Profiling of rough terrain

Carl Becker[1] , **Schalk Els**[1]

[1] *Aeronautical and Mechanical Engineering, University of Pretoria, Private Bag X20, Hatfield, 0028, South Africa*

carl.becker@up.ac.za, schalk.els@up.ac.za

Abstract

This study concentrates on obtaining profiles of rough terrain suitable for vehicle dynamics simulations cost effectively. Commercially available inertial profilometers are unable to profile the terrains of interest due to the severe roughness of these terrains. A mechanical profilometer is developed and evaluated by profiling obstacles with known profiles as well as rough 3-D test track profiles. Good correlation between the profiled and actual terrains is achieved. Realistic three dimensional (3-D) terrain models are generated from the terrain profiles. The Displacement Spectral Densities of the profiled terrains are found to contain discrete peaks and that a straight line fit would not be an accurate estimation for the specific rough terrains. Comparisons between the terrains defined in the International Roughness Index (IRI) and the present study indicate that the roughness index of the terrains profiled with the mechanical profilometer is significantly higher than the terrains normally profiled by inertial profilometers.

Keywords: Profilometer, rough terrain, Displacement Spectral Densities, 3-Dimensional profiles, International Roughness Index, Root Mean Square, Photogrammetry, Laser

1. Introduction

In South Africa, the commercial, military and off-road vehicle industries use the suspension test tracks at the Gerotek Test Facilities (2007) for ride comfort and durability tests over repeatable terrains. The terrains are cast in concrete, kept in good condition and are only used for testing and not driven on continuously. Terrain profiles of these tracks are not available and cannot be measured using commercially available inertial profilometers due to the severe roughness of the terrain which may cause damage to inertial profilometers. Also inertial profilometers often remove lower frequency content to eliminate drift on the integration.

This study concentrates on obtaining the terrain profiles of several of the frequently used rough test tracks on the Gerotek Test Facility. From these profiles realistic three dimensional (3-D) terrain models are generated. The 3-D terrain models can then be used in virtual vehicle simulations. This is done in order to correlate the dynamic response of the vehicle in virtual simulations with real life tests. Many commercial profilers are designed to measure road “roughness” from a manufacturing, quality control or characterising perspective. The requirement for the present study is for short distances (typically 100m) of accurate 3-D road profiles for use in vehicle dynamic simulations and that can be used to study the tyre-terrain interface in detail. The profiler was to be used for a few specific terrains and not for continuous measurements.

A mechanical profilometer, nicknamed the Can-Can Profilometer, was developed and initially evaluated by profiling simple obstacles with known profiles. The difference between the absolute dimension of the obstacle and the measured profile was within an accuracy of better than 5mm as described in section 4.

This study will concentrate on comparisons between Gerotek Belgian paving profiled with the use of the Can-Can Profilometer, photogrammetric measurements and a Laser Scanner and the Stuttgart-Unterturkheim test track Belgian paving profile, as profiled by Daimler AG with the use of photogrammetric measurements (OpenCRG, 2010). In addition a 4.2km rough mountain pass, 800m of rough off-road terrain and other tracks on the suspension track at Gerotek are profiled with the use of the Can-Can Profilometer, analyzed with the use of Displacement Spectral Densities (DSD) and compared with the International Roughness Index (Sayers and Karamihas, 1998).

2. Literature Survey

Imine et.al (2003) describes a profilometer as an instrument used to produce a series of numbers related in a well-defined way to a true profile. Some road profilometers only take a one-dimensional trace (or two traces) of the three-dimensional surface of the road. This removes all the lateral variation in the data, and assumes every time a vehicle drives along the road or terrain, it drives along exactly the same path (Sayers and Karamihas, 1998). On a typical rough test course, different paths mean different road profiles and possibly very different reliability and durability results. The fact that different paths mean different road profiles embraces the requirement for accurate full 3-D terrain profiles for valid simulation results.

Spangler (1964) states that an inertial profilometer makes use of an accelerometer which measures the vertical response of the vehicle travelling on the road. An inertial profilometer is capable of measuring and recording road surface profiles at speeds ranging from 16 to 112 km/h, thus the term High Speed Profiler. The vertical body motion (Inertial reference) was obtained by the double integration of the response measured by the accelerometer. The relative displacement between the pavement surface and the vehicle body was measured with a non-contact light (laser) or acoustic measuring system (Infrared or ultrasonic sensor) and was mounted on the vehicle body together with the accelerometer. The pavement elevation profile was obtained by subtracting the output from the height sensor from the absolute motion of the vehicle body (Kulakoski, Henry and Wambold, 1986).

The University of Tennessee, Knoxville (UTK) developed a Mobile Scanning System which is more flexible in the types of environments and structures that can be digitized when compared to methods utilizing aerial terrain scanning (Grinstead et al. 2005). Their system combines laser range scanners, high resolution video cameras, a Global Positioning System (GPS) and an Inertial Navigation System (INS) to measure the system's position and orientation. The instrumentation is mounted on a vehicle and the terrain is digitized to provide a geometrically accurate 3-D model of the terrain as the vehicle is driving. The system uses a downward looking laser range scanner to digitize the terrain. The profiling capability on rough terrains is limited to the mobility of the vehicle used and the amount of vibration induced on the instrumentation during profiling rough terrains.

The Vehicle Terrain Measurement System (VTMS), (Kern, 2007), consists of four major components: a scanning laser, an inertial navigation system, a data acquisition system and a power management system. The use of these components allows this system to record the measured profile and to place the profile in global coordinates. These components are mounted on the rear of the host vehicle. The VTMS is capable of measuring profiles both on-road and off-road. The scanning laser is mounted 2 m above the profiled terrain and scans the terrain surface over a width of 4 m. The spacing between sequential points in the grid is approximately 5 mm, however the spacing is not uniform. This is due to the scanning laser operating by directing a laser beam at a rotating prism. A second cause is that the lateral position depends on the vertical position of each point.

The positioning system used in the VTMS is a Differential Global Positioning System (DGPS). The DGPS produces global positioning with an accuracy of 20mm for a longitudinal distance travelled up to 10 km. Thus the final accuracy of the Vehicle Terrain Measurement System is confined to the 20mm accuracy of the DGPS. The DGPS consists of two units, the base unit which is stationary and the unit mounted in the host vehicle, which contribute to the accuracy obtained. The DGPS signal is then combined with the IMU measurements in a Kalman filter to produce the final prediction of the orientation and position of the host vehicle.

The OpenCRG® (2010) initiative was launched in October 2008 and its objective is the provision of a series of open file formats and open source tools for the detailed description, creation and evaluation of road surfaces. It is suitable for a broad range of applications including e.g. tyre and driving simulations. OpenCRG® is a format called Curved Regular Grid (CRG) which has been used internally for several years by Daimler AG. An entire suite of MATLAB® and FORTRAN tools have been developed for the handling, evaluation and generation of CRG data. The website, www.openCRG.org, is the main portal for information about OpenCRG®. It comprises of the latest news available concerning the data format, free and commercial tool-sets, test data etc. The terrain profiles available from OpenCRG® have been profiled with the use of time consuming photogrammetric measurements, on rough terrain, as well as fast measurements on public road with the use of inertial profilometers.

Due to the severe roughness of the terrains under consideration for the present study, none of the existing solutions were feasible. The inertial and high-speed profilers are not suitable for the use on very rough terrain where the vehicle speed is very low and the vibration on the system potentially very high. Suitable methods such as the “rod and level” and photogrammetric measurements are extremely slow and time consuming and therefore not suited for obtaining 3-D profiles efficiently. Although photogrammetry is suitable for short sections, it is very time consuming and resource intensive to measure hundreds of meters of terrain.

The roughness of a test course can be specified with the use of the Root Mean Square (RMS) elevation in the time domain or a Displacement Spectral Density (DSD) in the frequency domain (Gorsich et al., 2003). The roughness of a terrain can also be reported in a standardised way according to the ISO 8608 standard (International Organization for Standardization 8608, 1995). The RMS of the vertical displacement of the profile and the square root of the area under the Displacement Spectral Density should result in the same value.

The ISO 8608 standard specifies that for off-road profiles the reported spatial frequency range, measured in cycles/metre, should be from 0.05cycles/m (wavelength = 20m) to 10cycles/m (wavelength = 0.1m). The lower spatial frequency limit of 0.05cycles/m was accepted since the vehicle speed over off-road/ rough terrain was normally much less than the case for on-road terrains. The upper spatial frequency limit of 10cycles/m was consistent with the length of the tyre contact patch.

Another accepted method for comparing the roughness of different roads, is the International Roughness Index or IRI (Sayers and Karamihas, 1998). The IRI is calculated by simulating a quarter-car model, known as the Golden car, driving on the measured profile at 80 km/h. The absolute suspension travel of the quarter-car is added together and divided by the length of the input profile. The result of the absolute suspension travel divided by the length of the input profile produces the IRI value.

3. Can-Can Profilometer

The Can-Can Profilometer consists of a light weight, right angle triangular structure with a wheel on each corner of the structure (see Figure 1). The two rear wheels are mounted 4.5 meters apart and the front wheel is used to steer the structure. The rear wheel track width of 4.5 meters facilitates the profilometer in utilizing the smooth and level zero reference surfaces on either side of the profiled terrain on the Gerotek suspension track. A 12 Volt wiper motor is mounted on the frame of the wheel and a chain is used to drive the wheel. A speed control was used to vary the profiling speed of the profilometer. The speed of the profilometer is kept low to eliminate any dynamic effects of the profilometer.

A tilt sensor is mounted on the rear beam and provides the orientation of the rear beam in both pitch and roll directions. The rear beam is designed for a maximum deflection of 3mm at the centre of the beam with all the required equipment mounted on the beam.

Figure 1: The Can-Can Profilometer.

Thirty lightweight aluminium measuring arms are mounted 100mm apart on the rear beam of the structure and follow the profile of the terrain. The one end of each measuring arm pivots on a high precision single turn potentiometer on the rear beam and the other end is in contact with the terrain. The thirty arms allow the Can-Can Profilometer to profile a 3 meter wide section of the terrain. Each arm has a 30mm nylon wheel at the end which is in contact with the terrain. Nylon wheels are utilized since the nylon wheels were found to have a lower tendency to bounce on the terrain than rubber wheels.

The displacement at the tip of the arm is calculated by measuring the angle at the pivot point. The angles are measured with the use of the high precision single turn potentiometers. The output from the potentiometers is recorded with a data acquisitioning system after which the data is processed to produce the profile of the terrain. A data point is recorded at every 10.18mm travelled in the longitudinal direction for every arm.

4. Simple Obstacles

To verify correct operation and accuracy, the Can-Can Profilometer is tested on simple obstacles. The profilometer was used to profile a 55mm flat-top bump on a flat surface. The actual profile of the bump and the profile obtained from the Can-Can Profilometer are compared in Figure 2.

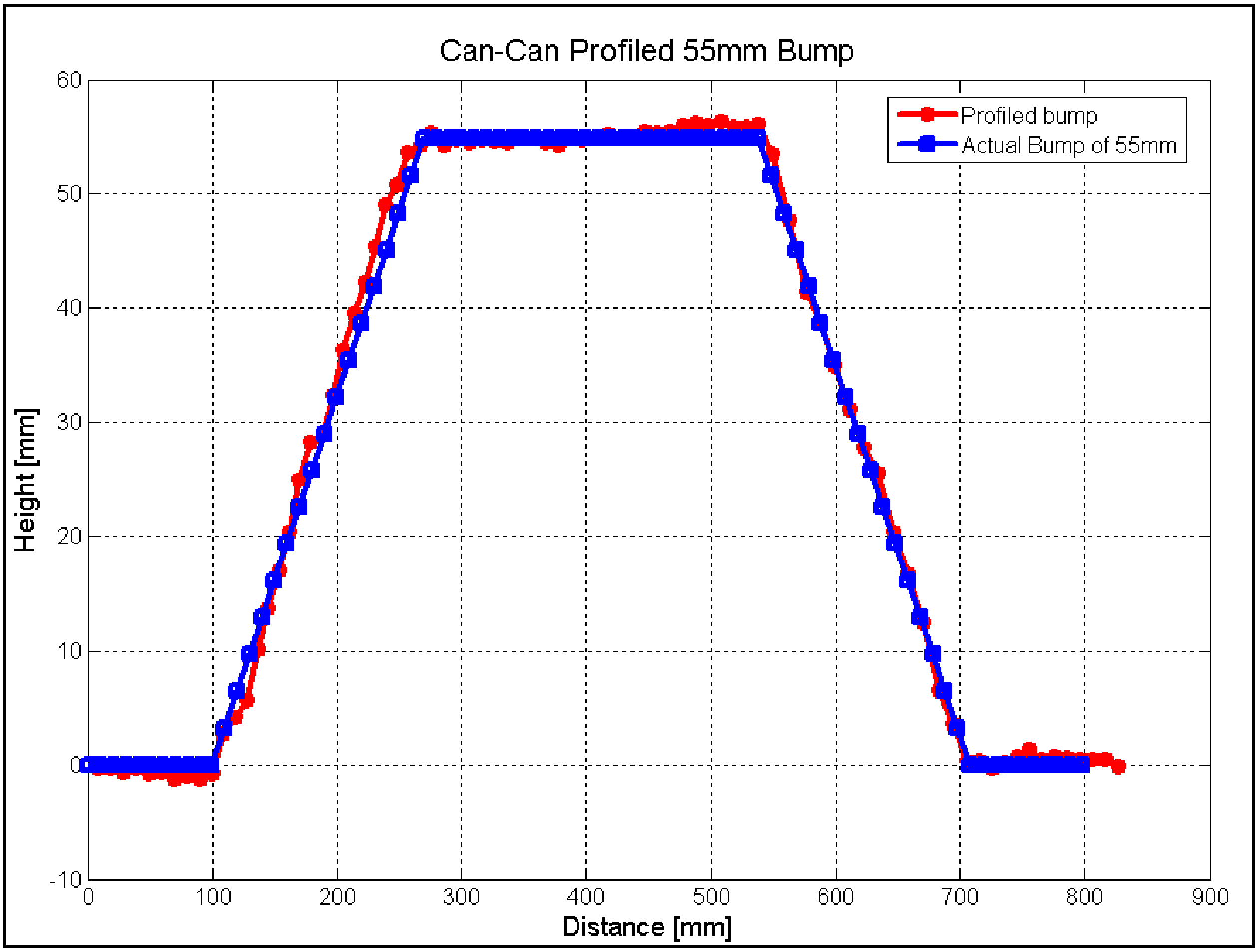

Figure 2: 55mm flat-top bump profiled with Can-Can Profilometer.

The Root Mean Square (RMS) value of the profile is 36.2mm and the RMS value of the actual bump is 37.7mm. The Root Mean Square Error (RMSE) represents the difference between the actual profile of the bump and the Can-Can profiled bump. The RMSE is calculated using the following formula:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(y_{i-actual} - y_{i-Can-Can}\right)^2}{n-1}} \quad \textbf{(1)}$$

Where:

y is the error in the vertical direction of the profile
n is the number of points in the profile.

The RMSE in the vertical direction is calculated at 2.7mm. The difference in the profiles at the top of the bump is due to the small wheels at the end of the arms, which have a diameter of 30mm. This error may be decreased with the use of even smaller wheels at the tips of the arms which is used to follow the profile of the terrain. Smaller wheels are not utilized simply because even if smaller wheels are used more noise will be present in the profile. The wheels on the arms of the profilometer are much smaller than the actual vehicle's wheels by a factor of 25 and the high frequencies measured by the smaller wheels will not have an effect on the response of the vehicle in the simulations. The corners at the top of the actual bump have a small radius and can be seen if the actual bump is plotted with a finer resolution.

The second test conducted on the Can-Can Profilometer assesses the profile of test bumps profiled with the wheels of the profilometer also moving slowly over obstacles. Figure 3 shows the actual test section which the Can-Can Profilometer profiled from left to right. The test section layout is as follows, the profilometer profiles a flat section with the left wheel of the profilometer moving over a 105mm flat-top bump, and then a 55mm flat-top bump is profiled without the profilometer moving over any obstacle. After the 55mm bump is profiled the profilometer's left wheel moves over a 105mm flat-top bump whilst profiling a 55mm flat-top bump. Figure 4 shows the measured profile of the test section. The top figure indicates the profile corrected using the tilt sensor data while the bottom figure indicates the uncorrected profile. Excellent results are achieved with the Can-Can Profilometer moving slowly over the obstacles in this test. The Can-Can Profilometer can profile a terrain up to 5km/h on a smooth terrain. The profiling speed of the profilometer is lowered with the increase of the roughness of the terrain to keep the dynamic movement and vibrations of the profilometer to a minimum.

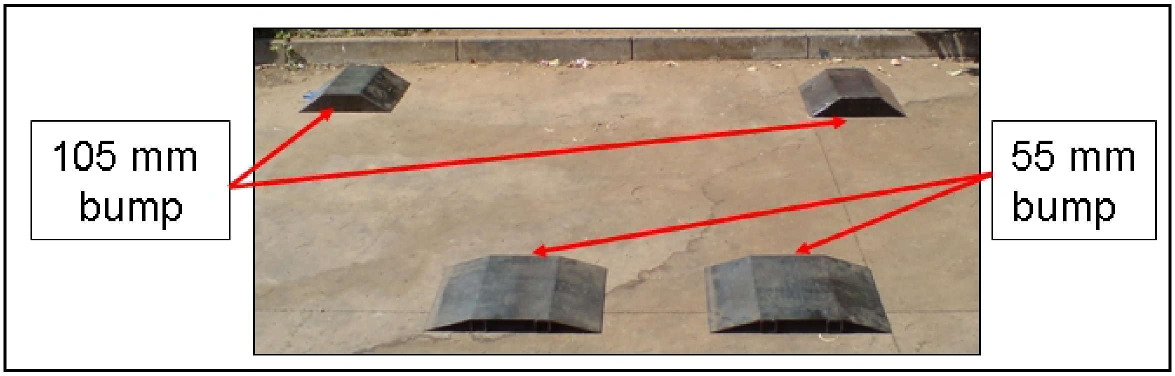

Figure 3: Final test section for Can-Can Profilometer.

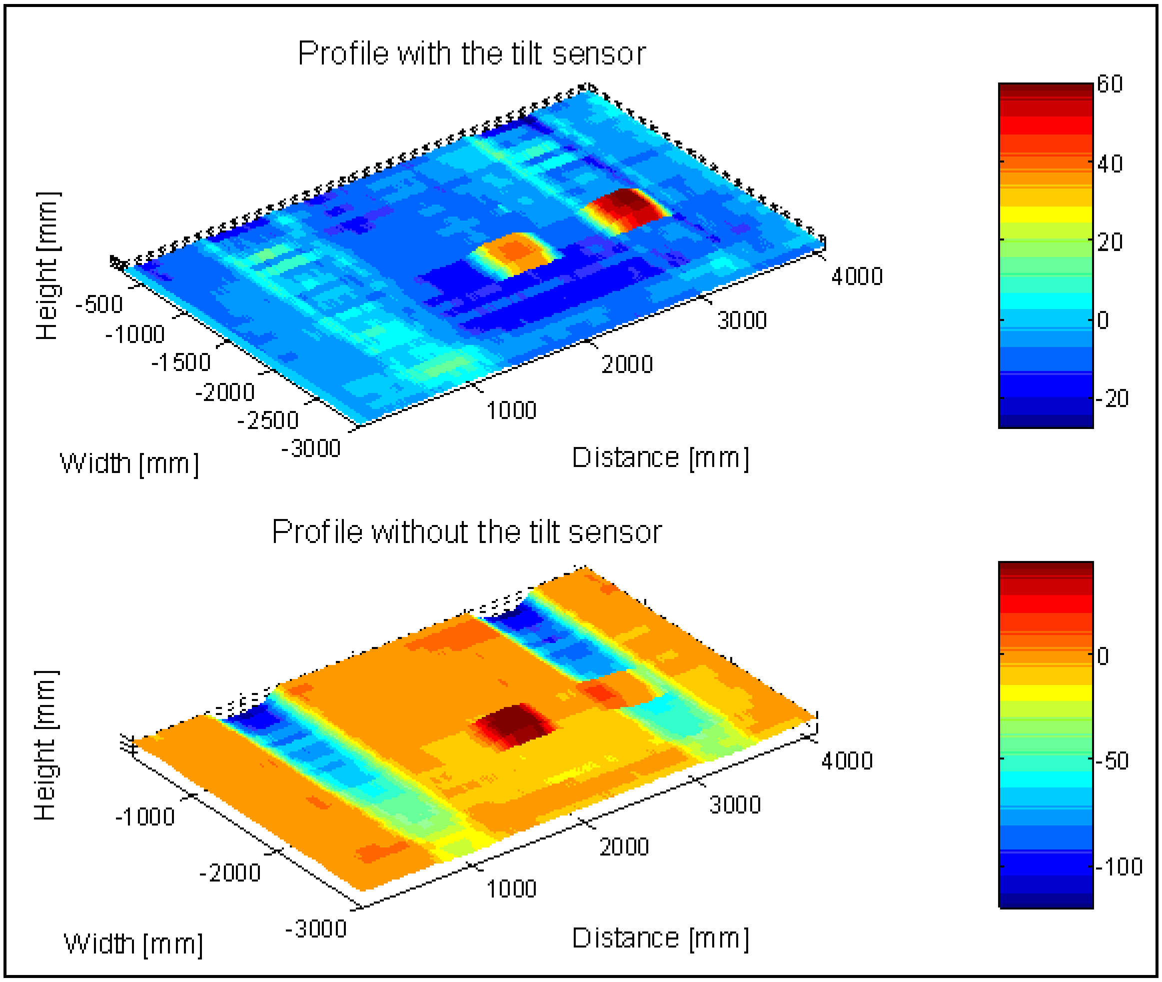

Figure 4: Profile of final test section for Can-Can Profilometer.

Figure 5 shows the profile obtained from arm 1. This arm profiled the two 105mm flat-top bumps just after the left wheel of the profilometer moved over them. Three lines are indicated in Figure 5 namely the raw profile of the arm, the roll angle measured by the tilt sensor and the profile obtained by correcting the raw measurement with the tilt sensor data. It is clear that the slow profiling speed produces an accurate profile of the profiled terrain due to the fact that the tilt sensor data resembles the flat-top bump. No dynamic effects from the movement of the profilometer were detected in the tilt sensor data. The error in the profiled terrain is less than 10%. The tilt sensor measurement was not perfect however improved results may be obtained with the use of higher quality sensor. The results thus obtained with the current sensor were acceptable and proved the functionality of the concept.

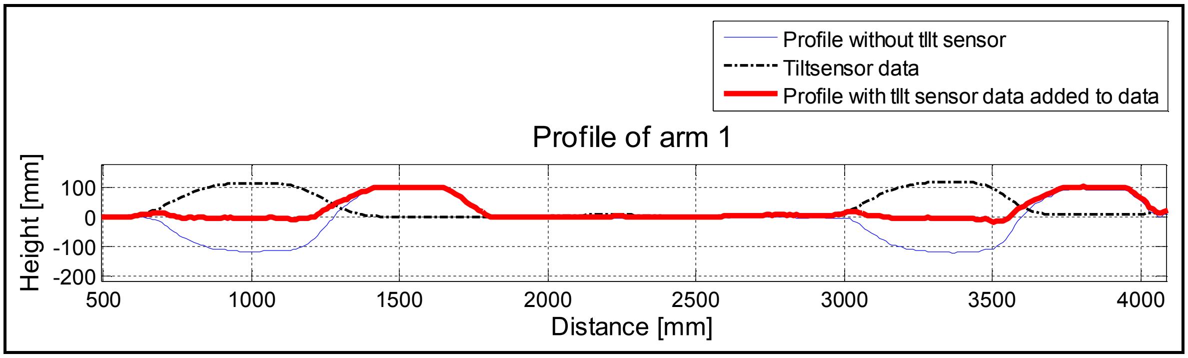

Figure 5: Profiles from arm 1 for final test section with Can-Can Profilometer.

The results obtained from the second test indicate that the Can-Can Profilometer is an accurate rough road profilometer. If very rough terrain is profiled the most accurate profile will be obtained by profiling the terrain as slowly as possible. The overall accuracy of the Can-Can Profilometer was found to be in the order of 5mm (or less than 10% compared to the exact profile) when the profilometer moved over large obstacles.

5. Measured Road Profiles

The profiles of different terrains, profiled mainly with the use of the Can-Can Profilometer, are presented in the following paragraphs. Four additional 100m terrains in the form of the Fatigue track, Angled corrugations, Parallel corrugations and Pothole tracks were also profiled at the Gerotek Test Facilities with the use of the Can-Can Profilometer. These tracks are not presented in this section however their International Roughness Indexes are compared in section 7.

5.1 Belgian Paving

The Can-Can Profilometer was used to profile the full 100m section of the Belgian paving at the Gerotek Test Facilities. The profile of the terrain is available as soon as the data is downloaded from the data acquisitioning system and run in a pre-written Matlab program. Figure 6 shows the Can-Can Profilometer in the process of profiling the Belgian paving. A section of the measured profile is shown in Figure 7. This is an excellent graphical representation of the Belgian paving with a grid size of 100X10mm. The height difference between the lowest and highest points indicated in Figure 7 is around 180mm.

Figure 6: Can-Can Profilometer profiling the Gerotek Belgian paving.

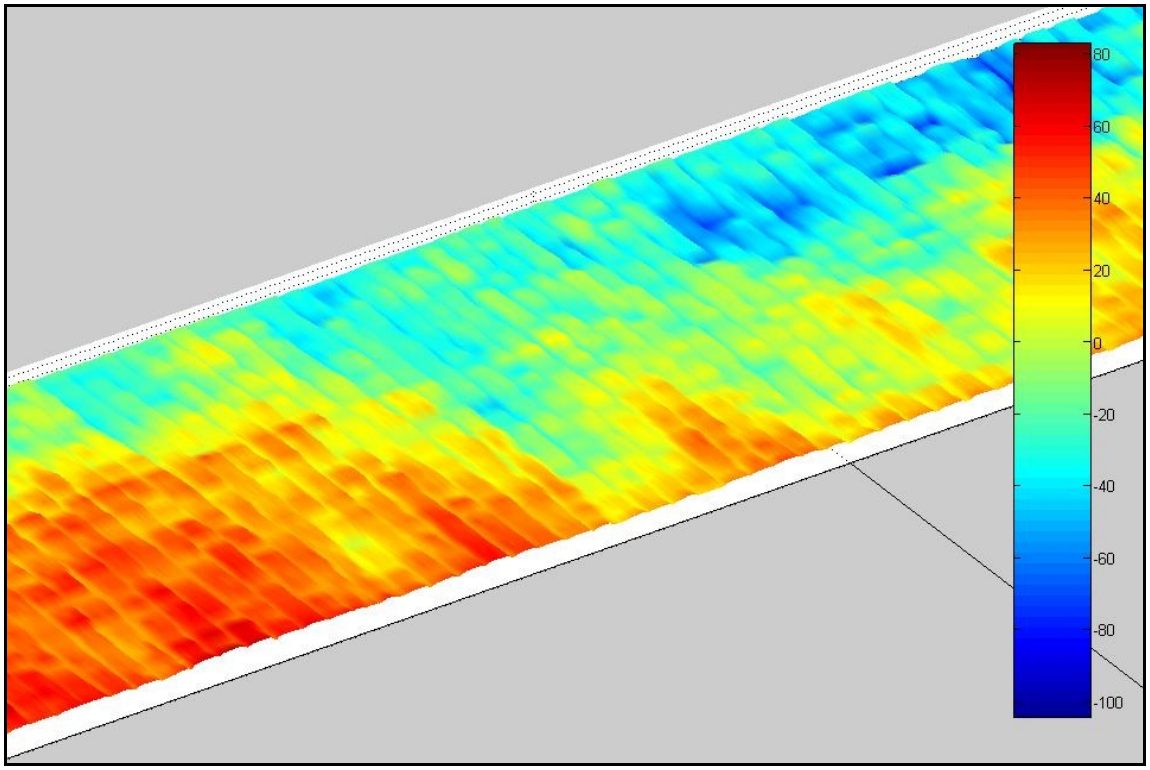

Figure 7: Can-Can profile of Gerotek Belgian paving.

The Can-Can Profilometer profiled the Belgian paving at a speed of 0.98km/h. The full 100m section of the Belgian paving, with smooth sections before and after the Belgian paving, was profiled in 8 minutes and the data reduction only required a few minutes.

Two additional profiling methods were also investigated and used to profile the Belgian paving at Gerotek. The first was with the use of an in-house developed Laser Scanner. The Laser Scanner profilometer utilizes a S80-MH-5 Data Sensor Laser Distance Sensor to measure the profile of the terrain from a vertical distance of 2m. The Data Sensor is mounted in a purposely built gimball which is mounted on a tripod and moved with the use of stepper motors. Figure 8 shows the set-up and operation of the Laser Scanner profiling the Gerotek Belgian paving at night.

Figure 8: Laser scanner in operation on the Gerotek Belgian paving at night.

The Laser Scanner was used to profile 40m of the Gerotek Belgian paving. A section of the measured profile is shown in Figure 9. This is a good graphical representation of the Belgian paving with a grid size of 60X60mm. The height difference between the lowest and highest point as indicated in Figure 9 is around 180mm.

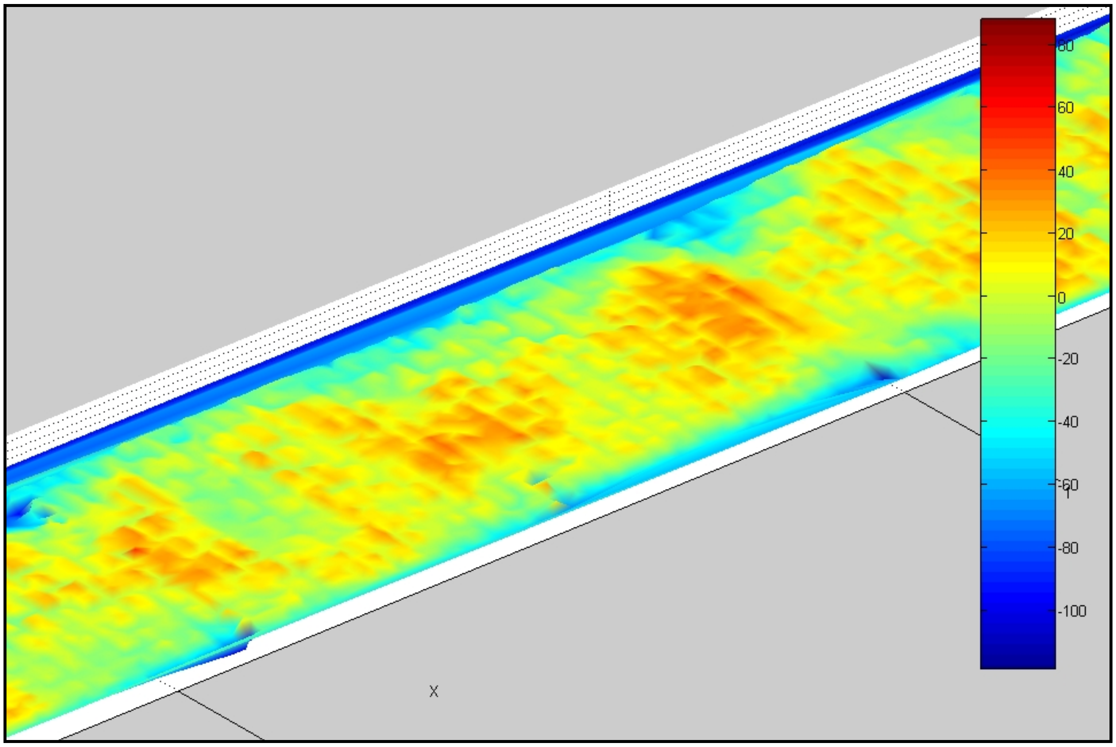

Figure 9: Laser Scanner profile of Gerotek Belgian paving.

The Laser Scanner is a time consuming profilometer when compared to the Can-Can Profilometer, however it remains a prospective profilometer still in the development phase. The Laser Distance Sensor has an accuracy of 5mm but the accuracy of the total system is limited by the gimball as well as the laser which can be improved by using a higher quality laser. The Laser Scanner profiles with an average longitudinal and lateral resolution of 60mm (limited by the step size of the stepper motors) and with a total profile width of 2.4m at a profiling speed of 8m/hour.

The second additional profiling method investigated was profiling with the use of photogrammetric measurements. A Pentax K10D Digital camera with an 18-55mm lens was used to photograph the Gerotek Belgian paving from above with each sequential photograph overlapping by 60%. The photographs of the Belgian paving were taken with the use of a purposely build tripod with 6m long legs as shown in Figure 10. The tripod elevated the digital camera to a height of 4m. With the camera positioned at 4m above the ground it was possible to capture the entire 4m width of the Belgian paving. A 50m section of the Belgian paving was profiled with the use of photogrammetry.

Figure 10: Tripod used to capture photographs of the Gerotek Belgian paving.

Figure 11 is a good graphical representation of the Gerotek Belgian paving as profiled with Photogrammetry. This profiling method has a 3mm accuracy but requires a great deal of time to produce the profile when compared with the Can-Can Profilometer.

Profiling a 50m section of the Belgian paving with the use of the Photogrammetric method required 15min/m to survey the control points and to capture the photographs. The mapping and processing of the photographs required in the order of 8hours/m^2. This required time scale to profile 1m^2 of terrain made the photogrammetric profiling method unfeasible to profile large sections of a terrain.

More terrain detail is apparent in Figure 11 if compared with the profile obtained with the Can-Can Profilometer in Figure 7. The height difference between the lowest and highest points as indicated in Figure 11 is also around 180mm.

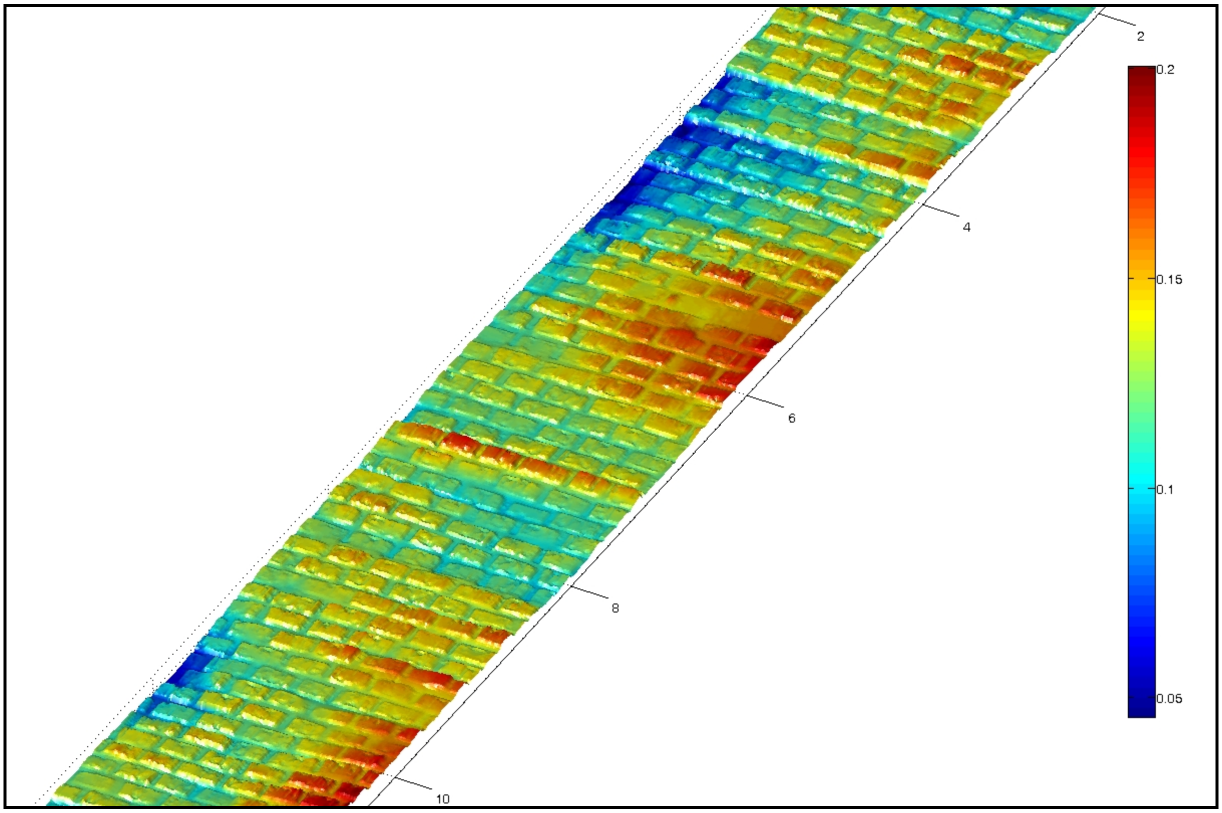

Figure 11: Gerotek Belgian paving profile from Photogrammetry.

The two additional profiling methods produced valid profiles of the Gerotek Belgian paving and compared well with the Can-Can Profilometer, however the Can-Can Profilometer remained the most efficient profiler. The additional profiling methods provided profiles of the same terrain with lower and higher resolutions where all three profiles of the Gerotek Belgian paving produced roughness coefficients of the same order of magnitude.

The Daimler-Benz/Mercedes Stuttgart-Unterturkheim test track has a Belgian paving section that was profiled by Daimler AG with the use of time consuming photogrammetric measurements as shown in Figure 12. This data is freely available from OpenCRG®. The profile of the Stuttgart-Unterturkheim Belgian paving indicates that an out of phase low frequency sinusoidal wave is incorporated into the Belgian paving as shown in Figure 13. The difference between the highest and lowest points on the track is around 140mm, compared to the 180mm on the Gerotek Belgian paving (without any low frequency sinusoidal wave).

The Displacement Spectral Density of the Can-Can profile of the Gerotek Belgian paving and the OpenCRG profile of the Unterturkheim Belgian paving are calculated, compared and examined in section 6.

Figure 12: Photogrammetric measurements of Belgian paving in Stuttgart (OpenCRG®, 2010).

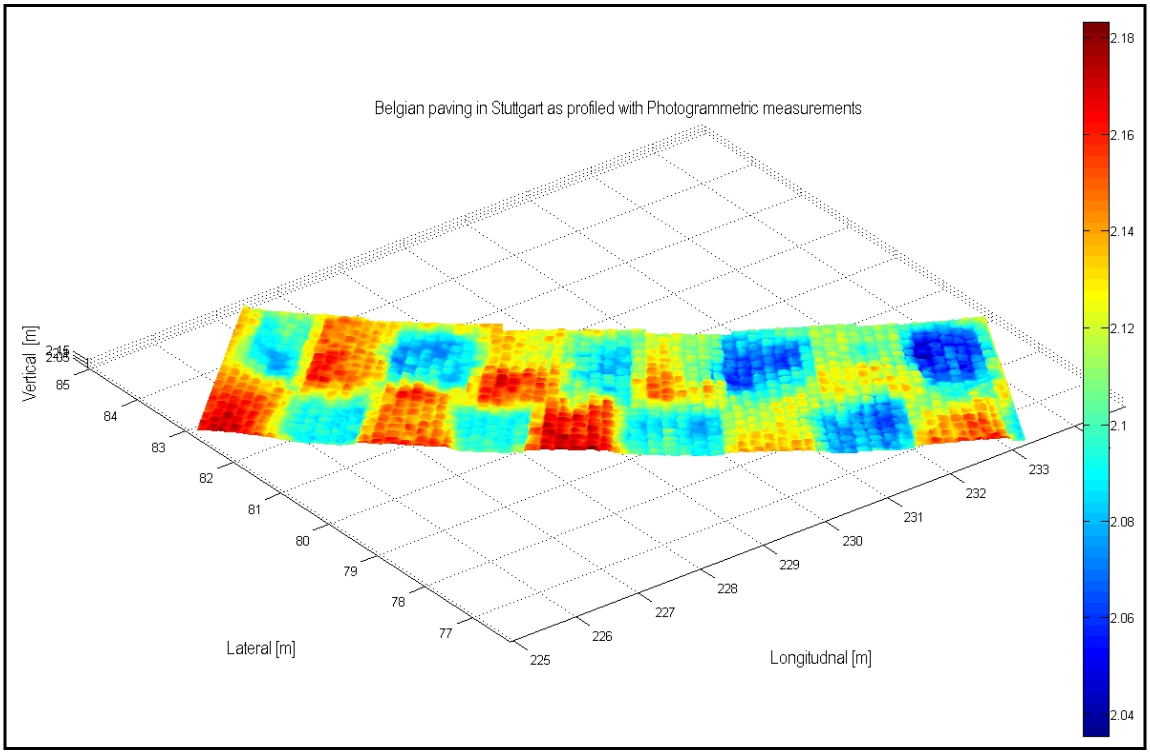

Figure 13: Photogrammetric profile of Belgian paving in Stuttgart.

5.2 Ride and Handling Track

The Ride and Handling track at Gerotek is 4.2km in length and is used for testing the ride comfort, driveline endurance and handling characteristics of a vehicle. The track consists of up and down hills, constant radius and decreasing radius turns, positive camber and negative camber corners and low speed as well as high speed corners. In addition the track also includes sections for low mobility vehicles and high mobility vehicles. For the purpose of this study only the low mobility vehicle sections were profiled with the use of the Can-Can Profilometer. Figure 14 shows an aerial photograph of the Ride and Handling track. The surface of the Ride and Handling track is transversely tined concrete.

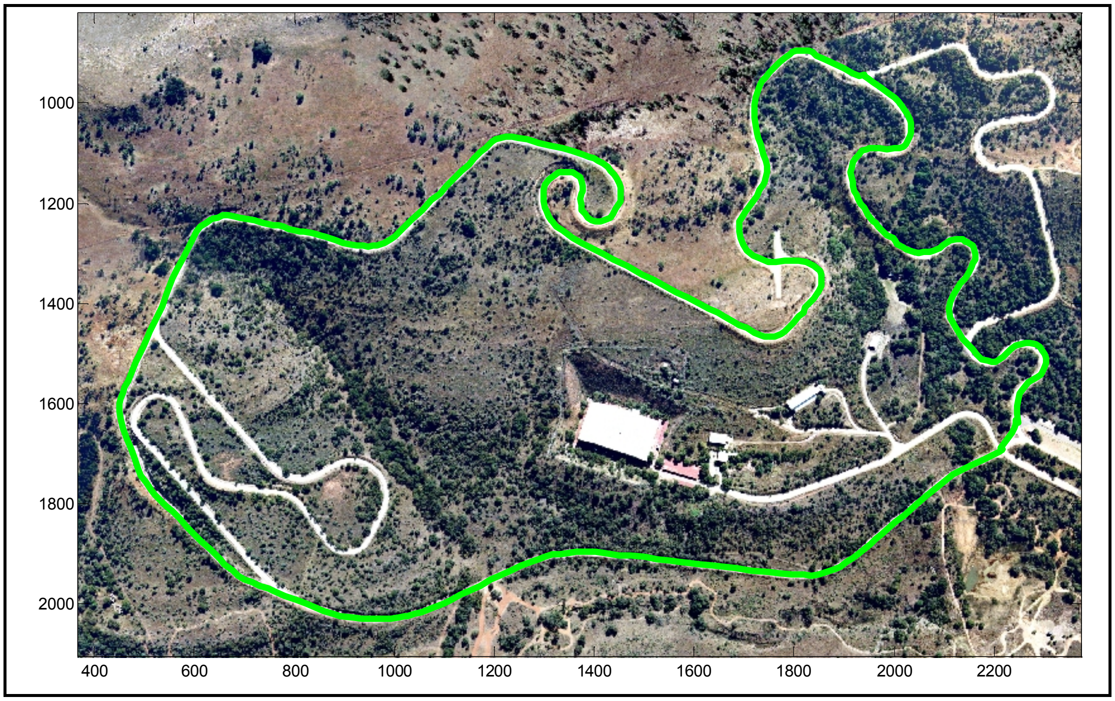

Figure 14: The profiled section of the Ride and Handling track at Gerotek.

The Ride and Handling track was profiled with the Can-Can Profilometer by marking control points on the concrete terrain with a spray can at 10m intervals. The spray can was triggered with a trigger mechanism which was built in-house.

The control points were surveyed with a Differential Global Positioning System (DGPS) and were used in placing the profile recorded by the Can-Can Profilometer in a global coordinate system. A spline was fitted through the surveyed control points and the Rodrigues' rotation formula (Rodrigues' rotation formula, 2008) was applied in orientating the profile of the track with the spline. This gave the global position and orientation of the Can-Can Profilometer frame on which the profile measured by the arms could be superimposed on. An exceptional 3-D profile of the Ride and Handling track was generated with this method. The Can-Can profiled Ride and Handling track is shown in Figure 15 and Figure 16.

The result of the profiled Ride and Handling track was representative of the actual Ride and Handling track and proved that the Can-Can Profilometer was capable of profiling a 4.2km mountain pass section within 8 hours.

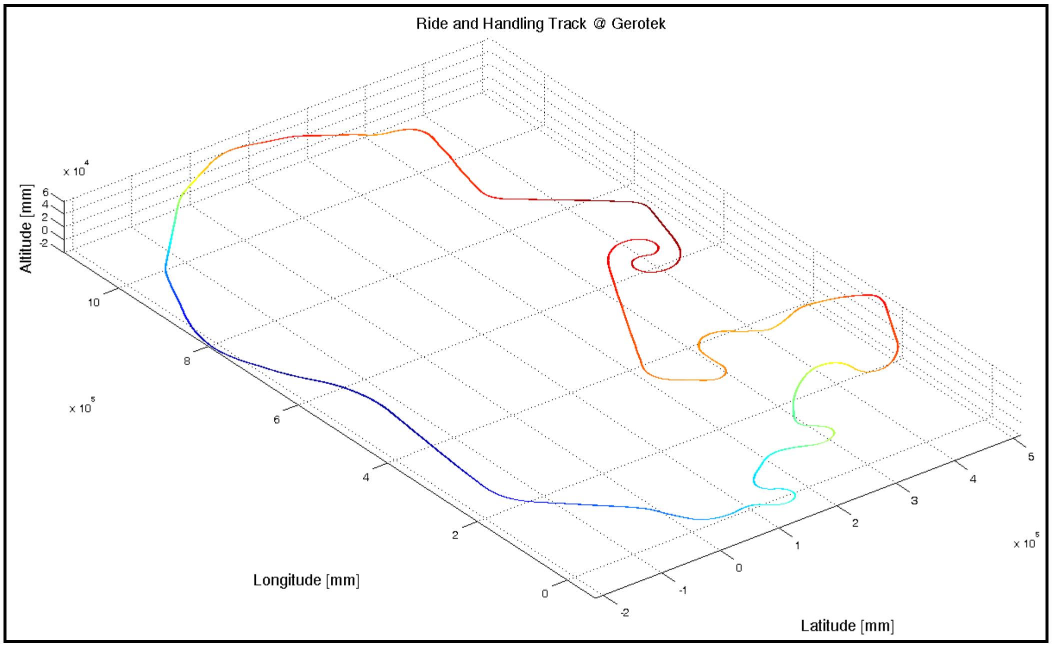

Figure 15: Ride and Handling track profiled with the Can-Can Profilometer (full 4.2km).

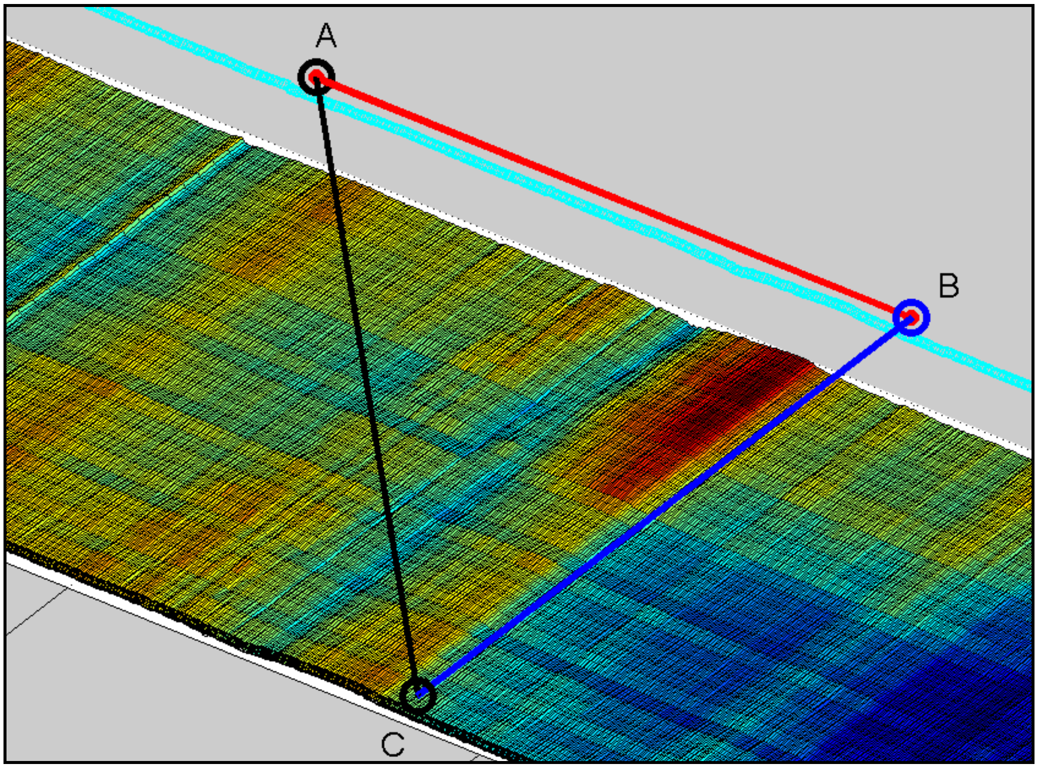

Figure 16: Close-up of the Ride and Handling track profile.

The Displacement Spectral Density of the Ride and Handling track is calculated, compared and examined in section 6.

5.3 Rough Track

The Rough track at Gerotek is used for evaluating the rough terrain mobility and structural endurance of all-terrain vehicles. The track tests vehicle durability under accelerated conditions, including: chassis, body, suspension, steering, axles, differential locks, mountings, etc. Relative movement between body and cabin, chassis and wheels are also evaluated together with ride comfort and interior noise levels. The layout and surface varies with hills, ditches, chassis twisters, bumps and rocks all embedded in concrete to maintain a permanent profile. The concrete surface is fairly coarse to provide sufficient traction. The track is extremely rough and only vehicles with large ground clearance will achieve vehicle speeds above 20km/h.

For the purpose of this study an 800m section of the track was profiled. This is a section of the track most frequently used for ride comfort assessment on extreme terrains. The profiled section is shown in Figure 17.

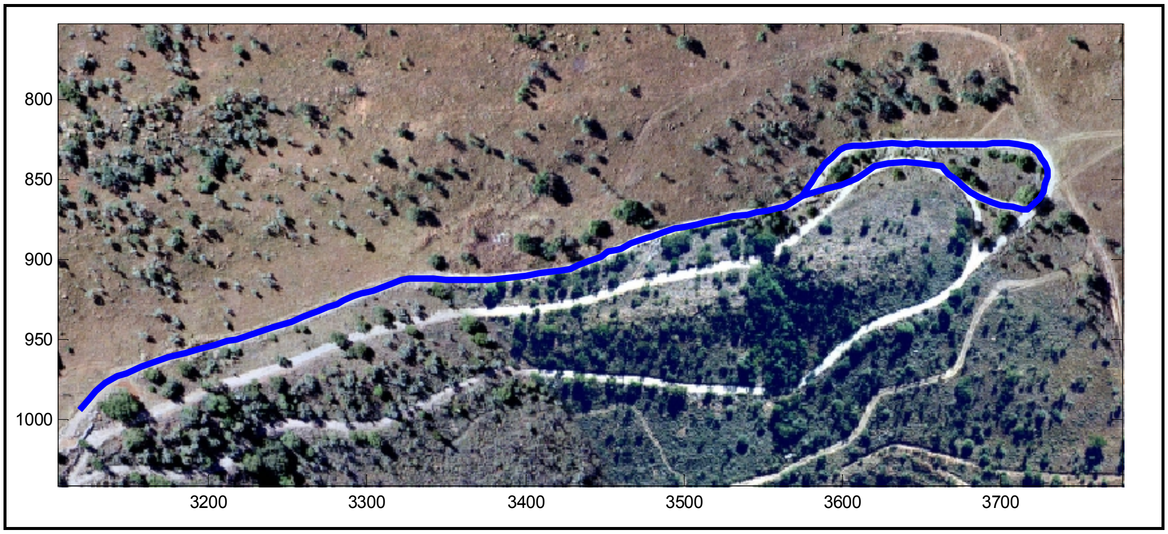

Figure 17: Profiled section of Rough track.

To reduce the vertical movement and input to the structure of the Can-Can Profilometer, a 9m long mobile track was manufactured from lip channel. One side of the Can-Can Profilometer runs on a mobile track when profiling the Rough track at Gerotek. The side of the Can-Can Profilometer running on the mobile track was the driver wheel and the front wheel used for steering. Guides were made that guided the wheels on the beam and prevented them from falling off the beams. The mobile track supplied the Can-Can Profilometer with a straight line reference between surveyed points which simplified processing the profile of the Rough track. This 9m long mobile track consisted of two

4.5m lip channel beams, each placed on three scissor jacks. The scissor jacks were used to stabilize the beams and adjust the height in order to maintain the reference for the rear beam of the Can-Can Profilometer. This simplified the movement of the Can-Can Profilometer over the very rough terrain due to the fact that only one wheel of the profilometer was in direct contact with the terrain.

The beams were placed end-on-end with one another on the edge of the Rough track (to follow the course of the Rough track) and the Can-Can Profilometer started on one beam and moved along the beam onto the following beam, after which the rear beam was placed in front of the front beam on which the Can-Can Profilometer was moving. This procedure was followed for the length of the profiled terrain. Figure 18 shows a section of the Rough track and Figure 19 shows the Can-Can Profilometer crossing from one beam to another.

Figure 18: A section of the Rough track at Gerotek.

Figure 19: Can-Can Profilometer crossing from one beam to another.

The front point of each beam had a reflective target that was surveyed with a Total Station at each placement of the beam as the Can-Can Profilometer was moving over the beams. The reflective targets on each beam also triggered a retro reflective optical sensor that recorded the position of each surveyed point in the data file. The optical sensor was mounted next to the drive wheel which enabled it to be triggered by the reflective targets on the beams.

As with the profiling of the Ride and Handling track, the surveyed points were used in generating a spline which was placed in a global coordinate system. Rodrigues' rotation formula (Rodrigues' rotation formula, 2008) was applied in orientating the profile of the track with the spline. The spline was linearly interpolated between the surveyed points with the correct amount of data points as required between each trigger. Figure 20 shows the full Can-Can profiled Rough track and Figure 21 is a close up of a section of the Rough track.

The result of the profiled Rough track was visually representative of the actual Rough track. A lot of detail was captured in the profile and the profile proved that the Can-Can Profilometer was capable of profiling an 800m section of very rough terrain in a relatively short period of time.

The Displacement Spectral Density of the Rough track is calculated, compared and examined in section 6.

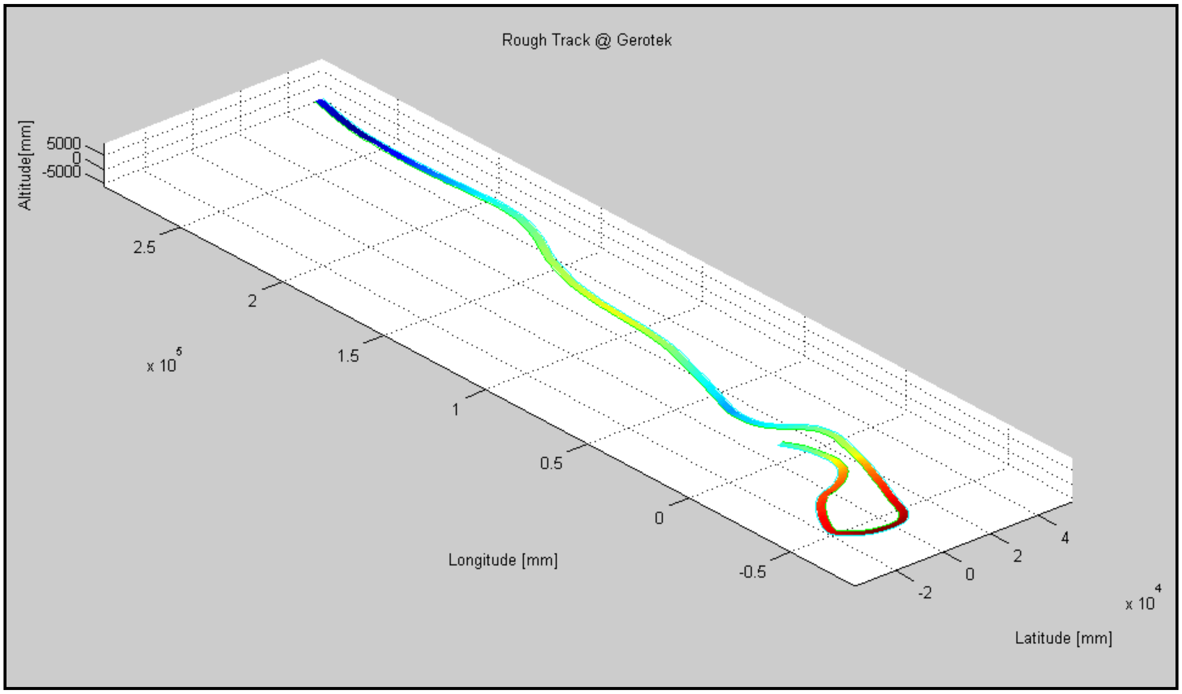

Figure 20: Profile of the Rough Track at Gerotek.

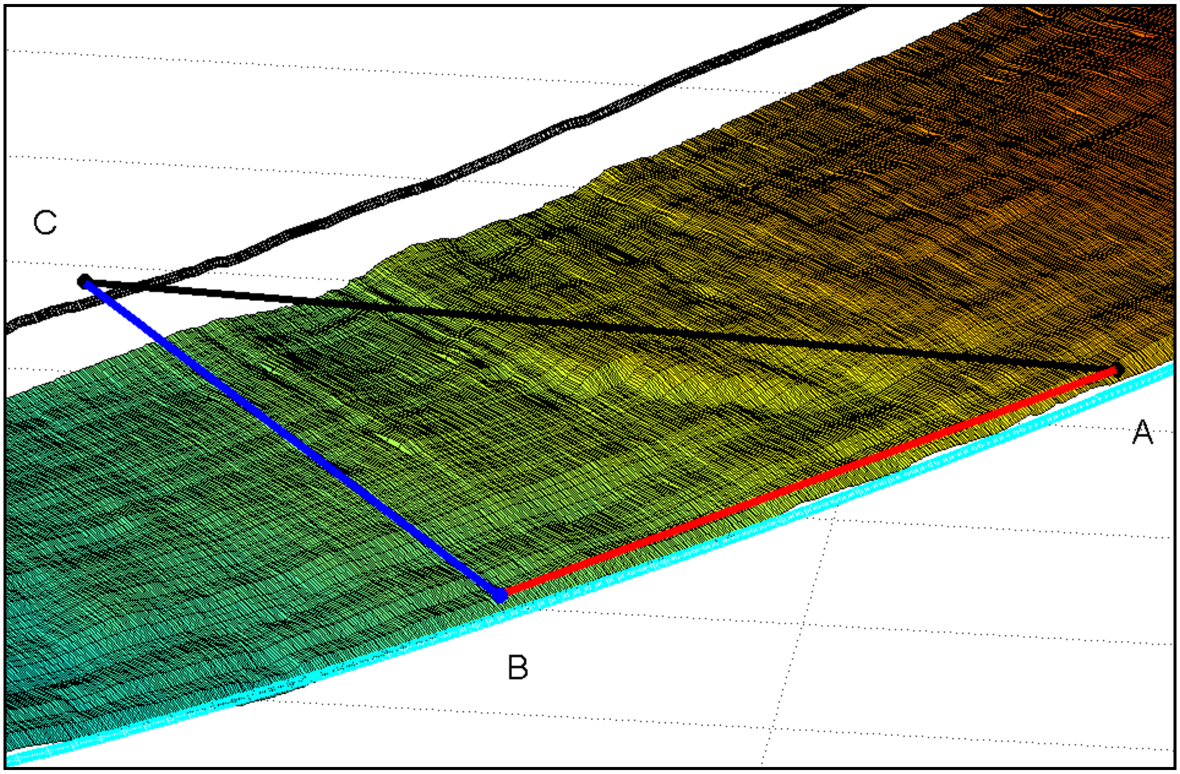

Figure 21: Close-up of the Rough track profile.

6. Displacement Spectral Densities

The Displacement Spectral Density $S_{xx}(\delta)$ of the road was calculated by dividing the squared Fast Fourier Transform X_δ of the road profile $x(d)$ by double the step in frequency ΔF as shown in equation 2:

$$S_{xx}(F) = \frac{\left|X_\delta(F)\right|^2}{2\Delta F} \qquad \textbf{(2)}$$

The squared Fast Fourier Transform is equivalent to the Fast Fourier Transform of the road profile X_δ multiplied with the complex conjugate of X_δ (Zaayman, 1988) as shown in equation 3:

$$\left|X_\delta(F)\right|^2 = X_\delta X_\delta^* \qquad \textbf{(3)}$$

The Displacement Spectral Density (DSD) of the Gerotek Belgian paving profiled with the Can-Can Profilometer was calculated for each arm of the profilometer after which the average of all 30 arms together was determined. The DSD of the Unterturkheim Belgian paving, profiled by Daimler AG, with photogrammetric measurements was calculated for each of the longitudinal lines in the profile after which the average of all the lines was determined. Figure 22 shows the DSD of the Can-Can profiled Gerotek Belgian paving, Photogrammetric profiled Unterturkheim Belgian paving as well as the DSD of a class-A (very smooth runway), class-D (unpaved road) and class-H road (very rough road), as prescribed in ISO 8608 (International Organization for Standardization 8608, 1995).

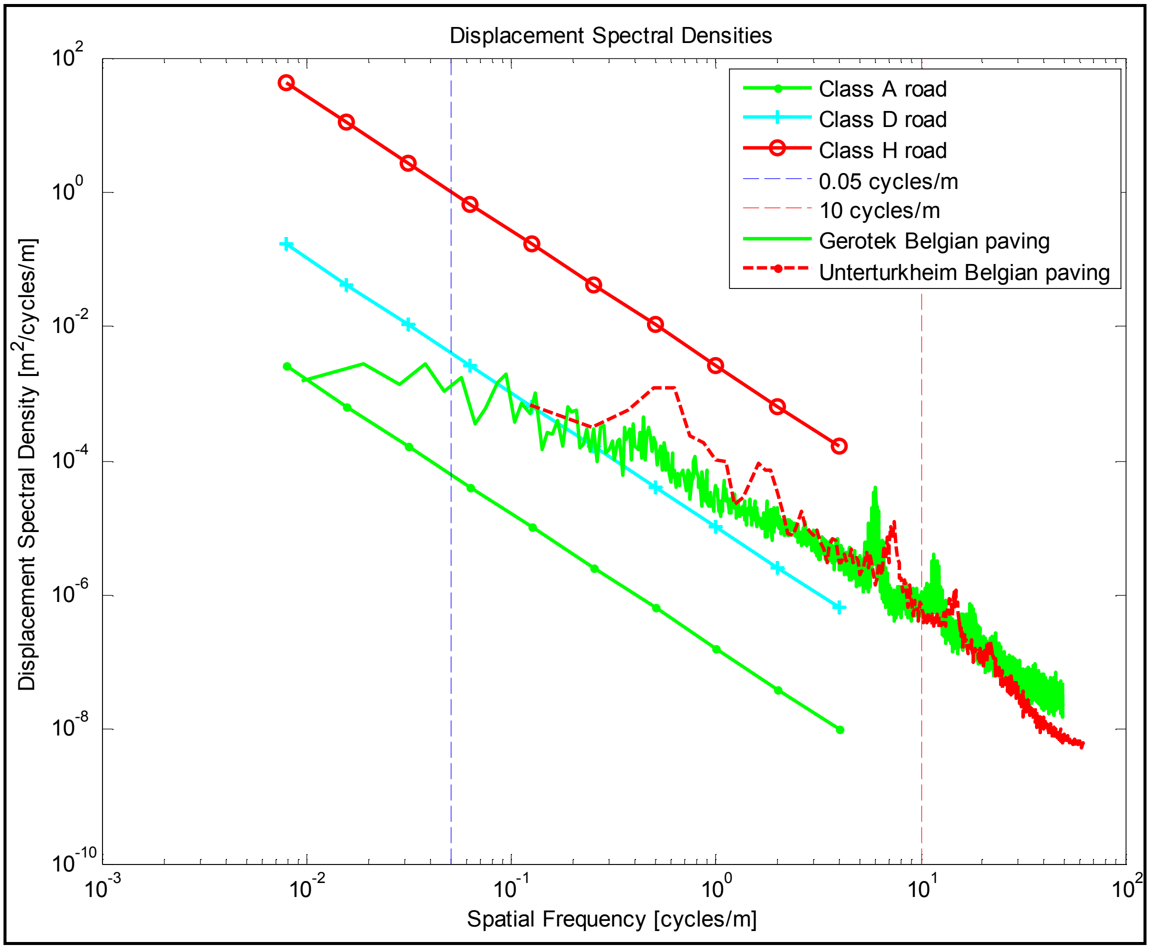

Figure 22: Displacement Spectral Density of the class A, D and H road with the Belgian paving profiles.

The peak at 6.07cycles/m in the Gerotek Belgian paving profiled with the Can-Can machine represents an average brick size of 164mm where the actual average brick size was close to 130mm. This difference in brick size is due to the shape of the bricks. The 90 degree direction change on the bricks was smoothed out by the small wheels at the end of the arms on the Can-Can Profilometer and resulted in a larger brick size. The correct brick size was obtained when the diameter of the small wheels was subtracted from the average brick size and resulted in a brick size of 134mm which correlates well with the Daimler AG profile of the Belgian paving at the Stuttgart-Unterturkheim test track. This is acceptable as the wheel on the actual vehicle is much larger and will not see the sharp 90 degree direction changes in the profile. The peak at 22.58cycles/m represents the average gap size of 44mm between the bricks. The upper and lower limits, 0.05 and 10cycles/m respectively, of the range of interest according to ISO 8608(1995) are also shown in Figure 22. The peaks at the lower frequency in the Daimler AG profile of the Unterturkheim Belgian paving coincide with the sinusoidal waves incorporated in the test track, as noted in Figure 13. This indicates that the roughness coefficient of the Unterturkheim Belgian is very high, which explains why Daimler AG used a photogrammetric profiler to profile the Unterturkheim Belgian paving instead of an inertial profiler.

Overall the DSD of the Gerotek Belgian paving profile and the Unterturkheim Belgian paving profile are very similar, indicating that if one profiles similar terrain with different profiling methods or profilers (which have different profiling durations), one may conclude with the same results. This also shows that the Can-Can Profilometer is a very cost effective and accurate profiler.

The peaks seen in the DSD is a clear indication that a straight line fit is not an accurate estimate for rough terrain, as the discrete frequencies at the peaks are not presented by the straight line approximation.

The DSD of the Ride and Handling track, as shown in Figure 23, indicates that the surface of the track is rather rough. The DSD of the Rough track is also shown in Figure 23 and it may be classified as a class-H road. The graph also indicates that the surface roughness of the terrain was also high. This was indicated by the amplitude of the right hand side of the graph. The roughness of the terrain surface is high to increase the available traction on the terrain. Note that the log scale makes the "noise" appear smaller.

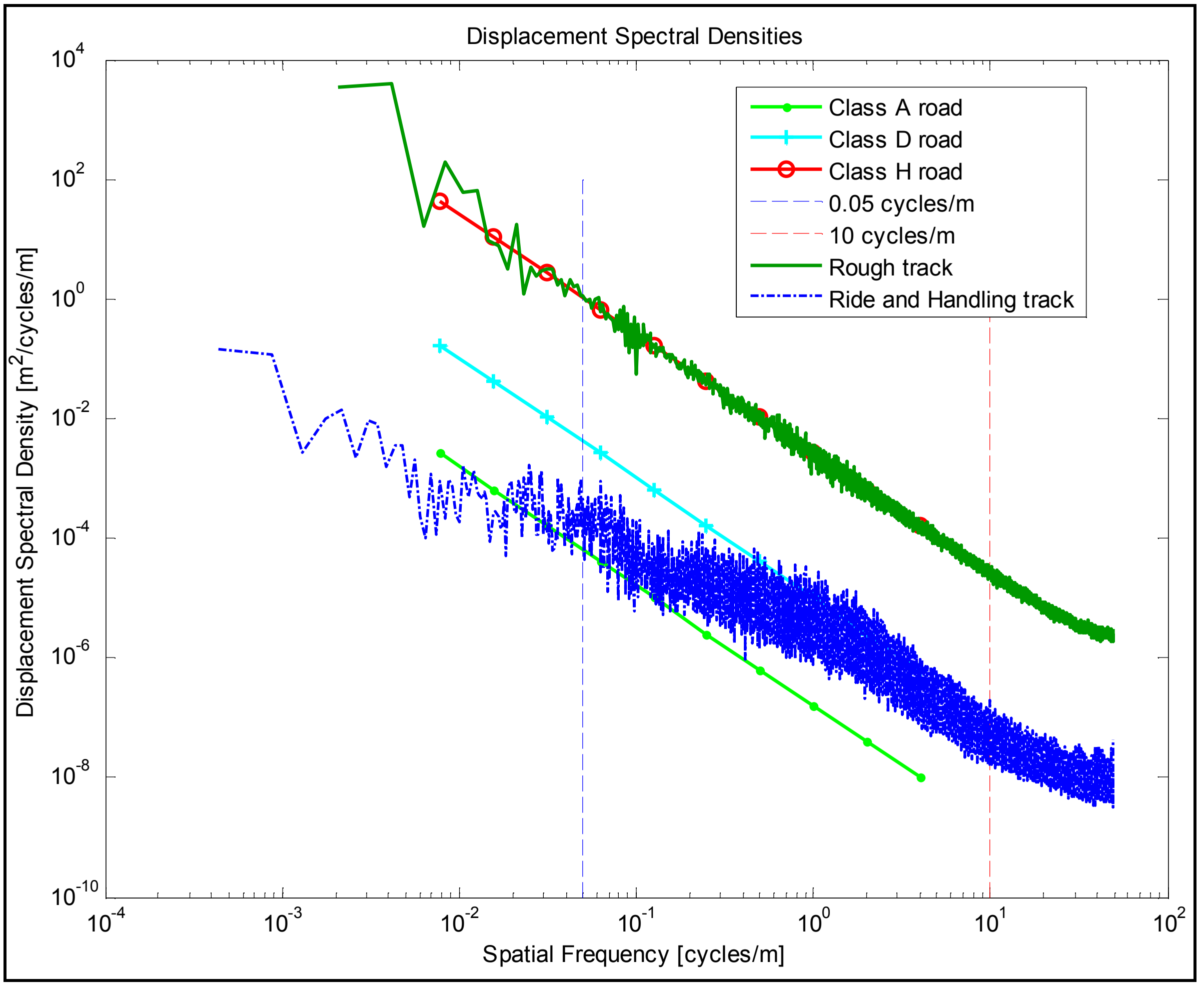

Figure 23: DSD of Ride and Handling and Rough tracks.

7. International Roughness Index

The International Roughness Index (IRI) was calculated with the use of a quarter-car model created in Simulink which represented the Golden Car Model with the spring and damper characteristics as specified by Sayers and Karamihas (1998).

The quarter-car parameters are specified, as in equation 4, as part of the IRI statistic and the simulated travel speed is specified as 80km/h. The Golden Car parameters are:

$$\frac{k_s}{m_s} = 63.3 \qquad \frac{k_t}{m_s} = 653 \qquad = \frac{c}{m_s} \quad 6 \qquad = \frac{m_u}{m_s} \quad 0.15 \tag{4}$$

where k_s is the spring rate, m_s is the sprung mass, k_t is the tyre spring rate, c is the damper rate and m_u is the unsprung mass.

A single 2-D line from each of the terrains profiled with the Can-Can machine were used as an input to the quarter-car model for all of the profiled terrains on the Gerotek Suspension Track as well as the profiled section of the Gerotek Rough Track.

The total suspension travel, as calculated from the quarter-car model, was divided by the distance travelled in order to obtain the International Roughness Index for each specific terrain. Figure 24 shows an example of the IRI vs. the distance travelled over the Belgian paving.

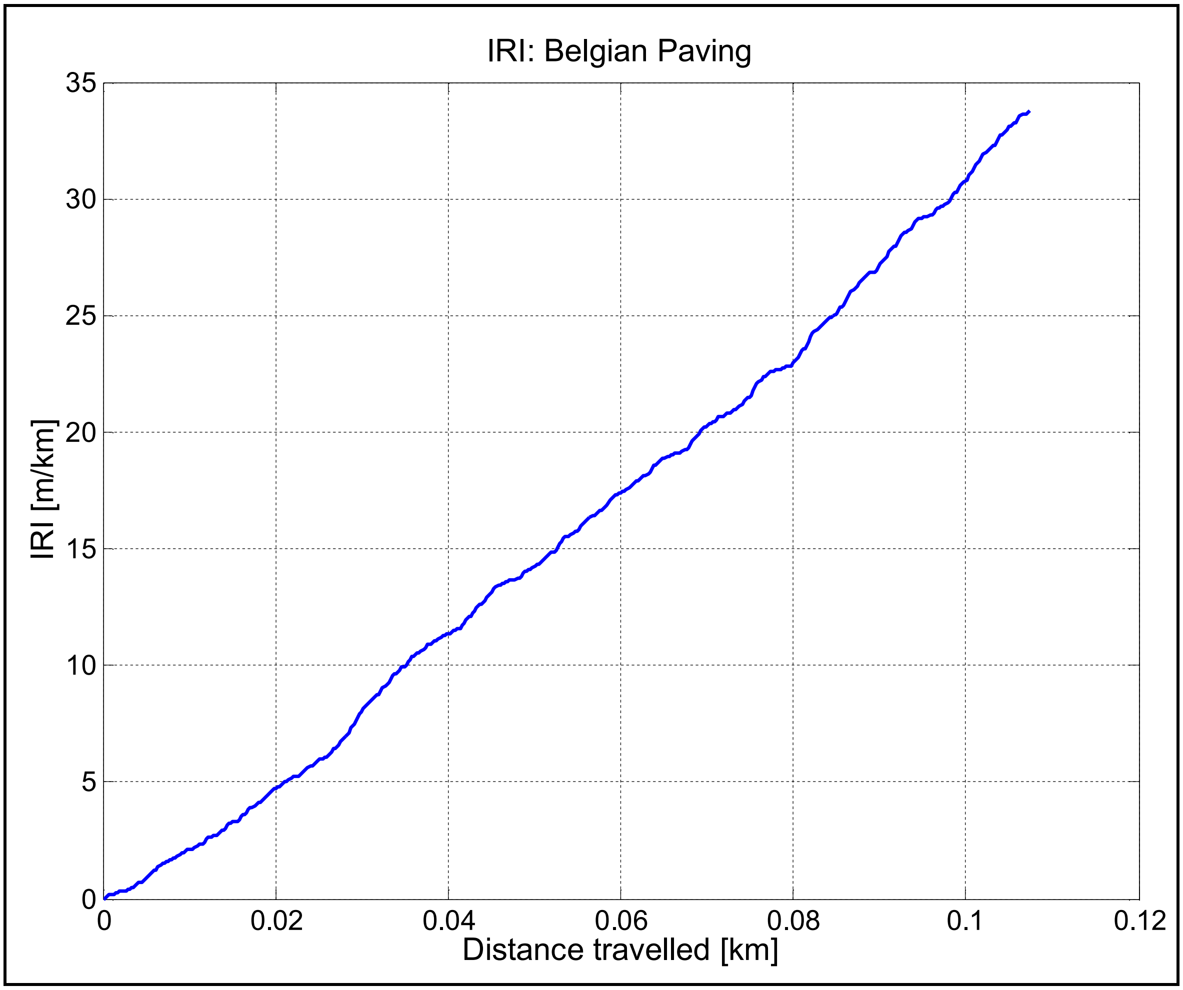

Figure 24: IRI vs. the distance travelled over the Belgian paving.

The calculated IRI for all of the profiled terrains are shown in Figure 25 together with the upper and lower limits for the different road classes. Most of the roads profiled in the current study are significantly rougher than the “rough unpaved roads” presented by Sayers and Karamihas (1998). It is also expected that the terrains of interest at the Gerotek Test Track are significantly rougher than the “rough unpaved roads” as these tracks are used for accelerated fatigue tests on vehicles. These tracks include the Belgian paving, Fatigue, Angled corrugations, Parallel corrugations, Pothole and Rough Tracks.

This is an indication that the trends supplied by the IRI are only valid for smoother terrains. These smoother terrains are typically asphalt or concrete roads. This is expected as the IRI was designed for the characterisation of asphalt and concrete roads. These asphalt and concrete roads are drastically smoother than the terrains which the present study concentrated on. The IRI uses a linear quarter-car model and is not compatible to the suspensions of most off- road vehicles. As a result it is recommended to use the profile of actual off-road terrains in simulations instead of statistically generated profiles.

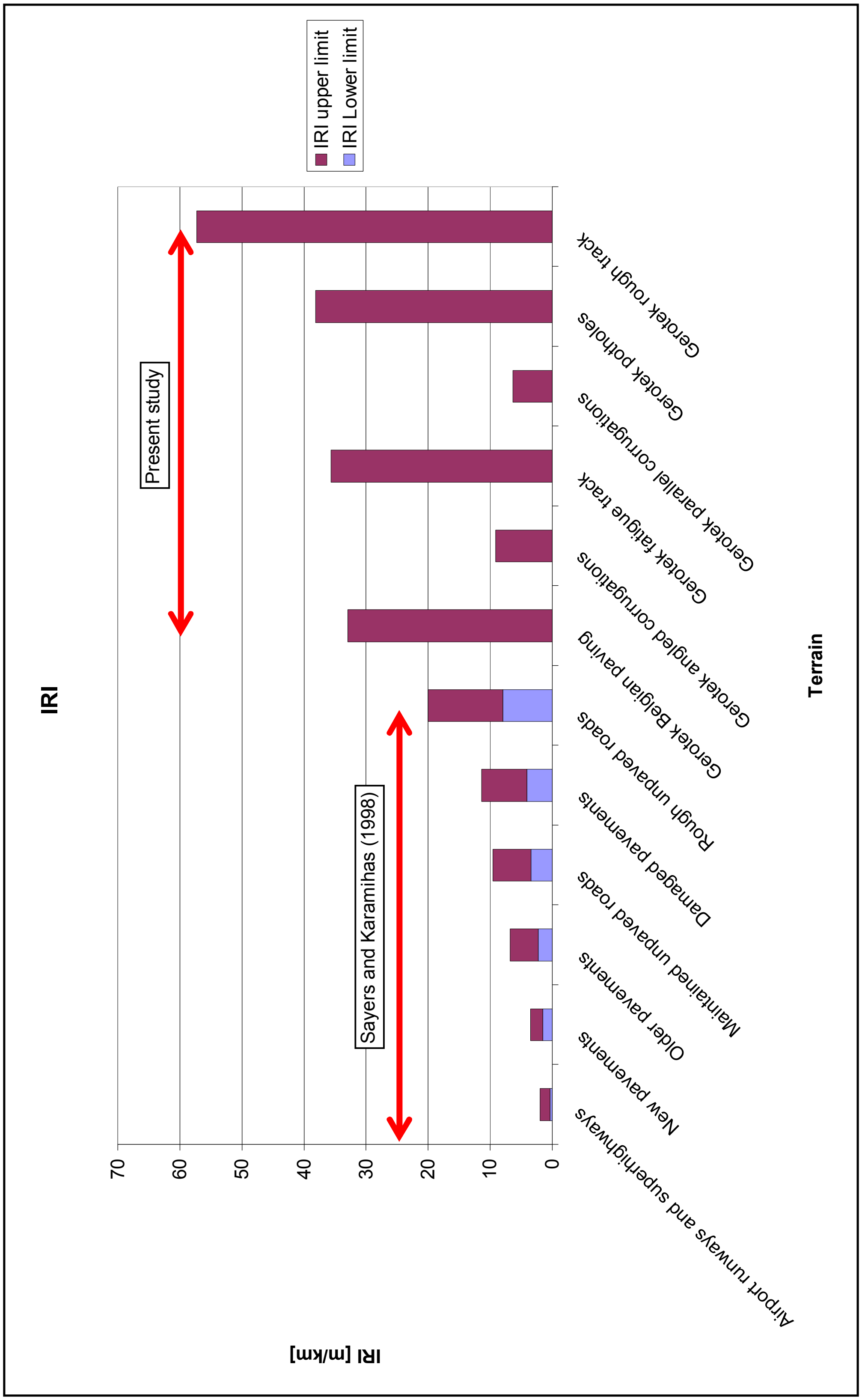

Figure 25: International Roughness Index.

8. Conclusion

Profiling rough off-road terrain is not a trivial exercise as many available profilometers cannot be used on very rough terrain.

It was found that the Can-Can Profilometer is a simple and effective profilometer with the ability to profile very rough terrain. The Can-Can Profilometer can profile a rough terrain with an accuracy of better than 5mm. The profiles obtained from the terrains were accurate and visually representative of the actual terrain. The Can-Can Profilometer produced profiles of the terrains quickly and effectively. The accuracy can be improved by using better quality, but more expensive, sensors.

The conclusion is made that the DSD of the profiled terrains were representative of the profiled terrain. The DSD of each of the profiled terrains provided information about roughness of the terrains and showed that a straight line fit approximation is not valid on some terrains as discrete frequencies at the peaks are not presented.

The IRI was calculated for each of the terrains profiled with the Can-Can Profilometer. This showed that the roughness of the terrains of interest in the current study were far higher than terrains profiled with inertial profilers and indicated that the DSD of the profiles were the superior method for characterising rough terrains. The full 3-D profile is however available for use with more advance tyre models.

It is also concluded that the Can-Can Profilometer is capable of profiling very rough terrain fast and accurately which would not be possible with a High Speed Profiler due to the severe roughness of the terrain together with the mobility and vibration limits of the vehicle and instrumentation respectively.

References

Gerotek Test Facilities, (2007), www.gerotek.co.za, Accessed 2007/02/27.

Gorsich, D.J., Chaika, M., Gunter, D., Karlsen, R., Haueisen, B., Sun, T. and Ferris, J., (2003), *Terrain Roughness Standards for Mobility and Ultra-Reliability Prediction*, SAE 2003-01-0218, pp 5-10.

Grinstead, B., Koschan, A., Page, D., Gribok, A. and Abidi, M.A., (2005), *Vehicle-borne Scanning for Detailed 3D Terrain Model Generation*, SAE(Society of Automotive Engineers) Commercial Vehicle Engineering Congress, Chicago, IL, November, 2005, SAE Technical Paper 2005-01-3557.

Imine, H., M'Sirdi, N.K. and Delanne, Y., (2003), *Adaptive Observers and Estimation of the Road Profile*, SAE 2003-01-1282, pp 175-180.

International Organization for Standardization, (1995), ISO 8608: *Mechanical vibration - Road surface profiles - Reporting of measured data*, ISO 8608:1995(E).

Kern, J.V, (2007)*, The Development of Measurement and Characterization Techniques of Road Profiles,* Master of Science in Engineering, Virginia Polytechnic Institute and State University, Danville, USA.

Kulakoski, B.T., Henry, J.J. and Wambold, J.C., (1986), *Relative Influence of Accelerometer and Displacement Transducer Signals in Road Profilometry*, Transportation Research Record, January, USA.

OpenCRG®, (2010), www.openCRG.org, accessed on 2010/07/20.

Rodrigues' rotation formula, (2008), Wikipedia, *Rodrigues' rotation formula*, www.wikipedia.org/Rodigues'_rotation_formula, Accessed 2008/01/10.

Sayers, M.W. and Karamihas, S.M., (1998), *The Little Book of Profiling* , University of Michigan, USA.

Spangler, E.B., (1964), *Road Profilometer Method for Measuring Road Profile*, General Motors Research Publication, GMR-452, Warren, MI, USA.

Zaayman, O.C.D., (1988), *Terrain profile roughness measurement and characterization*, Unpublished M.Eng Thesis, University of Pretoria, South Africa.

Biographical notes:

Carl Martin Becker obtained his degree in Mechanical Engineering at the University of Pretoria in 2005. Carl subsequently continued with his Master of Engineering degree and finished in 2008. He worked in industry for two years as a Test Engineer focusing on landmine protected vehicle. In 2010 he returned to the University of Pretoria and began with his research in vehicle dynamics together with the Vehicle Dynamics Group. His current research efforts are focused on vehicle dynamics, terrain profiling and the characterisation of tires and tire models for simulation purposes.

Pieter Schalk Els (Schalk) worked in industry, developing and testing military wheeled vehicles for 5 years. He was actively involved in many of the new technology projects developed by the company as well as applied research. Highlights include semi-active dampers for heavy vehicles (6 ton axle loads) as well as the world's first semi-active hydraulic rotary damper for a heavy vehicle. In 1999 he joined the Department of Mechanical and Aeronautical Engineering at the University of Pretoria as a permanent staff member and obtained a PhD from the University of Pretoria in 2006. He is the research leader of the Vehicle Dynamics Group. His current research efforts are focussed on the use of semi-active dampers, combined with semi-active springs and ride height adjustment to improve ride comfort, handling, rollover propensity and life of off-road and heavy vehicles. This includes tyre, terrain profile and suspension component characterisation and modelling as well as vehicle dynamics control.