL MOUNTAIN BIKE FRONT FORK SUSPENSION** (Sutherland, 1995:446)

Mountain biking is a sport undertaken on several ranges of public land tenures, such as protected areas, designated mountain bike trails, urban reserves, forests and commercial mountain bike parks. These terrains can be divided into three categories: Trail terrain;

Technical terrain; and Advanced terrain (Pickering *et al*., 2010). Trail terrain consists of non-technical terrain sections, meaning no route selection through roots, rocks and other obstacles that require a higher level of skill. Trails on this terrain in general are partly paved or well compacted with a smooth riding surface. Typical trails that can be ridden in this terrain are open single tracks, fire roads, cycle ways, farm roads and urban reserves. Technical terrain consists of single tracks and routes that require some riding skill to avoid obstacles such as roots, rocks and holes. Some tracks also include man-made technical features such as jumps, bridges, and ditches that are constructed of soil, clay, rocks and timber. Most off-road mountain biking is done on technical terrain because of its availability to people for recreational activities. The tests conducted for the study presented in this paper were done on technical terrain. Advanced terrain is beyond the capabilities of both trail and technical terrains and consists of pedalling over steeps mountain gradients and passing through fast technical downhill sections on rough terrains (Pickering *et al*., 2010; CTC, 2012).

Two factors that have a major influence on the way a mountain cyclist endures a trail are fitness level and handling skills. Experienced mountain cyclists would be confident riding anywhere, even if the trails do not really accommodate mountain biking. The level of skill and fitness more experienced cyclists possess, allow them to attempt mountainous terrain trails with steep gradients and difficult technical skill sections with a reasonable level of comfort (IMBA, 2012).

Heart rate is a way in which the energy efficiency of a cyclist can be measured during testing. A high heart rate relative to a cyclist’s maximum heart rate is an indication of a high level of energy exertion. However, heart rate measurements are variable and can easily be affected by surrounding conditions, such as body temperature, stress and anxiety (Davie, 2011). Heart rate data collected during testing in this study were not included as a category classification when creating the TCS, but were used as an indication of effort needed to overcome these sections.

Trail rating systems

Risk management is an important issue many bike park owners have to deal with. Allowing cyclists to use trails that are not well maintained and constructed can lead to severe injuries. Trail rating systems may contribute to lowering the risk of injuries through provision of information on the expected difficulty of the specific trail (IMBA, 2012). The International Mountain Bicycling Association (IMBA) is a non-profit association with a mission to create, enhance and preserve safe bike trails for mountain bikers all over the world (IMBA, 2012).

IMBA developed a basic rating system by evaluating at visible characteristics that help users in the planning of trails and trail systems. The rating system is called the Trail Difficulty Rating System (TDRS). It was adapted from the International Trail Marking System used at international ski areas (IMBA, 2012). The system is widely used in trail networks, and is mostly found in trails that are associated with holiday resorts.

The TDRS is based on four parameters that, when combined, provides a single indication of the trail difficulty as indicated in Table 1. The trail surface parameter is described from hardened, to widely variable and unpredictable. The trail width and grade provide quantifiable indications of these parameters. The TDRS does not constitute a standard and serves only as a basic indication to rate the difficulty of a mountain bike trail. The four parameters consider only the technical challenge of the track and do not take into account trail length and physical exertion from the cyclist. Apart from the trail width and grade, the other parameters are not quantified, and the system also does not provide an indication of the potential experience of the cyclist on the trail in terms of a parameter, such as rider comfort. Current trail ratings systems (IMBA) have no purpose unless the difficulty of each trail are well marked along the trail and also indicated on maps of recreational park trail systems. By ensuring this, cyclists will be able to plan ahead and help them to choose trails that match their level of skill (ASR, 2011).

***TABLE 1*: INTERNATIONAL MOUNTAIN BIKING ASSOCIATION (IMBA) TRAIL RATING SYSTEM** (IMBA, 2012:online)

Rating criteria	Easiest **White circle**	Easy **Green circle**	More difficult **Blue square**	Very difficult **Black diamond**	Extremely difficult **Double black diamond**
Minimum Trail width	>1800mm	>900mm	>600mm	>300mm	>150mm
Trail surface	Hardened or surfaced	Firm and stable	Mostly stable & some variability	Widely variable	Widely variable & unpredictable
Maximum trail grade	10%	<5%	<10%	<15%	<20%
Natural obstacles and Technical Trail Features (TTF)	None	Unavoidable obstacles <50mm; Avoidable obstacles may be present; Unavoidable bridges wider than 900mm.	Unavoidable obstacles <200mm; Avoidable obstacles may be present; Unavoidable bridges wider than 600mm; TTFs <600mm high, deck width>height.	Unavoidable obstacles <380mm; Avoidable obstacles may be present; May include loose rocks; Unavoidable bridges wider than 600mm; TTFs <1200mm high, deck width<½height; Short sections may exceed criteria.	Unavoidable obstacles <380mm; Avoidable obstacles may be present; May include loose rocks; Unavoidable bridges wider than 600 mm; TTFs >1200mm high, deck width unpredictable; Many sections may exceed criteria.

Vehicle–pavement interaction

A road profile is a two-dimensional image of a road surface taken on an imaginary line that shows the roughness, grade and texture of a road (Sayers & Karamihas, 1998). Profiles can be used to:

- Monitor the condition of a certain road network for Pavement Management Systems (PMS);
- Evaluate the quality of newly constructed or repaired sections;
- Diagnose the condition of certain sections and determine remedies; and
- Study the condition of certain section for research.

Road roughness is the deviation in elevation felt in a vehicle while riding along a certain road, the difference in vertical displacement acts on the wheels causing vibrations. Roughness is expressed in terms of unwanted accelerations on the body caused by road irregularities (Gillespie, 1992). The roughness is not only caused by vertical body bounce and pitch moments but also due to body roll movements (Sayers & Karamihas, 1998). In mountain bike riding the vertical bounce movements can be allocated to rough surfaces and transverse roll movements to large rocks causing the cyclist to be thrown off-balance.

Almost every automated road profiling system calculates the International Roughness Index (IRI) statistic. The IRI is a general pavement condition indicator and describes the profile roughness that causes vehicle vibrations. An IRI value is defined as the accumulated suspension movement divided by the distance travelled to give an index with units of m/km (Sayers & Karamihas, 1998). The IRI summarises the roughness qualities that impact vehicle response and is appropriate when roughness measures relate to:

- Overall vehicle operating cost;
- Overall riding quality;
- Dynamic wheel loads; and
- Overall surface condition.

Typical IRI values for vehicles on roads range between 1 and 20. However, in the application for this paper, the IRI is used as a general indication of riding quality, and it is appreciated that the IRI has originally been developed for cars with their respective dynamics.

For roads, the target is an IRI value as low as possible, however, higher levels of roughness are sought and provides the challenge for mountain biking. Road pavements with an IRI above 8m/km are almost impassable for most vehicles without decreasing their speed significantly. This is the range of riding qualities where mountain bike trails start to provide a decent challenge to the cyclist. The higher the IRI value, the more difficult it becomes and more skill and energy are needed by a mountain bike cyclist to overcome a section.

EXPERIMENTAL METHODOLOGY

Figure 3, on the next page, represents 7 terrains used for the experiment of this study.

Flat open grassland

Flat single track

Flat single track including artificial technical features

Uphill smooth gravel jeep track

Uphill technical single track

Downhill smooth gravel jeep track

Downhill rocky single track

***FIGURE 3*: SEVEN TERRAINS USED FOR THE EXPERIMENT**

Equipment, terrain and measures

A Diamond shape Titan Hardtail 29 inches mountain bike with a Deore XT group set, Shimano SL-M590-3 shifters, Draco White 180/180 brakes and a Shimano M522 24-32-42T chain wheel was used in the experiments (Titan Bicycles, 2012). Two X16-1C accelerometers were used to measure the vertical accelerations (GCDC, 2011). A calibrated mountain bike specific Global Positioning System (GPS) was used to record the different grades, elevation changes, speed and cyclist heart rate. The Groenkloof Nature Reserve is a popular area for mountain biking in Pretoria with numerous routes of different technical difficulty. Seven different terrains were selected for testing as shown in Figure 3. Before a test was done the width and length of each section was measured.

Acceleration sensors were mounted on the handle-bar and the seat post of the mountain bike. The handle-bar was chosen because it is the primary position in steering a mountain bike. A large amount of vibration would be damped by the front shock. The second accelerometer was placed on the seat post. Riding comfort and quality is directly related to vibration. If the vibration on the seat is too severe a cyclist would be forced to stand on the pedals which could lead to more physical fatigue.

A Response Type Road Roughness Measurements **(**RTRRM) model, based on the vertical acceleration response of a mountain bike riding on road roughness calibration sections was developed (Lukas, 2012) to calculate the roughness of the mountain bike trails. The model was calibrated at a cycle speed of 10km/h. Sections were tested one at a time with a standing start 5 m before the start of the section to reach the speed at which data collection was done. Each section was measured three times at 10km/h±1km/h, starting with the heart rate of the cyclist at below 90 beats per minute (BPM).

DATA COLLECTION

The difficulty of Mountain biking is a function of various parameters. For the purpose of the current study the following parameters were used to analyse the technical challenge of different sections:

- Trail section roughness in terms of IRI;
- Trail width;
- Average and maximum section gradient; and
- Artificial and natural features.

According to IMBA the physical exertion of a cyclist should not be measured to create an index. During the experiment the heart rate of the cyclist was monitored to provide a perspective on the physical exertion that the different types of trail sections have on the cyclist.

A Power Spectral Density (PSD) analysis was performed on the vertical acceleration data to identify the dominant frequencies for each section (Figure 4). The vibration energy that a cyclist absorbs during a section can be determined by calculating the area under a PSD graph. The effective width of a trail will have a contributing factor towards the difficulty of the section. The narrower the section the more handling skill will be required from a cyclist to keep the bicycle on the trail. Width measurements were taken every 5 m on a section from which the average width and maximum width were determined. The maximum gradient was the steepest part measured on a section that was at least 3m long. The average gradient of the sections is the total vertical displacement over the horizontal length.

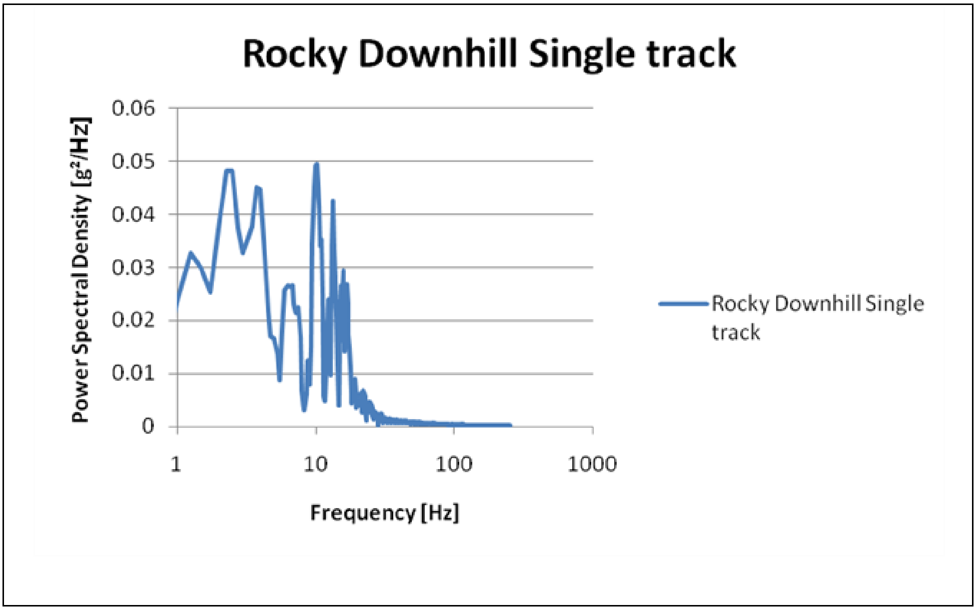

***FIGURE 4*: TYPICAL POWER SPECTRAL DENSITY (PSD) GRAPH FOR A SECTION USED IN THIS STUDY**

Artificial and natural features also contribute to the difficulty of a trail. The effect that features, such as rocks, roots, logs and holes have on a cyclist, will depend on a cyclist's skill. The height of each obstacle was measured from the trail surface up to the highest point. In cases of uneven obstacles the height was measured up to a point where it is the easiest to ride over. In the case of bridges the height above the ground, as well as the width of the bridge were measured. The effect that the artificial and natural features have on a section can be related to the vibration measurements taken over a section. The measurements of unavoidable obstacles, such as rocks, roots, holes and trees are shown in Table 2 (Jeep track trails has two wheel tracks compared to single track trails).

DATA ANALYSIS

Trail section analysis

The rocky uphill single trail section had the highest roughness (IRI of 62.3 m/km) and the flat single trail the lowest (IRI of 19.7 m/km). The uphill rocky single track section had the highest obstacle height and throughout the section many loose rocks occurred, thus resulting in the relatively high IRI value.

***TABLE* 2: RIDING QUALITY, WIDTH, MAXIMUM AND AVERAGE GRADIENT AND OBSTACLE HEIGHTS OF TEST SECTIONS AT GROENKLOOF NATURE RESERVE**

Different Sections	**IRI** (m/km)	**Average width** [m]	**Maximum width** [m]	**Maximum grade** [%]	**Average gradient** [%]	**Obstacle height** [m]
Open Grassland	38.1	>5	>5	2.0	1.0	<0.04
Flat single track	19.7	0.35	0.6	3.0	2.5	<0.02
Single track with features	28.0	0.8	0.8	5.5	5.0	<0.10
Uphill jeep track	56.5	2.4	3.0	15.0	9.7	<0.15
Uphill rocky single track	62.3	0.5	1.5	18.0	11.4	<0.30
Downhill jeep track	46.51	3.5	4.0	12.0	9.5	<0.10
Downhill rocky single track	52.37	0.6	1.0	12.5	12.0	<0.12

The grass section roughness was higher than the flat single track section possibly due to roots of the grass causing small vertical displacements that are picked up by the accelerometers. The higher IRI value of the grass could also be due to the flat single track section being used more often than the grass section resulting in the grass being totally removed and leaving the ground well compacted and relatively smooth.

It was found that as the height of natural obstacles increases, the IRI value of the section increased (Figure 5). The IRI values could vary from ride to ride, the reason being that the cyclist may on one ride hit a rock on the section causing a larger vertical displacement than the next time when travelling past the rock.

The effective width of each section was measured (Table 2). From these widths it was found that the effect it has on the physical exertion by the cyclist is minor, although it directly affected the level of comfort a cyclist experienced. It was evident that the effective width of a section is mainly influenced by natural and artificial features present. The rocky uphill section has an average width of 500mm and a maximum width of 1.5m but, with a rock of 300mm high, the cyclist will be forced to navigate a line around it. Experienced cyclists may traverse over the rock while inexperienced cyclists will either attempt to ride around the rock or dismount.

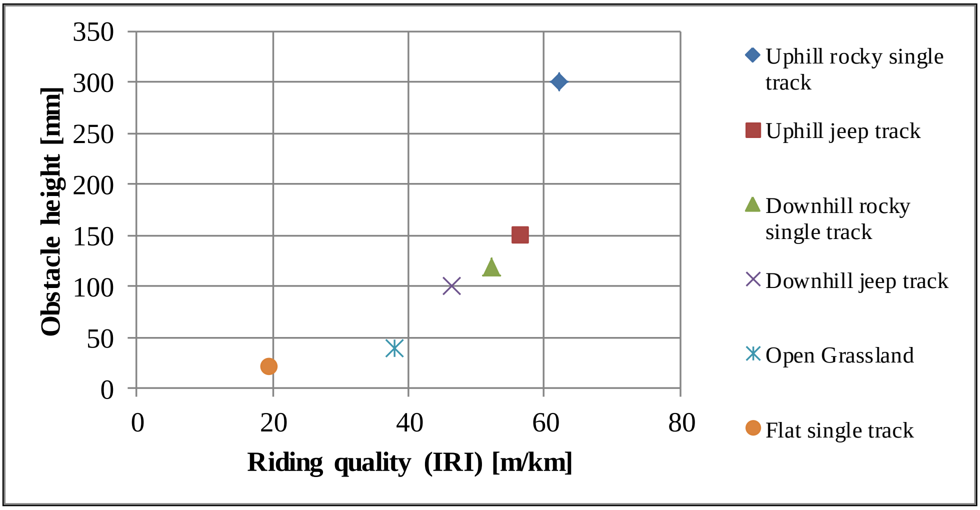

FIGURE 5: **COMPARISON BETWEEN RIDING QUALITY AND OBSTACLE HEIGHT ON THE SIX TRAIL SECTIONS**

In the case of artificial features the effective trail width is directly related to the width of the artificial feature. The height and width of the feature have an effect on the cyclist. The narrower the section and the higher it protrudes above the ground, the higher the level of handling skills that will be required from a cyclist. A relationship can be drawn between the level of comfort and the width of a trail, namely that the narrower the trail, the lower the level of comfort a cyclist will experience because there is a higher risk for a mistake which could lead to serious injury.

The trail gradient contributes significantly to the physical exertion of a cyclist. The steeper the uphill gradient of a section the more effort was needed to maintain a speed of 10km/h. Roughness also contributed to the difficulty on uphill sections. This effect was best experienced on the two uphill sections. Although the average gradient of both sections was similar, the roughness of the rocky uphill was much higher than the roughness on the uphill jeep track section. This higher roughness caused the cyclist to experience a lower level of comfort as the cyclist had to maintain focus on the pedal stroke to maintain speed while navigating between large rocks. On the jeep track the roughness was less, increasing the level of comfort and allowing the cyclist to mostly focus on maintaining speed.

On the downhill sections maintaining speed was not a concern. What contributed largely on the downhill section was the flow of turns through a section. The sharper the turn the more skill in braking and turning is expected from the cyclist due to the momentum of the bike going forward. Thus, from the gradient analyses it is clear that the steeper the gradient of the trail the higher level of fitness and bike handling skills will be needed to overcome the gradient.

Accelerations absorbed due to different roughness

As the cyclist completes a section, vertical accelerations are absorbed through the seat post and handle-bar. These accelerations can be interpreted as the vibration energy absorbed by the cyclist due to the unevenness of the trail. The different amounts of energy absorption per section are shown in Figure 6. The energy absorbed by the handle-bar and the energy absorbed by the seat post are different from one another on the uphill and downhill sections, but similar on the flat sections. This difference in energy absorption can be explained through simple physics.

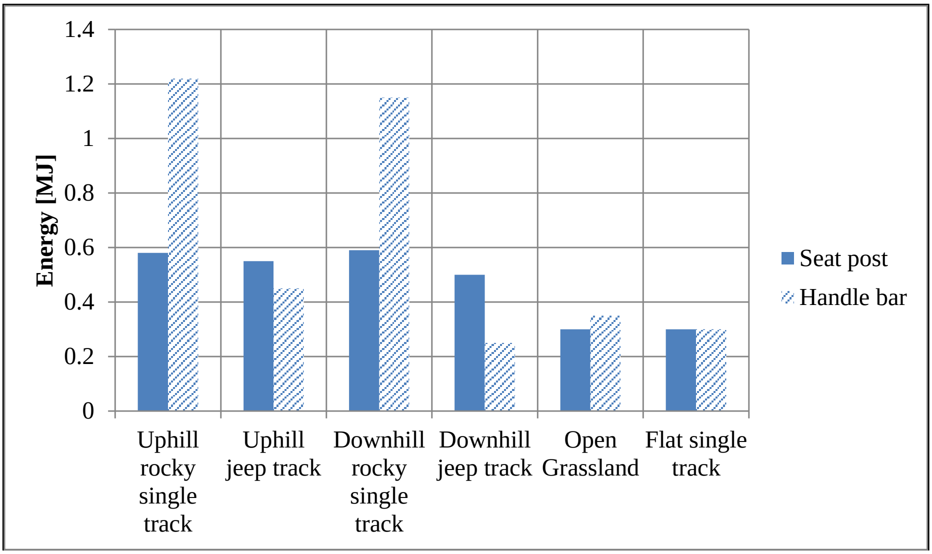

FIGURE 6: **ENERGY ABSORPTION OF CYCLIST ON THE SIX DIFFERENT TRAIL SECTIONS**

If the cyclist leans back on the uphill sections, the vertical accelerations on the handle-bar will be higher due to the smaller force placed on the handle-bar by the cyclist, leading to relatively high vertical accelerations and higher energy absorption, decreasing the level of comfort a cyclist experience. Rear wheel accelerations will decrease due to the higher mass placed on the rear wheel. This restricts most of the vertical accelerations. The lower energy absorption could also be due to the cyclist being able to have better control of the rear end of the bike by steering the front wheel of the bike over the more difficult obstacles thus leaving the rear wheel to follow over the smoother trail path. On the downhill the effect is opposite, with the angle of the downhill slope forcing the cyclist to lean forward while remaining seated, thus resulting in a higher mass on the front wheel. The lower pressure on the rear wheel causes higher vertical accelerations when travelling over obstacles.

The flat sections' energy absorption at the handle-bar and seat post is similar. This can be seen as a good indication that the cyclist placed equal pressure on the rear and the front wheel of the mountain bike. The flat single track had a very low relative IRI value thus increasing the level of comfort and lower level of vibrations. The grass soft surface increased the rolling resistance of the tyre that leads to a higher rate of physical exertion. With the grass section's IRI value slightly higher than the flat section, the energy absorbed can be expected to be higher as found. The higher roughness value can also be due to small indentations under the grass surface caused over a period of time. With the roughness on both of the flat sections being low due to few (or no) natural obstacles on the trail, results in a relatively low energy absorption and a high level of comfort experienced by the cyclist on the flat section.

Heart rate measurements analyses

Heart rate data were used in this paper as a general indication of the physical exertion of the cyclist during each of the measurements. The data were expressed as a ratio between the average heart rate measured over the section and the resting heart rate of the cyclist. One experienced cyclist was used for all measurements, and the cyclist rested until resting heart rate was attained before repeating measurements at 100 per cent effort for the specific cyclist. The data in Table 3 indicate that the cyclist required the lowest physical effort to ride the downhill jeep track, open grassland and flat single track sections, while the highest physical effort was required for the uphill jeep track.

***TABLE 3*: HEART RATE RATIOS AS INDICATION OF CYCLIST PHYSICAL EXERTION**

Trail sections	Heart rate ratio
Open Grassland	1.4
Flat single track	1.4
Uphill jeep track	2.0
Uphill rocky single track	1.7
Downhill jeep track	1.2
Downhill rocky single track	1.6

Additional analysis of the data indicated that the energy absorbed was related to the trail roughness (Figure 7) (roughness data were independently measured using separate bike and sensor), with major increases for trail roughness above 50m/km. Acceleration data from the fork are shown in Figure 7. Due to the fact that the rear wheel was less prone to lift off from the ground its acceleration data were more consistent than when riding a track section multiple times.

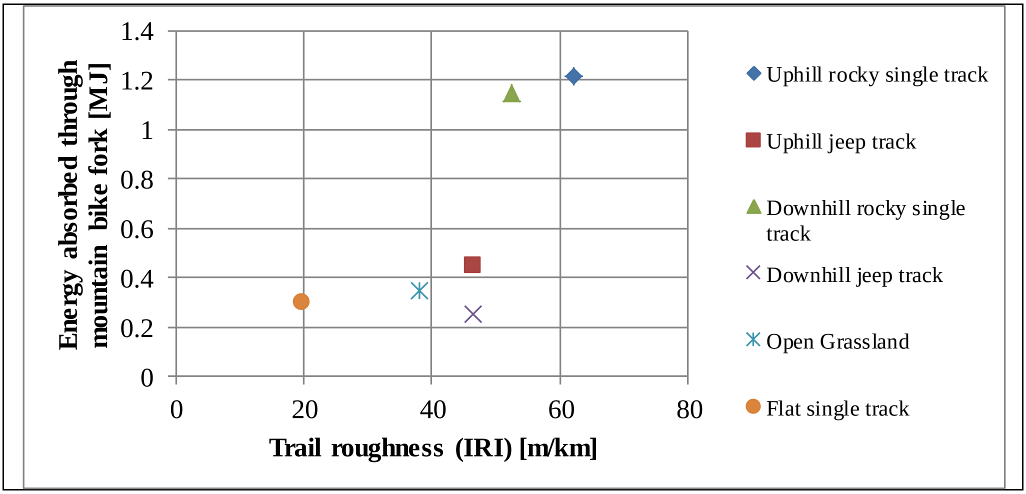

***FIGURE 7*: RELATIONSHIP BETWEEN TRAIL ROUGHNESS AND VIBRATION ENERGY ABSORBED**

IMPLEMENTATION OF INDEX

It is recommended that based on the results obtained from the study, the Trail Classification System (TCS) shown in Table 4 should be implemented on mountain bike trails as a means of informing mountain bike cyclists of the expected levels of difficulty, comfort and fitness requirements before cyclist start using the trail. It is mainly based on the IMBA system, with the addition of the V-PI principles, such as trail roughness and vertical acceleration data (providing a ride comfort indication), and the heart rate data (providing a fitness requirement indication).

CONCLUSIONS

Based on the findings and discussion, the following conclusions are drawn:

- Trail roughness defines the IRI value of a section with larger obstacles and more rocky areas causing the relatively higher roughness in the flow line.
- Trail width affects the comfort of a mountain bike cyclist with narrower trails causing lower levels of comfort and requiring higher skill levels.
- Trail gradient is the main contributor to difficulty of a mountain bike trail in terms of physical exertion on the mountain bike cyclist.
- The vibration energy absorbed by a mountain bike cyclist is directly related to the vertical accelerations from both seat post and handle bar caused by the trail roughness.

***TABLE 4*: RECOMMENDED RIDING QUALITY INDEX**

Trail features	**Easy: White**	**Moderate: Yellow**	**Difficult: Blue**	**Very difficult: Black**
Trail width	>2000mm	>1000mm	>500mm	>200mm
Trail surface	Relatively flat, wide roads with well compacted or paved surface. May be loose or muddy at times.	Soft loose surfaces, grass land and muddy at times. Short single track sections with small rocks, roots and obstacles.	Variable surface types. Lots of flowing single track with plenty of rocks, roots and obstacles.	Wide variety and unpredictable surfaces. Technical flowing single track with large rocks and obstacles. Ability to overcome static obstacles required.
Comfort indication (IRI)	<30m/km	< 45 m/km	< 60 m/km	<75m/km
Average trail gradient	<4%	<8%	<12%	>12%
Maximum trail grade	<5%	<10%	<15%	<20%
Natural and technical trail features	None	Bridges over challenging technical features. Unavoidable obstacles <50mm. Bridges wider than 1000mm	Technical features present with avoidable routes such as bridges, drops and cambers. Unavoidable obstacles <150mm. Drops <300mm. Artificial features <1000mm high	Unavoidable obstacles <300mm. Challenging technical features (rock gardens, bridges and unavoidable trees) present. Unavoidable obstacles <300mm. Drops >300mm. Artificial features <1000mm high
Required fitness level	Low. Active lifestyle.	Medium. Regular trail riding.	Seasoned cyclist. Technically competent.	Very active lifestyle. Technically very competent.

REFERENCES

ASR (ACTION SPORTS IN RESORTS) (2011). "Mountain bike trail difficulty rating system." Hyperlink [http://www.asr-sig.com/?p=258]. Retrieved on 27 February 2012.

BROWN, S. (2012). "Bicycle frame geometry." Hyperlink [http://sheldonbrown.com/index.html]. Retrieved on 2 March 2012.

CESSFORD, G. (1995). *Off-road impacts of mountain bikes*. Wellington (New Zealand): Department of Conservation.

CLARKE, K. (2002). National Mountain Bicycling Strategic Action Plan. Bureau of Land Management. BLM/WY/PL-03/001+1220. Washington D.C.: U.S. Department of the Interior, Bureau of Land Management

CTC (2012). "Mountain Bike Leader Award terrain types." Hyperlink [http://www.promtb.net/courses/leaderawards/terrain.htm]. Retrieved on 6 March 2012.

DAVIE, M.C. (2011). "Mountain bike suspension systems and their effect on cyclist performance quantified through mechanical, psychological and physiological responses". Unpublished PhD dissertation. University of Glasgow, Scotland. Hyperlink [http://theses.gla.ac.uk/2432/]. Retrieved on 13 June 2013.

GCDC (GULF COAST DATA CONCEPTS) (2011). "USB-Accelerometer 3-axis Self Recording Accelerometer X16-1C." Hyperlink [http://www.gcdataconcepts.com/xlr8r-1.html]. Retrieved on 1 March 2012.

GILLESPIE, T.D. (1992). *Fundamentals of vehicle dynamics*. Warrendale, PA: Society of Automotive Engineers.

IMBA (INTERNATIONAL MOUNTAIN BICYCLING ASSOCIATION) (2012). "Mountain biking resources." Hyperlink [http://www.imba.com/resources]. Retrieved on 2 March 2012.

KHAN, S. (2003). "Pressure in a bicycle tyre". Hyperlink [http://hypertextbook.com/facts/2003/SharaKhan.shtml]. Retrieved on 18 March 2012.

LUKAS, B. (2012). Calibrating response type road roughness measurement systems using mountain bikes. Unpublished B.Eng thesis. Pretoria: University of Pretoria.

MOUNTAIN BIKE HALL OF FAME (2012). "The history of mountain biking." Hyperlink [http://mtnbikehalloffame.com/page.cfm?pageid=4]. Retrieved on 13 June 2013.

NILGES, P. (2005). Mountain bike tyre rolling resistance. Unpublished PhD dissertation. Cologne (Germany): German College of Physical Education.

NINERBIKES (2012). "26v29: The art and science behind 29 inch wheels." Hyperlink [http://www.ninerbikes.com]. Retrieved on 29 February 2012.

PICKERING, C.; CASTLEY, J.G.; HILL, W. & NEWSOME, D. (2010). Environmental, safety and management issues of unauthorized trail technical features for mountain bicycling. *Landscape and Urban Planning*, 97: 58-67.

SAYERS, M.W. & KARAMIHAS, S.M. (1998). *The little book of profiling*. Ann Arbor, MI: University of Michigan.

SPARKS, J. (2007). "Understanding bicycle geometry." Hyperlink [http://jon-sparks.suite101.com/understanding-bicycle-geometry-a34106]. Retrieved on 9 March 2012.

SUTHERLAND, H. (1995). *Sutherland's handbook for bicycle mechanics* (6th ed.). Berkeley, CA: Sutherland Publication.

TITAN BICYCLES (2012). "Bike Catalogue." Hyperlink [http://titanracingbikes.com/Specs.aspx?Bike=29RElite]. Retrieved on 20 February 2012.

WILSON, D.G. (2004). *Bicycling science* (3rd ed.). London, (UK): The MIT Press.

Prof Wynand JvdM STEYN: Department of Civil Engineering, University of Pretoria, Lynnwood Road, Hatfield 0002, Republic of South Africa, Tel.: +27 (0)12 420 2171, E-mail: wynand.steyn@up.ac.za

(Subject Editor: Prof Kim Jenkins)